

Protected Areas Resilient to Climate Change, PARCC West Africa



Projected Impacts of Climate Change on Biodiversity in West African Protected Areas



ENGLISH

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Table of Contents

ACKNOWLEDGEMENTS.....	4
EXECUTIVE SUMMARY	5
1. INTRODUCTION.....	6
2. METHODS.....	9
3. RESULTS.....	15
4. DISCUSSION.....	24
5. REFERENCES.....	27
ANNEX 1: EXCLUDED SPECIES	35
ANNEX 2: COUNTRY LEVEL SPECIES TURNOVER MAPS	39
ANNEX 3: CHANGE IN CLIMATE SUITABILITY ACROSS THE NETWORK FOR RED LISTED SPECIES.....	58
ANNEX 4: 'HIGH PRIORITY' SITES IDENTIFIED FOR TWO OR THREE TAXONOMIC GROUPS	61

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Executive Summary

With climate change driving changes in species' distributions and abundance patterns, it is crucial to evaluate the effectiveness of current conservation strategies aimed at protecting biodiversity. Protected areas (PAs) are a core component of this effort, yet their static nature makes their continued effectiveness particularly vulnerable as species' ranges shift in response to changing climatic conditions. Tropical and sub-tropical regions contain the majority of global biodiversity, yet are also projected to experience some of the most extreme changes in climate. West Africa is one such region, and here threats to biodiversity are further exacerbated by extensive habitat loss, which has left a highly fragmented landscape, with many of the region's protected areas becoming increasingly isolated. This has the potential to reduce the ability of the PA network to protect the region's biodiversity as species' ranges shift. To date, the potential impact of climate change on the region's PA network has yet to be fully assessed.

We used models that link species' distributions to biologically important climatic variables that are likely to define species' distributions. We then used projections of future climatic conditions and estimates of dispersal potential to assess impacts of changing climatic conditions on faunal (birds, mammals and amphibians) distributions and representation across the region's PA network.

Climate change impacts on West African biodiversity across the region's PA network are projected to increase during the 21st Century. By 2100, 91% of amphibian, 40% of bird, and 50% of mammal species are projected as 'extremely likely' to have reduced climate suitability across the region's PA network. No amphibian species, and only three bird and one mammal species, are projected as 'extremely likely' to experience improved climate suitability in the region by 2100.

We explored the importance of dynamically altering climate (i.e. using decadal climate data to modify species' spatial responses) over time. However, we found, for this region, that the added complexity had only a limited impact on simulated species responses. Consequently, we used simulated spatial responses to climate change based on a mean change in suitability for future periods for all assessments of future change.

Individual PAs are likely to both lose and gain species as distributions shift, resulting in changes to faunal communities. Species turnover is a measure of loss and gain of species at a site relative to species richness and provides a measure community change between time periods. Higher species turnover indicates a greater shift in projected community composition and suggests high climate change impacts. Species turnover (95% CI) for amphibians in PAs is projected to increase from 26.5% (23.1, 31.3) in the period up to 2040 to 45.7% (35.1, 71.7) by 2100. Impacts for birds and mammals are lower, yet still represent considerable impacts to communities, with species turnover by 2100 projected at 32.4% (20.3, 45.9) and 34.9% (21.8, 56.2) for birds and mammals, respectively.

We used a resampling approach to identify PAs that were in the upper quartile of projected species turnover for each taxonomic group for each time period, using three uncertainty tolerance thresholds (95%; 85%; 75%) to indicate those impacts for which we have most confidence. At the 95% uncertainty level, 80 out of 1,987 PAs are identified as being highly impacted for two or more taxa for the 2040 period. However, this falls to only five PAs by 2100. Accepting greater uncertainty, the number of multi-taxa (two or more) 'high impact' sites identified by 2040 increases to 134 at 85% uncertainty and 194 at 75% uncertainty. The majority of the multi-taxa 'high impact' PAs identified are located in the Guinea Forest region, with most of the PAs occurring within Ivory Coast.

These projected impacts represent a significant threat to the region's biodiversity, which is already under considerable pressure from habitat loss and hunting. This study has highlighted areas of greatest potential impact of climate change on PAs. Where species are likely to decline, steps must be taken to locate and properly protect potential refugia and to maximise connectivity between sites to facilitate range shifts.

1. Introduction

Protected area (PA) networks are a core component of the global effort to conserve biodiversity against multiple and increasing anthropogenic threats. At present, more than 13% of the global land surface is designated as a PA (Coad *et al.* 2010; Bertzky *et al.* 2012). Although much variation exists in the quality of protection provided (Craigie *et al.* 2010; Laurance *et al.* 2012), PA status can significantly reduce impacts of anthropogenic threats (Bruner *et al.* 2001; Adeney *et al.* 2009). Most PAs designated for biodiversity conservation have been selected because they protect an important habitat or population at the time. However, climate change is driving shifts in species' ranges (Hickling *et al.* 2006; Chen *et al.* 2011; VanDerWal *et al.* 2013), and this redistribution of species against a background of static PA networks has the potential to decrease their effectiveness as a conservation strategy. It is therefore crucial to assess the potential for existing PA networks to maintain climate suitability for species into the future in order to mitigate impacts and ensure robustness of the network to climatic changes (Araújo *et al.* 2011).

Projections of climate change impacts across taxonomic groups have predicted moderate to large range shifts for the majority of species (Huntley *et al.* 2008; Lawler *et al.* 2009; Barbet-Massin *et al.* 2012), with many species also undergoing range contractions (La Sorte & Jetz 2010) and declines in abundance (Gregory *et al.* 2009; Huntley *et al.* 2012; Visconti *et al.* 2015). Similarly, projected climate change impacts on protected area networks have predominantly predicted moderate to high turnover and declining representation of species (Coetsee *et al.* 2009; Hole *et al.* 2009; Araújo *et al.* 2011; Bagchi *et al.* 2013). Where protected areas are projected to remain suitable for a species into the future, predictions suggest that many populations will decrease in abundance (Johnston *et al.* 2013).

The West Africa region contains high levels of biodiversity and endemism (e.g. West Guinea Forests; Orme *et al.* 2005) across multiple taxa (Kier *et al.* 2009). This region is also projected to experience extreme changes in climate in future, including the disappearance of rare climates and the emergence of novel conditions (Williams *et al.* 2007). Compounding these potential climate change impacts, West Africa has seen considerable habitat loss, with a large proportion of tropical forests either degraded or converted to agricultural land (Norris *et al.* 2010). This has produced a highly fragmented landscape and led to the increasing isolation of protected areas (DeFries *et al.* 2005). In such a landscape, PA networks are especially important for protecting biodiversity, but the small size and isolation of many of the regions PAs increases the vulnerability of these sites to external pressures (i.e. hunting, logging and stochastic events). The additional impacts of climate change could threaten the effectiveness of the PA network and leave many species without necessary protection.

Projected impacts of climate change on birds for a subset of West African PAs and other non-protected sites of importance for birds (Important Bird Areas (IBA); Hole *et al.* (2009)) have suggested small to moderate impacts, with only a few areas, e.g. northern Senegal, projected to undergo high levels of species turnover. Hole *et al.* (2009) also assumed that species are able to perfectly track changing climate suitability, taking no account of species' specific dispersal and, therefore, likely underestimating impacts. No comprehensive assessment has been made for the region's existing PA network and no other taxonomic group has been evaluated. Thus, it is difficult to draw up broad adaptation guidelines from this limited assessment, with patterns of impacts expected to differ across taxa (Lawler *et al.* 2009) due to different patterns of exposure and vulnerability (Foden *et al.* 2013).

Climate change is already impacting biodiversity (Sinervo *et al.* 2010; Cahill *et al.* 2013) and is likely to be a major driver of population declines and extinctions in the future (Maclean & Wilson 2011). Predicting the potential impacts of climate change on biodiversity is crucial if we are to set appropriate conservation priorities and instigate management for the mitigation of future impacts (e.g. Heller & Zavaleta 2009). Climate change can impact populations through many different

mechanistic pathways (Geyer *et al.* 2011), both directly and indirectly, and with both positive and negative consequences (Davey *et al.* 2012; Ockendon *et al.* 2014). Climate induced changes in species distributions, resulting from local extinction and colonisation events are one of the most frequently documented impacts of climate change on biodiversity (Parmesan *et al.* 1999; Parmesan & Yohe 2003). Observed species' latitudinal and elevational range shifts have been greatest with higher levels of warming (Chen *et al.* 2011) and, although many species are currently able to track observed shifts in their climate niche (Chen *et al.* 2011), the populations of less vagile species are likely to undergo rapid range contraction with increasing climatic changes (Devictor *et al.* 2008).

Continually shifting species ranges are problematic for conservation management as conservation strategies must account for this temporal aspect, along with the associated uncertainty, in their spatial planning (Carvalho *et al.* 2011). Consequently, the area of habitat required to conserve the full range of current biodiversity into the future often increases considerably when accounting for these projected shifts in species distributions (Hannah *et al.* 2007). Reducing uncertainty within projections of future species distributions is of paramount importance because it enables better allocation of limited resources. Correlative models associating species distributions with bioclimatic variables are the dominant methodology for predicting species range shifts under future climate change scenarios. The strengths and weaknesses of this approach have been widely discussed (e.g. Araújo & Peterson 2012) with suggestions for improving predictive accuracy and increasing ecological relevance that include the incorporation of demographic data, habitat selection and species-specific traits (Huntley *et al.* 2010). However, the inclusion of such elements into models of species future distribution is often hampered by the complete or partial absence of data, which is especially problematic in many biodiversity rich regions of the world.

Whether a species' range size increases or decreases will, in part, depend on the balance between the loss and gain of areas of suitable climate (climate space), although the response of other interacting biotic components of a species' range are also likely to be important (Menendez *et al.* 2008; Schweiger *et al.* 2008). However, in order to take advantage of newly available climate space a species must be able to track shifting climate and, consequently, intrinsic dispersal ability will be crucial in determining the fate of many species (Schloss *et al.* 2012, Visconti *et al.* 2015). Highly dispersive species are more likely to keep up with the rate of climatic shifts, but species with low dispersal ability must adapt *in situ* (i.e. Quintero & Wiens 2013; Vedder *et al.* 2013), persist within local climate refugia (i.e. Morelli *et al.* 2012) or else suffer local extinction.

Recently, several studies have incorporated some measure of dispersal potential within projections of species' future distributions, although the approaches vary greatly in complexity. The simplest approach is to consider only extreme scenarios (no dispersal vs. full dispersal; e.g. Coetzee *et al.* 2009; Araujo *et al.* 2011). Approaches that are intermediate in complexity include, allowing a species to track changing climates at a constant rate (Reside *et al.* 2012) and allowing a species' range to shift by a distance based on the product of natal dispersal and number of generations over the study period (Barbet-Massin *et al.* 2012; Baker *et al.* 2015). These approaches omit any consideration of how climate suitability changes over time, and the consequences this has for dispersal in intermediate time-steps, such that species may jump over climatic barrier, either transient or permanent, that in reality would prohibit movement between patches with suitable climate. More complex approaches that account for changing climate and barriers to dispersal are likely to provide a better indication of likely range shifts for a species, especially when modelled on a fine temporal scale, i.e. annual dispersal (Engler & Guisan 2009; Early & Sax 2011; Lawler *et al.* 2013). However, the effect of climate-dispersal interactions on assessments of climate change impacts on biodiversity has yet to be evaluated across a broad spatial scale. This is important because there could be regional hotspots for the climatic inhibition of dispersal (e.g. areas of severe or rapid climate change and/or more sensitive species) and, thus, spatial heterogeneity both in the distribution of species affected by climate-dispersal interactions, and in regions where colonisations of suitable climate space are prevented.

In this study, we provide the first multi taxa assessment of climate change impacts to biodiversity within West Africa's existing protected area network. Correlative species distribution models and regional climate data were used to evaluate potential climate change impacts on West African protected areas for three taxa; birds, mammals and amphibians, incorporating individual species' dispersal abilities using available data. Impacts of climate change at both a community (species turnover, which is a measure of loss and gain of species at a site relative to species richness) and individual species (change in species' specific climate suitability across the network) level between the baseline period (1971-2000) and three future time periods (2011-2040; 2041-2070; 2071-2100) were calculated from estimates of modelled climate suitability and dispersal potential. Uncertainty in these projected impacts due to different climate projections and modelling methodologies were calculated, after also accounting for spatial dependency of species. These uncertainties were used to assess confidence in projected impacts and to identify robust 'high impact' sites for conservation prioritisation. This study highlights several areas that are likely to be impacted by climate change across multiple taxa, and also demonstrates the importance of considering uncertainty in projected impacts. Finally, we then undertook a regional scale assessment of the impacts of incorporating dynamic climate suitability into projections of climate-driven species range changes for species using a dynamic dispersal model. We predict that areas projected to be climatically unsuitable (either permanently or transiently) for a species will interact with dispersal traits and reduce the potential to colonise newly suitable climate space relative to dispersal assumptions that do not consider climate suitability. Thus, the effective availability of a species' climate niche will be reduced for some species in spite of apparent dispersal potential. We assess the impact of dynamic dispersal on projected change in species richness, relative to the unlimited dispersal scenario, to test whether the incorporation of this extra dispersal process alters projected climate change impacts for West African Avian diversity.

2. Methods

Regional climate models

Climate data for this study were produced by the Met Office Hadley Centre (MOHC) for the period 1949 to 2100. The approach, described in more detail by Buontempo *et al.* (submitted), uses the MOHC regional climate modelling (RCM) system, PRECIS (Jones *et al.*, 2004), with the SRES A1B scenario, at a ca. 50km² resolution for the Africa CORDEX domain (Giorgi *et al.* 2009). PRECIS is a physically-based model that enables the dynamic downscaling of General Circulation Models (GCM) to an ecologically relevant spatial scale. Described within the RCM are processes including dynamical flow, the atmospheric sulphur cycle, clouds and precipitation, radiative processes, the land surface and deep soil. In order to set the RCM within a global climate context, the RCM is driven at the boundaries by time dependent large-scale fields (e.g. wind, temperature, water vapour and surface pressure, and sea-surface temperature), which are provided by the HadCM3 General Circulation Model (GCM; Gordon *et al.*, 2000). It is important to provide a measure of uncertainty in the climate projections, and here this is provided using a Perturbed Physics Ensemble (PPE), where uncertainty is sampled systematically by perturbing uncertain parameters. For this study, a 17-member perturbed physics ensemble was used to assess uncertainties in atmospheric parameterizations (Murphy *et al.*, 2007; Collins *et al.*, 2011). From this GCM ensemble, five members (different formulations of a forecast model) were selected for dynamical downscaling based on two criteria. Firstly, the projections for the historical period were compared to observed climate data and models that failed to capture important climate patterns (e.g. seasonal temperature cycles) were discarded. Secondly, from the remaining models, a five-member ensemble was selected that captured the full range of uncertainty in projections of future temperature and precipitation (see Buontempo *et al.*, submitted, for more details).

Four bioclimatic variables were calculated for each time period from the monthly RCM data for each of the five ensemble members: mean temperature of the warmest month, mean temperature of the coldest month, precipitation seasonality and an aridity index (mean precipitation/potential evapotranspiration). Precipitation seasonality was calculated as the coefficient of variation of mean monthly precipitation. These four bioclimatic variables have been shown previously to be good predictors of species ranges in tropical and sub-tropical systems (Bagchi *et al.* 2013), defining tolerance to thermal extremes and water availability. The influence of these bioclimatic variables on a species' ability to persist in a landscape will not always be a direct function of the bioclimatic variable itself, but will often operate through impacts on vegetation or food (e.g. Pearce-Higgins *et al.* 2010). Thus, water availability, quantified here using the aridity index, a metric that has been used extensively for modelling the distribution of plants (e.g. Platts *et al.* 2010; Franklin 2013; Platts *et al.* 2013), will largely affect bird and mammal distributions indirectly through impacts on vegetation (Choat *et al.* 2012), but will have more direct impacts on amphibians. For the baseline (1971-2000) and three future periods ('2040' = 2011-2040; '2070' = 2041-2070; '2100' = 2071-2100), the variables were calculated as means over the periods.

Species Distribution modelling

Species distribution polygons for the breeding ranges of all extant bird (from BirdLife International and NatureServe 2013), mammal and amphibian (IUCN 2013) species were gridded onto a 0.44° grid (ca. 50km² at the equator), which corresponds to the native resolution of the RCM climate data. A species was considered to occur in a cell if the overlap between the distribution polygon and the cell was ≥10%, which is a liberal threshold that helps ensure that species with restricted ranges are represented. Species were only included in the analysis if ≥75% of their African breeding range occurred within the RCM extent. This cut-off was chosen to remove species with a substantial portion

of their breeding range beyond the RCM extent and, thus, species for which we were unable to model a large proportion of the species-climate relationship. All species with breeding ranges occupying fewer than five cells were also omitted from the analysis due to difficulties in modelling such sparse data (see Table 1 for exclusion details and Annex 1 for a full list of excluded species). This removed seven Critically Endangered species (5 amphibian; 2 mammal), 12 Near Threatened species (7 amphibian; 5 mammal), 15 Endangered species (8 amphibian; 3 bird; 4 mammal), eight Vulnerable species (2 amphibian; 6 mammal), 27 Data Deficient species (19 amphibian; 9 mammal) and 80 species of Least Concern (10 amphibian; 58 bird; 12 mammal).

We used a jack-knife resampling approach to modelling species' distributions as a function of bioclimate in order to quantify the uncertainty in modelled distributions introduced by uncertainty in the climate data, modelling methodologies and spatial dependency in species' distributions (Hole et al. 2009; Bagchi et al. 2013; Baker et al. 2015). The following explanatory text is adapted from Bagchi et al. (2013). To deal with the issues of spatial autocorrelation, we estimated the transferability of the fitted models to spatially segregated test data (k-fold partitioning) and then used a nonparametric jack-knife to estimate the uncertainty in model predictions. The data were split into sampling units defined on the basis of African ecoregions (Olson et al., 2001). The same ecoregion often occurs in several, geographically distinct locations; non-contiguous areas of an ecoregion were considered separate sampling units. A few very large ecoregions (greater than 450,000 km² in area, roughly 6° x 6°) were split into smaller sampling units by intersecting them with a 6° x 6° grid and treating parts of the ecoregion in different grid squares as separate sampling units. This ensured that subsequent blocks formed by grouping the sampling units were similar in size. We grouped sampling units into 10 blocks so that the mean of the bioclimatic variables differed little among blocks but each block spanned the full range of bioclimates. This ensured that block and bioclimate were orthogonal and avoided truncation of species response curves, which can cause problems when analysing segregated data (Thuiller et al., 2004). The baseline distribution of each species (1971-2000) was modelled as a function of the bioclimatic variables for each jackknife combinations of the RCM climate projection and block (leaving one block out in turn) using four modelling methodologies (generalised linear models (GLM), generalised additive models (GAM), generalised boosted models (GBM) and random forests (RF)). For each species, after cross-validation to optimise model performance, 100 models were fit to the blocked baseline distribution data, i.e. each combination of block (5), RCM climate projection (5) and modelling methodology (4) (see Bagchi *et al.* 2012 for full methodological details).

Species' specific dispersal ability was incorporated into projections of future range shifts following the methodology of Barbet-Massin *et al.* (2012), where values for climate suitability were adjusted by a colonisation probability. This latter value was derived by assuming that a species' natal dispersal probability as a function of distance is described by a gamma distribution (shape = (mean distance/sd)²; scale = mean distance/shape) and that independent natal dispersal events across a time period (e.g. 30 years) can be described by the sum of *x* gamma distributions, where *x* equals the number of natal dispersal events expected within the period (length of period (years)/minimum age first breeding (years)). This distribution was rescaled so that the distance at which the probability of dispersal is maximised was equal to 1. All unoccupied cells located at less than or equal to this distance from an occupied cell were assumed to be colonisable over the focal time period and their climate suitability unaltered. Climate suitability for all cells located at greater distances from occupied cells was rescaled as a function of distance (climate suitability x colonisation potential), based on the rescaled gamma distribution, such that suitability decays with distance (see Barbet-Massin *et al.* (2012) for further details).

Species-specific estimates of mean natal dispersal distance and age of first breeding were available for all birds (BirdLife International). For non-volant mammals, we obtained species' specific body mass and age-of-first-breeding data from two data sources (Ernest 2003; Jones et al. 2009), with missing values inferred from closest relatives, and used allometric equations (Sutherland *et al.* 2000) to estimate median dispersal distances from these data. For Chiroptera, there are no similar

allometric equations; however, categorical mean natal dispersal estimates are available from IUCN (Foden et al. 2013; Carr et al. 2014). We used the mid-point of these estimates as the mean natal dispersal for these species. No similar data are available for amphibians, but a literature search suggested mean annual dispersal distances of 0.2km yr⁻¹, with infrequent longer distance dispersal events are representative (e.g. Araújo *et al.* 2006, Smith & Green 2006). We therefore set mean natal amphibian dispersal equal to 1km and assumed annual dispersal events.

There were no comprehensive estimates available for the standard deviation of natal dispersal and, therefore, we used a value [mean × 1.5] that fits the range of standard deviations of natal dispersal estimated for European birds (Paradis *et al.* 2002) and based on recapture data. This value assumes a higher probability of long distance events than a negative exponential distribution, which is probably realistic for most species. Nonetheless, further research on dispersal in tropical species is necessary to better parameterise models of dispersal.

The median and 95% CI climate suitability, with future periods adjusted for dispersal potential, was obtained from across the 100 estimates of climate suitability (climate ensemble (5) × SDM (4) × block (5)), thus, accounting for uncertainty in climate projections, modelling methodology, and spatial dependency.

Dispersal modelling

To evaluate the interacting effects of dynamically changing climate suitability and species dispersal potential, we used the R package ‘MigClim’ (Engler & Guisan 2009; Engler *et al.* 2012), which has been specifically designed to model dispersal incorporating habitat suitability data from species distribution models. At each time step the model checks whether each unoccupied cell is suitable (climate suitability > 0) and, if true, calculates the probability of a cell being colonised (P_{Col}) as follows:

$$P_{Col} = \left(1 - \prod_{i=1}^n (1 - P_{Disp_i}) \right) \times P_{Clim} \quad \text{Eqn. 1}$$

where P_{Disp_i} is the probability of dispersing to the target cell from source cell i , which is derived from a dispersal kernel. P_{Clim} is the climate suitability of the target cell and n is the number of cells with potential dispersers. Dispersal was modelled in a similar way to that described in the previous section, but here additionally incorporating changing climatic suitability over time. We used ‘MigClim’, using a gamma distribution with shape = (mean/SD)² and scale = SD²/mean (following Barbet-Massin *et al.* 2012), where the mean was derived from species-specific trait data (BirdLife International) and the SD was set equal to 2 × mean dispersal distance, which represents the upper value derived from empirical data (Paradis *et al.* 2002; Barbet-Massin *et al.* 2012). Species’ dispersal estimates were taken from BirdLife International’s database and comprises banded estimates of mean natal dispersal distance in the classes <5 km; 5-24 km; 25-49 km; 50-99 km; 100-199 km. The probability of dispersing to a cell at a given distance from the source cell was calculated for cells up to a distance of 20× the mean natal dispersal distance. Each dispersal probability was then divided by the sum of dispersal probabilities within this area of potential dispersal, such that the summed dispersal probability was equal to one (Chipperfield *et al.* 2011). Species were assigned to these classes based on data from published and unpublished estimates collated from a wide variety of sources (deriving from various studies involving marked individuals), with estimates extrapolated from related species with similar body size where primary estimates were not available). We used the mid-point of these bands in our analysis. We focussed on birds only in this comparative analysis as birds were the only taxonomic group to have good estimates of dispersal potential for most species.

The dispersal modelling was carried out at a spatial resolution of c. 5km (vs. c. 50km RCM resolution) in order to better represent the dispersal for species that have a low mean natal dispersal

distance (i.e. sub-50km). The initial distribution was based on the modelled probability of occurrence for the baseline climate data (1971-2000), but converted to binary presence/absence using the average probability/suitability approach, which was found to be robust across a range of prevalence (Liu *et al.* 2005). The modelled distribution might, by chance, predict false presences in areas widely spatially separated from the observed distribution due to similarity in climatic conditions. We constrained the initial predicted distribution to those cells that fall within two c. 50km grid cells (c. 100km) of a presence (as inferred from the range polygons) so that the initial state of the simulation is a close approximation of the recorded distribution. The baseline distribution was then disaggregated to c. 5km resolution.

For the dynamic-climate scenario, climate suitability was updated decadal using the species' specific projected decadal suitability. Climate suitability for future projections were not converted into binary suitable/unsuitable data, but were used directly within the dispersal model as a measure of climate suitability. Thus, a cell with a modelled climate suitability of 0.8 is twice as suitable as a cell with a suitability of 0.4. However, to be consistent with the baseline modelled distribution data we set all values less than the species' specific threshold for binary presence/absence to zero. Once the modelled climate suitability in a cell falls below this threshold the cell will experience a local extinction. This prevents cells from continuing as source cells despite having very low climate suitability. Each of the climate suitability projections was then disaggregated to c. 5km resolution. Once colonised, a cell was only capable of producing dispersing progeny after a time period equal to the age of first breeding was reached. Thus, if a species starts breeding at age three years a cell would need to be colonised for three years before it will start to act as a source population. Data on age of first breeding came from BirdLife International's world bird database). The model outputs were converted back to a 50km resolution, with each c. 50km cell considered colonised if any of its constituent c. 5km subcells were colonised. Due to the random component of the dispersal model, for each species the dispersal model was run five times using the same initial distribution, climate suitability and dispersal estimate, with the consensus (colonised/uncolonised) for each cell across the five replicates used as the final output. To contrast with the dynamic-climate and static climate models, we also evaluated range extents assuming an unlimited-dispersal and a no-dispersal scenario. The former assumes that a species can occupy the full extent of the projected climate suitability for a particular time period and, thus, is defined as the full extent of the projected range.

The effect of dispersal on projected climate change impact was assessed by calculating the change in species richness between the baseline period and the end-of-century (2070-2099 time period) for each cell across the region. This was done separately for both the dynamic climate and dispersal projections and for projections where static, end-of-century climate suitability was used. Here, we chose to use an end-of-century projections for evaluation of impact, rather than the mid-century projections presented elsewhere, as we were comparing impacts within species for the same broad modelling approaches and climate scenarios (with and without dynamic climate effects). Hence, the high uncertainty amongst end-of-century models that we have reported elsewhere (Baker *et al.* 2015) is less important than in situations where we are interested in the likely impacts of climate change in real-world scenarios. Running these dynamic models until 2100 permitted the detection of differences between dynamic and static models that may have been rather limited in the short-time span between current and mid-century (2040-2069) projections.

Protected area assessment

Protected area polygons were obtained from the WDPA (IUCN and UNEP-WCMC 2013), and gridded on to a 0.44° grid (RCM resolution; ca. 50km²), calculating the percentage overlap of each PA with each grid cell. For this analysis, we only include PAs that have known boundaries (i.e. omitting point-only data), given the considerable uncertainty introduced when attempts are made to approximate the location of the PA using buffers (Visconti *et al.* 2013).

Previous studies have carried out PA specific assessments of climate change impacts by downscaling climate data to fine resolutions (e.g. c. 5km²) for each PA and projecting species distributions directly at this finer resolution (Hole *et al.* 2009; Bagchi *et al.* 2013). However, the uncertainty introduced into the model projections by downscaling climate projections to such fine resolutions is unknown. We take a more conservative approach by assuming the PA has the climate suitability of the cell(s) in which it is embedded. Whilst this is likely to produce poor predictions for PAs that represent outlying climatic conditions within a cell (as might occur for example with mountain-top PAs), most PAs in this region share a similar climate to the surrounding landscape at a 50km² scale. In order to assess this uncertainty, and to provide an indication of where we must use more caution in interpreting our predictions, we compared the altitudinal profiles of each PA with the profile of the cell(s) in which it is embedded. Each PA and ca. 50km² cell was disaggregated to ca. 90m² resolution and intersected with 90m² resolution altitude data (Jarvis *et al.* 2008) using bilinear interpolation to correct for a slight offset in projections from original data. For each PA, we sampled 200 altitudinal units randomly (weighted by the proportion of the PA in a cell) and 800 from the cell(s) as a whole, and calculated the mean difference in altitude between the two samples. Figure 1 shows the PAs where the mean difference between the altitudes for the two samples was greater than 100m (approx. equal to 1°C lapse rate (Danielson *et al.* 2003)), which is likely to suggest a biologically meaningful outlier. The predictions for these PAs should be treated with greater caution.

For each PA, a weighted mean of climate suitability for each species was calculated, with weights equal to the percentage of a PA's extent that overlaps a cell. The change in species richness for PA j (ΔS_j) was calculated as:

$$\Delta S_j[t_2] = \sum_{k=1}^s P_{jk}[t_2] - \sum_{k=1}^s P_{jk}[t_1]$$

where, P_{jk} = weighted climate suitability of species k in PA j , t_1 = baseline (1971-2000) and t_2 = future [2040; 2070; 2100] time periods. Species turnover for each PA ($T_j[t]$) between two periods was calculated using the Bray-Curtis index, a measure of dissimilarity between two communities, using the weighted climate suitability, as:

$$T_j[t_2] = \frac{\sum_{k=1}^s |P_{jk}[t_2] - P_{jk}[t_1]|}{\sum_{k=1}^s P_{jk}[t_1] + \sum_{k=1}^s P_{jk}[t_2]}$$

These calculations were carried out separately for each of the resampled climate suitability projections. Thus, 100 estimates of each impact metric were produced and the 95% quantiles from across these values was used to assess uncertainty.

For each species, the change in climate suitability across the PA network was measured as the summed weighted climate suitability for the future period divided by the baseline period. Where this value was > 1 , a species was projected to gain climate suitability across the PA network; and where this value was < 1 , a species was projected to lose climate suitability. For each species, this projected change in climate suitability was calculated for each of the resampled projections and the 95% quantiles used to assess confidence in the projections. Where 95% CI of these projections do not span unity (i.e. consensus on projected change), we term changes as “extremely likely”, following the terminology of the IPCC 4th assessment report.

Identifying ‘high impact’ sites robust to uncertainty

In order to identify sites that are consistently projected to experience the greatest impacts from climate change, using species turnover as a metric of impact, we used a bootstrap resampling

approach to sample across the ensemble of projections, quantifying the proportion of times a PA was projected to experience a level of species turnover in the highest quartile across all the region's PAs. Thus, for each of the three major taxonomic groupings (birds, mammals, amphibians), we randomly selected one of the five RCM climate projections and then for each PA we randomly selected a projected turnover estimate from the 20 turnover values, derived from varying SDM and block, relevant to that projection. The resultant estimates were divided into quartiles based on the values for all PAs. This procedure was repeated 10,000 times and the percentage of species turnover estimates falling with the upper quartile from the 10,000 replicates was recorded. Those PAs in which $\geq 95\%$ of the turnover estimates fell within the upper quartile were given a score of 1, and all other sites 0, and the scores combined across taxa. Thus, PAs scoring 1 are consistently ranked amongst the highest impacted sites for one of the three major taxonomic groupings, whereas, those scoring 2 or 3 are high impact sites for two or three groups, respectively. This analysis was carried out for the three future time periods separately, to look at the impact of increasing uncertainty on identifying robust conservation targets, and for two lower uncertainty thresholds of $\geq 85\%$ and $\geq 75\%$.

3. Results

Species distribution modelling

Species distributions models were run for 1,286 species across all taxa, from an initial pool of 1,443. Table 1 summarises the number of species excluded for each criteria. Models for all species within each taxon showed good model discrimination throughout (median AUC: amphibian = 0.98; birds = 0.97; mammals = 0.97; Table 1).

Taxa	Regional species pool	Number of species excluded by criteria (sequentially)			Number of species included	Median AUC (95% quantiles)
		<75% RCM overlap	<5 presences	Single block		
Amphibians	206	24	23	9	150	0.98 (0.92, 0.99)
Birds	830	61	0	1	768	0.97 (0.89, 0.99)
Mammals	407	29	7	3	368	0.97 (0.87, 0.99)

Table 1. Summary statistics showing the initial number of species from each taxonomic group that had some breeding range within the West African region, the number of species excluded by each exclusion criteria, and the total number of species included in the analysis. The results for the exclusion criteria are nested from left to right, such that the numbers shown are the numbers removed after the exclusion by the preceding criteria. Median AUC across all species distribution model is shown with the upper and lower 95% quantiles in parentheses.

Assessment of climate change impacts on PA networks

Across the region, 1987 protected area polygons were selected for analysis; a number that excludes 195 PAs that are currently only mapped as a point location, or sites that are designated as Biosphere Reserves (because they may include large areas that are not considered protected areas). For 11% of PAs (219), the mean elevation difference between the PA and the 50km² cells in which it is embedded was greater than 100m, suggesting that the PA's climate could be dissimilar from the mean climate of these cells. Figure 1 highlights the location of these PAs, and results for these PAs should be treated with additional caution.

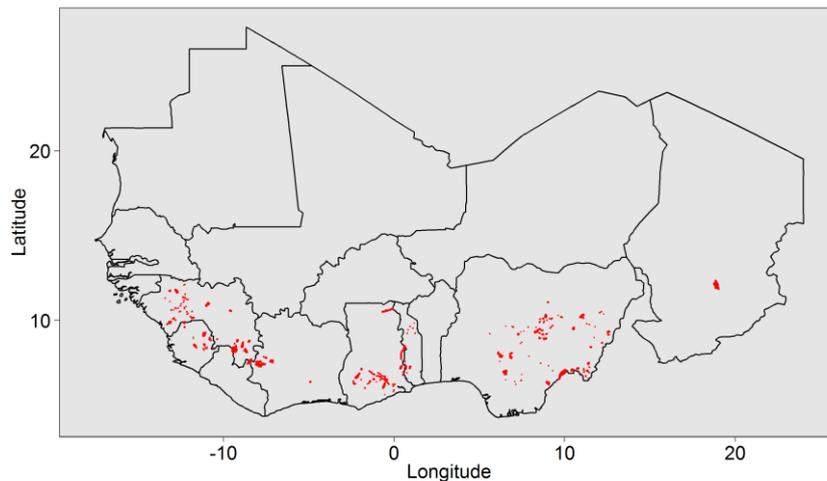


Figure 1. Location of PAs that have a ‘dissimilar’ altitudinal profile, as a surrogate for climate, from the cell(s) in which they are embedded. A mean difference >100m between the altitudinal profile of the PA and the cell(s) are considered to represent a difference that could affect the biodiversity found in the PA.

Projected impacts on amphibian representation in PAs

Amphibian species turnover across the region’s PA network is projected to increase over the next century, with a median (95% CI) projected turnover of 45.7% (35.1, 71.7) by 2100 (Table 2). However, the uncertainty around these projected impacts is considerable (Fig. 2a; Annex 2), which makes it difficult to quantify impacts for many of the region’s PAs by 2100. Nonetheless, in several species richness countries, such as Ivory Coast and Ghana, the lower bounds of uncertainty are projected to exceed 40% turnover by 2100, suggesting high turnover across projections, and these areas are consistently projected to experience higher impacts across all time periods. The projected turnover by 2040 suggests that early intervention may be necessary to mitigate climate change impacts for amphibians, with some countries projected to experience >30% species turnover during this period. Such patterns are reflected in the projected change in species richness (Table 3), where the median change across the region’s PAs is projected to be -8.1 species (-9.9, -4.9) by 2100.

When considering the median estimate of climate suitability, calculated across the ensemble of projections, for each amphibian species, climate suitability decrease for all 150 species in all time periods. When uncertainty in these projections was considered, no amphibian species were projected as ‘extremely likely’ to gain climate suitability during the century. By contrast, 91% (137) of species were projected to be ‘extremely likely’ to lose climate suitability by 2100, with the remaining species showing no consensus (2040; Gain (G) = 0, Lose (L) = 145, No Consensus (NC) = 5; 2070; G = 0, L = 144, NC = 6; 2100; G = 0, L = 137, NC = 13).

Of the 150 amphibian species included in this analysis, 30 are currently classified as critical (CR), endangered (EN), vulnerable (VU) or data deficient (DD) (CR = 1; EN = 13; VU = 13; DD = 3). The climate suitability across the PA network is projected to decline for all 30 species based on the median estimate in all time periods. When uncertainty is taken into account 87% (26), 90% (27) and 77% (23) of species are projected to be ‘extremely likely’ to lose climate suitability by 2040, 2070 and 2100, respectively, with ‘no consensus’ for the remaining species. See Annex 3 for list of these amphibian species and their projected change in climate suitability.

Projected impacts on bird representation in PAs

Bird species turnover across the region’s PAs is the lowest of the three taxonomic groups considered in this study, increasing from a median (95% CI) projected turnover of 14.0% (10.5, 20.5) by 2040, to 32.4% (20.3, 45.9) by 2100 (Table 2). Once again, the uncertainty in these projected

impacts by 2100 is considerable (Fig. 2b; Annex 2), but suggest that the western portion of the Guinea Forest will experience the greatest impact on species turnover and richness (Table 3).

The median climate suitability across the region's PA network for bird species suggests that 12.5% (100) of species will experience increased climate suitability by 2040 and 80, 5% (668) of species will experience declining suitability; by 2100, only 9.9% (82) of species are projected to have improved climate suitability. When uncertainty in the projections is considered, only 1.6% (12) of species are projected as 'extremely likely' to experience improved climate suitability by 2040 [*Anthoscopus punctifrons*, *Butastur rufipennis*, *Ciconia abdimii*, *Estrilda troglodytes*, *Falco alopex*, *Muscicapa aquatica*, *Nectarinia pulchella*, *Pterocles quadricinctus*, *Serinus leucopygius*, *Streptopelia decipiens*, *Vanellus spinosus*, *Vanellus tectus*], and this decreases to three species by 2100 [*Egretta gularis*, *Streptopelia decipiens*, *Tockus erythrorhynchus*]. By 2100, 39% (302) of bird species are projected as 'extremely likely' to experience declining climate suitability across the region's PA network (2010-2039: G = 12 L = 393, NC = 363; 2040-2069: G = 5, L = 341, NC = 422; 2070-2099: G = 3, L = 302, NC = 463).

Of the 768 bird species included in this analysis, 29 are currently classified as critical (CR), endangered (EN), vulnerable (VU) or data deficient (DD) (CR = 0; EN = 3; VU = 20; DD = 6). Based on the median estimates, climate suitability across the PA network is projected to decline for the majority of these species over all time periods (2040 = 86.2% (25); 2070 = 79.3% (23); 75.9% (22)). When uncertainty is taken into account 38% (11), 31% (9) and 28% (8) of species are projected to be 'extremely likely' to lose climate suitability by 2040, 2070 and 2100, respectively, with 'no consensus' for the remaining species. See Annex 3 for list of these bird species and their projected change in climate suitability.

Projected impacts on mammal representation in PAs

Mammal species turnover across the region's PA network is lower than the projected turnover for amphibians, and comparable to bird impacts, with median species turnover increasing from 15.7% (12.1, 22.4) to 34.9% (21.8, 56.2) between 2040 and 2100, respectively (Table 2; Fig. 2c; Annex 2). The highest losses of species richness are projected to occur, once again, across the western Guinea Forests (Table 3).

The median climate suitability across the region's PA network for mammal species suggests that 9% (33) of species will have increased climate suitability by 2040, declining to 5.2% (19) by 2100. The remaining species are projected to have reduced climate suitability across the network. When uncertainty in the projections is considered, only two species are projected as 'extremely likely' to gain climate suitability by 2040 [*Hipposideros ruber*, *Pipistrellus rusticus*], which decreases to one species by 2100 [*Damaliscus lunatus*]. By 2100, >50% of mammal species are projected as 'extremely likely' to experience declining climate suitability across the region's PA network (2040; G = 2, L = 198, NC = 168; 2070; G = 2, L = 183, NC = 183; 2100; G = 1, L = 185, NC = 182).

Of the 368 mammal species included in this analysis, 61 are currently classified as critical (CR), endangered (EN), vulnerable (VU) or data deficient (DD) (CR = 5; EN = 12; VU = 17; DD = 27). Based on the median estimates, climate suitability across the PA network is projected to once again decline for the majority of these species over all time periods (2040 = 93.4% (57); 2070 = 90.2% (55); 90.2% (55)). When uncertainty is taken into account, 49% (30), 44% (27) and 46% (28) of species are projected to be 'extremely likely' to lose climate suitability by 2040, 2070 and 2100, respectively, with 'no consensus' for the remaining species. See Annex 3 for list of these mammal species and their projected change in climate suitability.

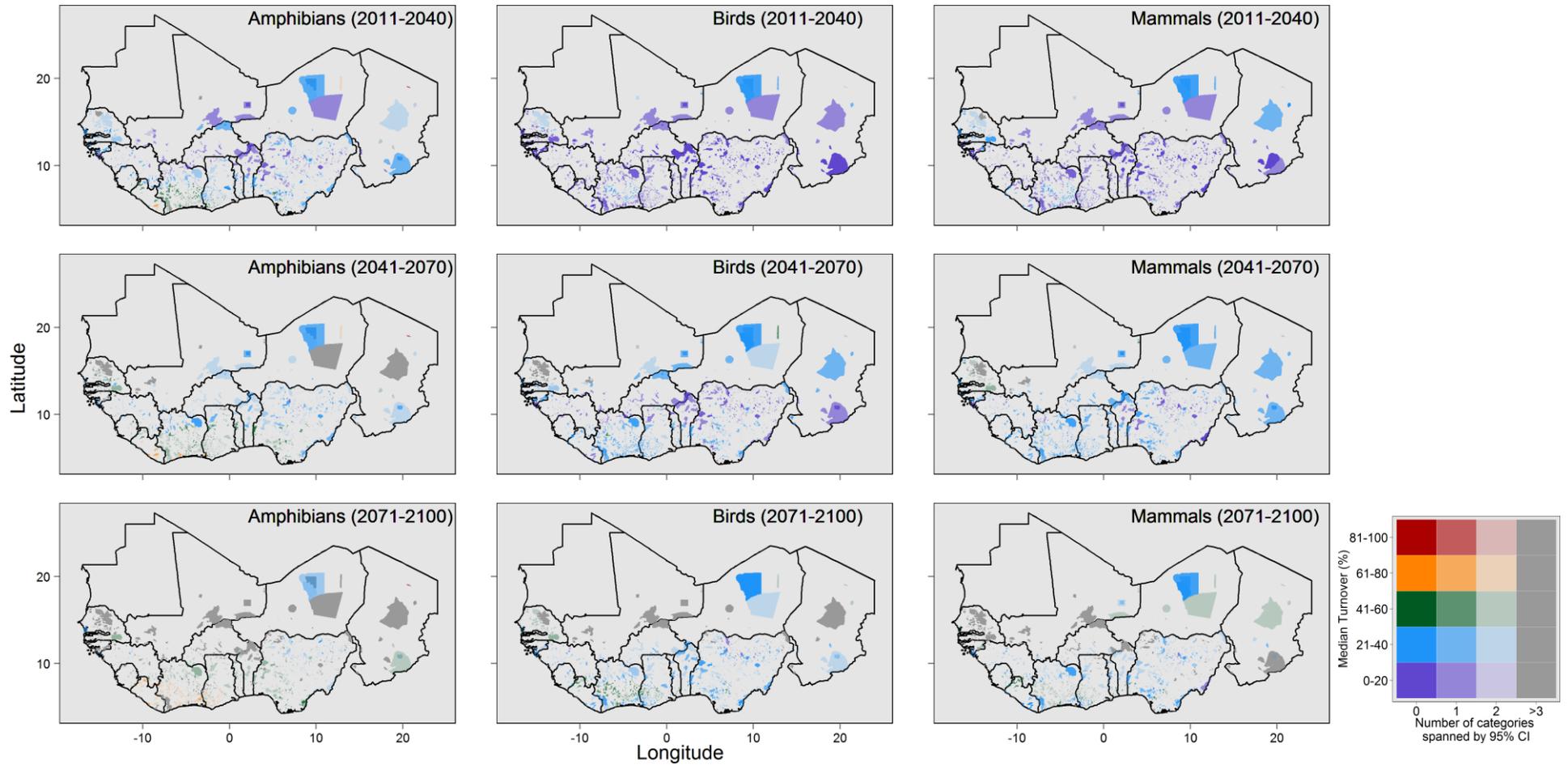


Figure 2. Projected species turnover (Bray-Curtis index), as a measure of change in community composition reflecting both gain and loss of species, between the baseline period (1971-2000) and three future periods (2011-2040; 2041-2070; 2071-2100) for A) amphibians, (n=150) B) birds (n=768) and C) mammals (n=368). Colours reflect the category encompassing the median projected turnover and the colour intensity, fading to grey as uncertainty increases indicates the uncertainty in these projected impacts based on the number of median turnover categories spanned by the 95%CI.

Country	PA (n)	Amphibian species turnover (%)			Bird species turnover (%)			Mammal species turnover (%)		
		2011-2040	2041-2070	2071-2100	2011-2040	2041-2070	2071-2100	2011-2040	2041-2070	2071-2100
ALL	1987	26.5 (23.1, 31.3)	36.8 (29.3, 50.9)	45.7 (35.1, 71.7)	14.0 (10.5, 20.5)	23.4 (15.6, 31.0)	32.4 (20.3, 45.9)	15.7 (12.1, 22.4)	27.5 (17.1, 34.7)	34.9 (21.8, 56.2)
BEN	28	21.5 (17.3, 29.6)	36.6 (23.2, 50.5)	46.7 (33.2, 71.8)	12.3 (8.8, 20.0)	20.1 (12.6, 32.8)	32.1 (19.0, 43.4)	13.6 (9.6, 22.1)	26.5 (16.2, 34.3)	32.5 (20.6, 55.4)
BFA	75	17.4 (10.4, 28.2)	27.1 (12.2, 47.5)	39.8 (16.3, 73.8)	9.8 (7.6, 19.8)	16.9 (9.0, 31.7)	30.4 (11.6, 48.1)	14.6 (10.2, 23.4)	25.3 (12.6, 35.9)	35.0 (15.0, 66.5)
CIV	239	40.3 (32.7, 50.8)	49.1 (39.3, 71.2)	59.3 (44.6, 80.4)	18.9 (15.2, 24.9)	29.8 (21.5, 40.2)	39.8 (28.7, 53.0)	19.6 (15.1, 27.0)	31.7 (23.1, 46.3)	42.6 (29.2, 64.0)
GHA	256	38.3 (29.4, 55.2)	50.1 (36.2, 68.7)	60.5 (45.2, 80.4)	17.5 (15.1, 23.5)	29.5 (21.4, 41.8)	38.9 (27.8, 53.0)	18.0 (14.4, 24.3)	31.0 (21.4, 44.8)	41.4 (29.4, 62.0)
GIN	106	21.5 (17.2, 26.8)	27.7 (20.8, 38.2)	36.2 (26.5, 68.7)	15.6 (11.5, 20.2)	18.0 (13.7, 28.7)	25.7 (17.4, 35.3)	14.9 (11.4, 23.7)	22.2 (15.6, 30.4)	29.3 (19.2, 47.3)
GMB	12	35.5 (15.0, 51.1)	48.0 (20.6, 65.9)	56.6 (32.2, 75.5)	16.4 (8.8, 27.5)	28.8 (17.3, 46.4)	42.8 (23.4, 60.3)	23.3 (10.0, 36.9)	39.5 (22.1, 59.7)	52.3 (29.3, 73.0)
GNB	19	22.9 (11.9, 34.6)	35.6 (19.9, 62.2)	50.4 (25.8, 81.3)	14.0 (10.0, 18.9)	23.0 (15.7, 32.4)	31.3 (19.2, 55.9)	16.1 (10.4, 25.4)	29.3 (18.0, 46.4)	43.3 (25.0, 71.1)
LBR	16	49.5 (40.1, 61.9)	56.5 (43.2, 70.9)	65.6 (53.1, 82.2)	16.9 (13.7, 23.8)	24.8 (19.8, 36.5)	37.6 (27.4, 49.7)	20.0 (15.8, 30.6)	28.9 (21.9, 39.3)	39.7 (30.2, 53.9)
MLI	32	18.5 (11.5, 27.1)	26.3 (12.7, 53.3)	39.4 (17.2, 88.4)	10.9 (7.1, 21.1)	21.5 (9.8, 32.7)	32.5 (14.0, 69.7)	16.8 (10.4, 22.7)	27.5 (13.5, 41.0)	38.4 (18.1, 78.9)
NER	15	23.2 (18.2, 34.3)	27.6 (20.7, 41.8)	34.6 (21.3, 74.1)	14.9 (9.2, 27.7)	23.7 (13.0, 32.2)	32.6 (15.6, 56.8)	18.3 (13.6, 26.1)	28.4 (19.2, 34.9)	37.1 (23.5, 66.0)
NGA	969	24.5 (21.1, 30.1)	33.8 (26.4, 44.6)	41.2 (32.4, 63.9)	12.1 (8.8, 18.3)	20.2 (13.7, 28.8)	29.6 (17.2, 41.3)	14.5 (11.0, 20.0)	24.4 (15.2, 30.5)	31.6 (18.7, 50.0)
SEN	109	26.8 (19.9, 39.2)	45.3 (26.0, 61.6)	60.9 (33.7, 82.0)	19.0 (11.3, 27.4)	37.2 (20.6, 52.9)	49.9 (28.4, 74.5)	24.7 (15.4, 39.9)	46.4 (26.0, 66.5)	57.5 (31.2, 84.1)
SLE	36	41.4 (31.6, 51.1)	48.9 (36.7, 67.1)	53.7 (40.1, 78.9)	18.6 (14.6, 27.3)	28.0 (20.8, 38.1)	35.6 (24.9, 44.9)	19.8 (15.0, 26.8)	29.7 (21.6, 40.9)	39.3 (25.1, 51.9)
TCD	14	24.0 (15.6, 35.4)	32.9 (20.9, 58.9)	45.1 (24.5, 84.7)	11.4 (8.4, 20.3)	21.6 (11.1, 30.1)	31.9 (13.7, 59.5)	16.9 (9.8, 22.8)	28.1 (13.1, 40.3)	36.5 (16.1, 68.7)
TGO	61	24.2 (17.9, 35.3)	40.4 (24.0, 54.6)	50.2 (35.4, 74.0)	13.7 (11.5, 25.2)	23.0 (15.8, 36.0)	34.2 (21.3, 43.8)	15.0 (11.4, 25.4)	27.7 (16.8, 35.2)	34.7 (23.4, 56.3)

Table 2. Median (95% CI) projected species turnover (%) between the baseline period (1971-2000) and three future time periods (2011-2040; 2041-2070; 2071-2100) for each taxon, calculated across all PAs in the region and for each country separately. BEN = Benin, BFA = Burkina Faso, CIV = Cote d'Ivoire, GHA = Ghana, GIN = Guinea, GMB = Gambia, LBR = Liberia, MLI = Mali, NER = Niger, NGA = Nigeria, SEN = Senegal, SLE = Sierra Leone, TCD = Chad, TGO = Togo. PARCC project countries are in bold characters.

Country	Amphibian change in species richness (n)			Bird change in species richness (n)			Mammal change in species richness (n)		
	2011-2040	2041-2070	2071-2100	2011-2040	2041-2070	2071-2100	2011-2040	2041-2070	2071-2100
ALL	-3.5 (-6.0, -2.5)	-5.8 (-8.3, -3.5)	-8.1 (-9.9, -4.9)	-19.4 (-27.4, -13.8)	-29.7 (-43.0, -14.8)	-42.6 (-71.6, -19.7)	-8.9 (-11.7, -6.1)	-14.2 (-23.2, -8.3)	-21.4 (-36.6, -11.8)
BEN	-2.6 (-3.6, -1.9)	-4.0 (-5.4, -2.7)	-5.0 (-7.0, -3.7)	-12.5 (-17.7, -8.1)	-18.3 (-28.8, -10.5)	-24.4 (-38.1, -11.6)	-6.1 (-8.6, -4.1)	-10.5 (-15.8, -7.0)	-13.9 (-23.0, -7.9)
BFA	-2.1 (-6.0, -0.1)	-4.1 (-8.2, -0.6)	-7.4 (-9.6, -1.9)	-12.7 (-20.6, -1.1)	-15.3 (-32.6, -0.0)	-29.7 (-70.2, -3.2)	-7.2 (-12.5, -1.9)	-12.3 (-21.1, -3.8)	-18.4 (-32.5, -4.8)
CIV	-8.7 (-11.1, -7.2)	-10.5 (-13.7, -8.4)	-13.0 (-16.6, -10.3)	-44.6 (-64.4, -24.9)	-56.7 (-85.2, -36.8)	-72.2 (-97.6, -43.3)	-17.7 (-24.4, -13.0)	-26.2 (-42.2, -20.0)	-35.7 (-52.9, -24.3)
GHA	-8.9 (-11.9, -7.2)	-11.2 (-14.6, -8.4)	-13.5 (-17.9, -10.4)	-43.1 (-58.4, -21.1)	-56.0 (-86.5, -32.9)	-70.0 (-104.0, -40.0)	-16.8 (-23.1, -11.8)	-26.4 (-44.1, -18.2)	-35.4 (-55.7, -23.1)
GIN	-2.9 (-5.3, -2.1)	-4.2 (-9.2, -2.1)	-6.9 (-11.8, -3.8)	-29.5 (-44.4, -7.2)	-18.6 (-31.9, -5.8)	-27.5 (-56.7, -12.6)	-7.9 (-15.7, -4.7)	-14.3 (-25.8, -7.1)	-22.2 (-38.5, -10.6)
GMB	-2.5 (-8.3, 1.1)	-3.6 (-9.7, 0.3)	-4.1 (-13.4, -0.3)	-20.8 (-71.4, 5.9)	-47.5 (-90.5, -3.8)	-65.6 (-131.1, -3.5)	-10.2 (-25.5, 2.5)	-18.8 (-35.0, -1.8)	-24.5 (-45.3, -5.2)
GNB	-1.5 (-2.6, -0.2)	-2.7 (-3.7, -0.8)	-3.4 (-4.7, -1.2)	-9.7 (-19.4, -3.7)	-15.9 (-32.6, -5.7)	-22.3 (-43.0, -7.4)	-4.4 (-8.5, -1.9)	-9.5 (-15.0, -3.4)	-12.1 (-19.3, -4.5)
LBR	-4.6 (-7.4, -2.9)	-5.1 (-7.9, -2.8)	-5.8 (-8.2, -3.5)	-17.8 (-27.4, -8.3)	-22.6 (-35.9, -9.4)	-29.9 (-46.7, -15.3)	-7.6 (-11.0, -2.3)	-9.7 (-14.6, -3.8)	-12.0 (-20.0, -5.7)
MLI	-1.3 (-2.6, -0.2)	-2.3 (-4.0, -0.5)	-3.9 (-5.4, -1.4)	-4.6 (-10.4, -0.1)	-10.6 (-20.8, -1.1)	-20.0 (-42.5, -4.9)	-3.5 (-6.2, -1.2)	-7.0 (-12.3, -1.6)	-11.3 (-19.6, -3.4)
NER	-0.2 (-0.8, 0.0)	-0.4 (-1.3, 0.0)	-0.8 (-2.4, 0.0)	-0.3 (-2.8, 2.1)	-0.7 (-7.6, 0.3)	-1.6 (-22.2, 0.5)	-0.7 (-2.4, -0.2)	-1.9 (-4.8, -0.0)	-3.2 (-9.4, -0.0)
NGA	-2.4 (-5.4, -1.1)	-4.3 (-7.5, -1.5)	-7.0 (-9.3, -2.5)	-10.6 (-29.6, -4.7)	-24.0 (-42.5, -4.7)	-36.6 (-65.8, -7.6)	-6.5 (-9.1, -3.3)	-10.8 (-19.1, -3.6)	-15.9 (-32.6, -6.1)
SEN	-1.0 (-2.9, -0.5)	-1.9 (-4.3, -1.0)	-2.5 (-5.6, -1.4)	-10.8 (-22.9, -0.5)	-24.4 (-41.2, -8.1)	-31.2 (-52.0, -14.8)	-5.3 (-9.5, -1.6)	-9.9 (-15.0, -5.0)	-11.6 (-17.7, -6.4)
SLE	-7.2 (-9.3, -5.3)	-8.4 (-11.4, -6.0)	-9.6 (-12.9, -6.3)	-35.5 (-45.7, -25.4)	-50.4 (-70.0, -28.3)	-61.3 (-78.9, -22.3)	-14.9 (-20.2, -9.4)	-21.4 (-30.7, -12.6)	-27.4 (-36.2, -13.4)
TCD	-1.0 (-1.8, -0.3)	-1.3 (-2.2, -0.3)	-1.8 (-2.9, -0.6)	-3.6 (-6.5, -0.6)	-3.0 (-7.5, -0.4)	-6.2 (-19.8, -0.5)	-1.7 (-2.9, -0.5)	-2.5 (-5.3, -0.7)	-3.7 (-9.7, -0.6)
TGO	-7.8 (-11.0, -5.8)	-12.5 (-15.4, -7.8)	-15.0 (-19.3, -10.3)	-33.9 (-59.3, -20.0)	-53.6 (-82.4, -33.6)	-67.3 (-108.3, -36.3)	-18.8 (-26.7, -12.9)	-30.4 (-42.6, -20.6)	-39.6 (-64.9, -23.0)

Table 3. Median (95% CI) projected change in species richness between the baseline period (1971-2000) and three future time periods (2011-2040; 2041-2070; 2071-2100) for each taxon, calculated across all PAs in the region and for each country separately. BEN = Benin, BFA = Burkina Faso, CIV = Cote d'Ivoire, GHA = Ghana, GIN = Guinea, GMB = Gambia, LBR = Liberia, MLI = Mali, NER = Niger, NGA = Nigeria, SEN = Senegal, SLE = Sierra Leone, TCD = Chad, TGO = Togo. PARCC project countries are in bold characters.

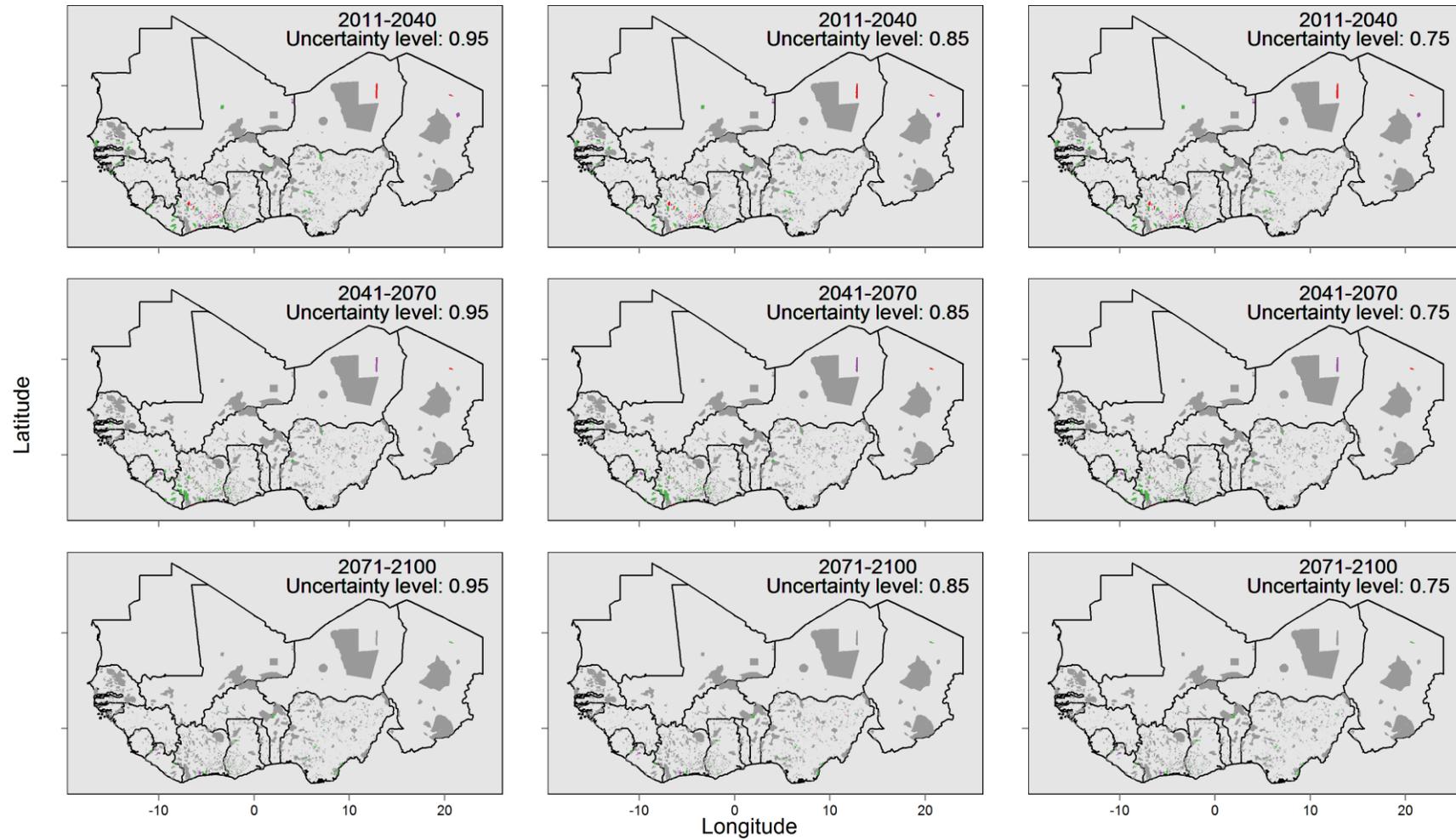


Figure 3. 'High impact' PAs robust to uncertainty identified via a bootstrapping procedure that determined the percentage of time a site was ranked in the upper quartile for species turnover across estimates of uncertainty in three different time periods and for three levels of uncertainty tolerance. The colour represents the number of taxa for which the PA was identified as being 'high impact' for a given level of uncertainty tolerance: Red = three taxonomic groups; Purple = two taxonomic groups; Green = one taxonomic group; Grey = not a robust 'high impact' site.

Identifying high impact cross-taxa conservation targets robust to uncertainty

At the 95% uncertainty level, 26 PAs (see Annex 3) are identified that are consistently projected to experience levels of species turnover in the upper quartile across the region's PAs ($n = 1987$ polygons) for all three taxa for the period up to 2040, and 80 PAs are identified for two or more taxa over this same period (Table 4). By 2070, seven PAs are projected to be in the upper quartile for three taxa (four in Cote d'Ivoire, two in Ghana, and one in Chad), and by 2100 only a single PA is projected to be (Banie in Guinea), and six PAs for two or more taxa. Relaxing the level of uncertainty that a PA is in the upper quartile for projected species turnover across the region's PAs to 85% or 75%, results in the number of multi-taxa (two or more) 'high impact' sites increasing to 134 and 194, respectively, by 2040. The number of 'high impact' sites identified for two or more taxa by the end-of-century using these relaxed uncertainty levels declines to 17 and 28 PAs, respectively. The majority of the multi-taxa 'high impact' PAs are located in the Guinea Forest region, with most of the PAs occurring within the Ivory Coast. With relaxed (85% and 75%) levels of uncertainty, 'high impact' multi-taxa sites are also identified in neighbouring countries of Liberia and Ghana, and in the northerly countries of The Gambia and Senegal.

	Uncertainty level =	95%			85%			75%		
		3	2	1	3	2	1	3	2	1
Number of taxa =		3	2	1	3	2	1	3	2	1
Time period	2011-2040	26	54	185	54	75	244	66	128	299
	2041-2070	7	20	136	22	78	236	49	109	301
	2071-2100	1	5	84	5	12	111	7	21	169

Table 4. Number of PAs identified as 'High impact' robust to uncertainty via a bootstrap resampling procedure that determined the percentage of time a site was ranked in the upper quartile for species turnover across all the region's PAs, sampling from across the 100 estimates of projected species turnover for each PA, in three different time periods and for three levels of uncertainty tolerance. The 'high impact' sites were identified for each taxonomic group separately and the congruence in these assessments is shown by the number of sites identified for multiple taxa simultaneously.

Projected changes in bird species distributions modelled using dynamic models and dynamic climate

The incorporation of dynamic dispersal across landscapes with changing climates can affect projected range shifts, notably resulting in a marked reduction in the number of species able to colonise an area (Fig. 4). Of the five focal PARCC countries, only Liberia and Sierra Leone appear to be affected by this additional layer of modelling, but the major impacts occur across Ivory Coast and, in particular, affect the species rich Guinea Forest and coastal regions (Fig 4c).

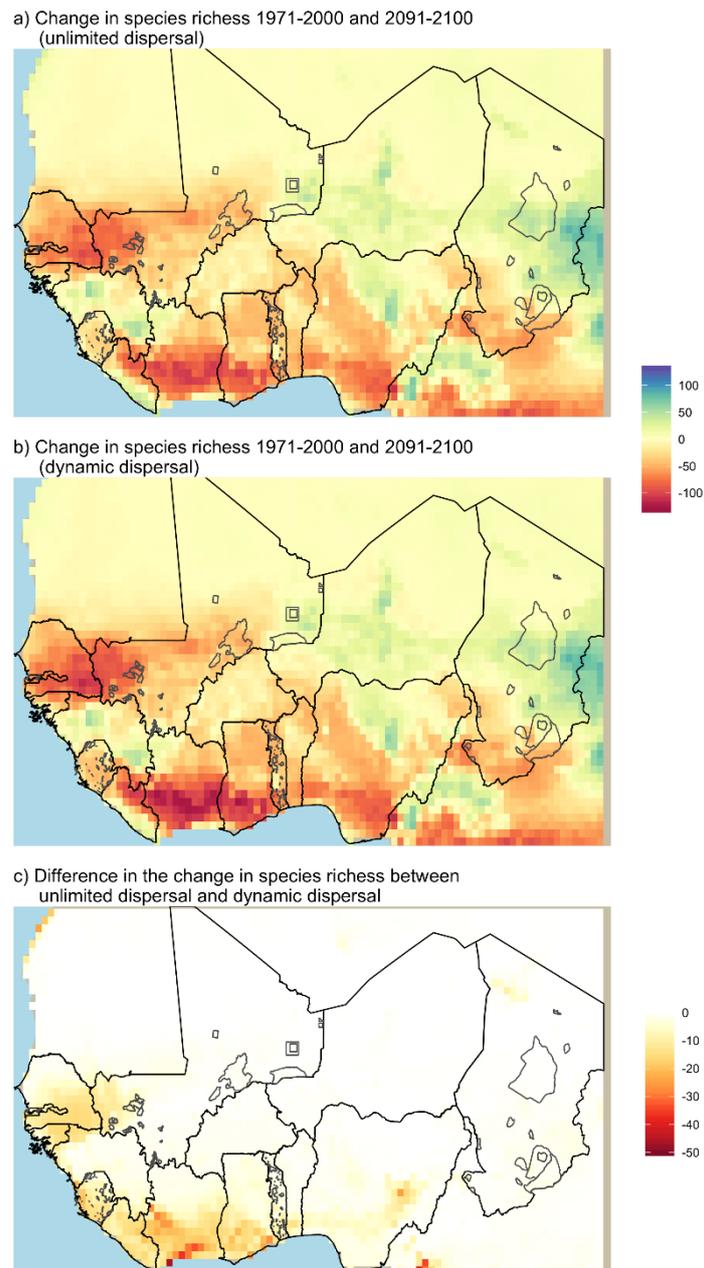


Figure 4. The change in bird species richness between the baseline (1971-2000) and the end-of-century (2091-2100) using: a) a static future climate and dynamic dispersal and b) dynamically changing climate and dispersal modelling. Panel (c) shows the difference between (a) and (b) with zero indicating that there is no difference in species richness between the two dispersal scenarios and negative numbers indicating that species richness projections based on the dynamic dispersal models are lower than those based on unlimited dispersal.

Thus, these results show that changing climate suitability can interact with species' specific dispersal potential to reduce projected climate driven range shifts, which in turn alters continental scale patterns of climate change impact on avian species richness, with potential important implications for regional conservation prioritization across some areas. However, because climate across West Africa is projected to change at a moderate rate, the impacts of incorporating dynamically changing climate data are relatively limited across much of West Africa (see the very limited impact in Figure 4c above). In areas of the world where climate is changing much more rapidly, e.g. as is happening currently in Arctic regions, incorporating such dynamically changing climate into dispersal models could markedly affect projections of species range shifts.

4. Discussion

Climate change has the potential to impact the fauna of West Africa severely, and to reduce the effectiveness of the protected area network to conserve the region's biodiversity. Across the network, substantial impacts are projected for all three taxa studied by 2100, although there is considerable spatial heterogeneity and uncertainty in these projections. At a country level, the highest estimates of climate change impacts (upper bounds of 95% CI) by 2100 for all three taxa predict levels of turnover exceeding 60% of species, with even higher impacts projected for amphibians in parts of the network. In parts of the region, many PAs could become unsuitable for a high proportion of species currently protected. Such drastic changes in communities could severely impact functionality (i.e. productivity), where lower species richness is likely to reduce functional diversity, which could decrease a community's ability to buffer environmental changes due to the loss of complementarity and redundancy of functional traits (Allan *et al.* 2011; Hooper *et al.* 2012; Reich *et al.* 2012). There is considerable uncertainty in these estimates, with the more optimistic of projections suggesting that many species may gain climate space, at least in the short term. However, even in the most optimistic scenarios, PAs are projected to experience changes in species composition and a loss of species richness, with consequences for ecosystem function and stability that are often unknown (Wardle *et al.* 2011).

By modelling the uncertainty in projections of species responses to climate change, we are able to identify PAs that are consistently projected to experience the highest climate change impacts for each of the three taxonomic groups. Furthermore, we are able to identify PAs that are projected to experience 'high impacts' for multiple taxa, which might be priority sites for further assessment. Substantial impacts were consistently projected by 2040, even with a strict threshold for uncertainty (95%), for PAs across southern Ghana, Ivory Coast and Liberia, with many PAs identified as robust 'high impact' sites for multiple taxa. This region contains much of the remaining tropical forest in West Africa, with these three countries containing the vast majority of the Upper Guinea Forests endemic bird area (Stattersfield *et al.* 1998), which hosts 15 endemic restricted range bird species. The biodiversity of the area is rather poorly known, with three (plus two suspected) bird species new to science having been discovered there in recent decades (Stattersfield *et al.* 1998). The fact that these areas have been heavily deforested, such that movement among forest PAs for species is reduced, may serve to exacerbate future climate change impacts.

Species turnover is projected to be particularly high for all taxonomic groups in The Gambia and Senegal region, although only a few of these PAs were identified as 'high impact' sites at the higher uncertainty levels (95%, 85%), and then only in the period up to 2040. Hole *et al.* (2009) projected severe impacts for IBAs in northern Senegal using different species distributions, climate data and modelling approaches. Our results suggest greater caution must be taken in assuming severe impacts in the region due to the substantial uncertainty inherent in such projections. Several isolated PAs in Niger and Chad (i.e. Oasis du Kawar (Ramsar Site) and Lakes of Ounianga (World Heritage Site); see Annex 3) are classified as 'high impact' sites at the highest uncertainty threshold for two or more taxa. However, as such areas have relatively low species richness compared to tropical regions, these high impacts are probably affecting relatively fewer species compared to the tropical PAs. Nonetheless, these changes could still result in a large impact on the functioning of these ecosystems (Brown *et al.* 1997).

By 2070-2099, uncertainty in the projections reduced the number of 'high impact' sites identified, especially at the highest uncertainty threshold, where the only site identified as 'high impact' for multiple taxa is located in southern Ivory Coast. This shows the importance of considering uncertainty in conservation prioritisation, where there must be a careful balance between impact and risk, both of which increase through time. Conservation management decisions need to consider the costs of being 'wrong' and, perhaps, accept greater uncertainty when the costs of making an incorrect

prioritisation decision are high, i.e. loss of critical species or functional groups. Because conservation funds are limited, the consequences of allocating resources to sites falsely identified as 'high impact' are as important as underestimating impacts and missing mitigation opportunities elsewhere. Thus, identifying management priorities presents analytically complex problems with many potentially valid solutions. The explicit incorporation of uncertainty into the decisions will help maximise the effectiveness of limited resources.

Correlative species distribution modelling is the dominant methodology for assessing potential climate change impacts on future species distributions, although recent trait-based (Foden *et al.* 2013) and mechanistic (Kearney & Porter 2009; Buckley *et al.* 2010) approaches have also been developed. Whilst the correlative SDM approach makes several simplifying assumptions (Araújo & Peterson 2012), such as species distributions being at equilibrium with climate, the results have often been found to match closely with independent observational data (Hill *et al.* 1999; Araújo *et al.* 2005; Gregory *et al.* 2009) and predictions from mechanistic models (Kearney & Porter 2009; Buckley *et al.* 2010). The accuracy of future projections is more difficult to assess, even if good validation datasets are available for models developed and tested on contemporary or historical data, as long-term distributional shifts might be affected by, for example, novel climates (Williams & Jackson 2007; Williams *et al.* 2007; Hobbs *et al.* 2009) or community dissociations (Araújo & Luoto 2007) that have yet to become evident. Comparisons between correlative and mechanistic models (e.g. biophysical or life-history models) have found some congruence in predictions of future range shifts (Kearney *et al.* 2010), but also substantial differences (Kearney & Porter 2009). Currently, when assessing climate change impacts on broad spatial scales and including many species from multiple taxonomic groups, the correlative SDM approach is likely to provide the best available option, given the lack of species' specific trait data (which is especially true in poorly studied tropical systems) to inform trait-based and mechanistic approaches.

When projecting species climate suitability to protected areas that are often smaller than the ca. 50km² scale used to model the species-climate relationship, there are several difficulties and sources of uncertainty. The climatic conditions predicted for a single cell are representative of the mean climate expected in this cell, but cannot capture the finer scale climatic variability within this area. Spatial variability in climatic conditions found below the resolution of the climate models could still provide refugia for species when the surrounding landscape is experiencing conditions incompatible with a species' ability to persistence. Microclimates have been shown to reduce an animal's exposure to climatic variability and allow persistence within a landscape (Scheffers *et al.* 2014). Thus, a PA could potentially experience a very different climate to the surrounding landscape if the PA is located in an area that is particularly distinct from the conditions found in the surroundings. This could be particularly relevant in areas of high relief, where PAs are located on land of low agricultural quality on high elevation and steep ground. For the analyses here, this is of less concern as, apart from some higher ground in Guinea and central Niger, West Africa is almost uniformly of low relief. PAs that are located at the extremes of a cell's elevational profile are most likely to be climatically different from the surrounding landscape, and, consequently, support different species. We have attempted to identify PAs that are located at elevational extremes with respect to the cell from which they are embedded, and our analysis highlighted ca. 10% of the PAs that should be treated with additional caution.

Here we have evaluated potential climate change impacts to species from three taxonomic groups across West Africa's protected area network and identified 'high impact' sites robust to the uncertainty in the climate data and modelling methodologies. After accounting for uncertainty, the region projected to experience the greatest impact is the Guinea Forest, with the highest density of 'high impact' targets for two or more taxa located in the Ivory Coast and Southern Ghana. Amphibians are projected to experience more substantial impacts by 2100 than either birds or mammals. This is rather worrying, as much better data currently exist on the distributions of the latter two taxa globally, meaning that most climate impact assessments on biodiversity in the tropics tends to focus

on these groups. Our work demonstrates that more substantial impacts may be suffered by poorly recorded taxa than currently projected by most climate impact studies in tropical systems, which focus on well recorded groups. The greater projected impact on amphibians may be due to their tendency to have smaller ranges, perhaps in part dictated by their mobility and, as a result, their climatic niche is narrow and suitable climate is less likely to persist in the PAs they occupy.

Finally, our exploration of the impacts of incorporating dynamically changing climate data into distribution models that also incorporate dispersal, suggested that the change in predictions are relatively limited across much of West Africa. This in turn suggests that models using static future climate projections, the current norm for most current species distribution modelling will provide useful results for species in the majority of situations. However, in areas where climate is changing rapidly, and where there is the potential for spatio-temporal bottlenecks in species responses to climatic change, such dynamic climate and dispersal models could provide additional insight

In the absence of dynamic-climate, the potential for many species to respond to climate change by tracking their shifting climatic niche is overestimated, even when accounting for species' specific dispersal potential (i.e. static-climate scenario, as per the main analysis here and Baker *et al.* 2015). Whilst unlimited dispersal assumptions are clearly inappropriate for many species, estimates of dispersal that fail to include interactions with the environment can also vastly overestimate the likely dispersal potential of species. The consequences of these failures to track shifting climatic niches for individual species could be severe (see separate individual species figures), but there are also implications for spatial patterns of biodiversity due to considerable spatial heterogeneity in the effect of dynamic-climate on species dispersal and, consequently, on regional species richness.

However, the deficits in the number of species projected to colonise a grid cell under the two different dispersal scenarios is only high in some localized areas of West Africa (e.g. parts of the Guinea Forest). As these countries are already projected to experience the greatest impacts of climate change to their biodiversity over the next century, these results are unlikely to alter conservation priorities across the region. Thus, the dispersal approach employed in Baker *et al.* (2015), and the main text of this document, is likely to be adequate for assessing the broad patterns of impacts across the region. Where research focused on individual species or was conducted at a finer resolution, where habitat patches and physical barriers to dispersal can be incorporated, there is likely to be considerable merit in using models to project the potential impacts of climate change on species and communities.

In conclusion, we have shown that the fauna of the western section of the Guinea Forest region is highly vulnerable to climate change impacts and, thus, the region's protected area network is likely to undergo severe changes in species representation and declines in species richness in the future. We recommend these 'high impact' PAs as key sites for future focus on climate change impacts on biodiversity. However, due to the great uncertainty in end-of-century projections, we encourage conservation planning decisions to be based on early- (and, perhaps, mid-) century impact projections. This will reduce potential errors arising from adaptive management based on end of century projections with high uncertainty, and will maximise the likelihood of success of early intervention opportunities for which we have greater confidence.

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Annex 1: Excluded species

List of species excluded based on the criteria described in the methods sections.

Species (binomial)	Taxonomic group	Red list category
<i>Alexeteron jynx</i>	Amphibian	CR
<i>Amietophrynus cristiglans</i>	Amphibian	DD
<i>Amietophrynus perreti</i>	Amphibian	VU
<i>Arthroleptis brevipes</i>	Amphibian	DD
<i>Arthroleptis cruscum</i>	Amphibian	EN
<i>Arthroleptis krokosua</i>	Amphibian	EN
<i>Arthroleptis langeri</i>	Amphibian	DD
<i>Arthroleptis nimbaensis</i>	Amphibian	DD
<i>Astylosternus occidentalis</i>	Amphibian	LC
<i>Cardioglossa alsco</i>	Amphibian	CR
<i>Cardioglossa nigromaculata</i>	Amphibian	NT
<i>Cardioglossa schioetzi</i>	Amphibian	EN
<i>Crotaphatrema tchabalmbaboensis</i>	Amphibian	DD
<i>Didynamipus sjostedti</i>	Amphibian	EN
<i>Geotrypetes angeli</i>	Amphibian	DD
<i>Geotrypetes pseudoangeli</i>	Amphibian	DD
<i>Hylarana fonensis</i>	Amphibian	DD
<i>Hyperolius bobirensis</i>	Amphibian	EN
<i>Hyperolius chlorosteus</i>	Amphibian	NT
<i>Hyperolius nimbae</i>	Amphibian	EN
<i>Hyperolius occidentalis</i>	Amphibian	LC
<i>Hyperolius soror</i>	Amphibian	DD
<i>Hyperolius sylvaticus</i>	Amphibian	LC
<i>Hyperolius viridigulosus</i>	Amphibian	VU
<i>Hyperolius zonatus</i>	Amphibian	NT
<i>Kassina wazae</i>	Amphibian	DD
<i>Leptopelis bequaerti</i>	Amphibian	DD
<i>Leptopelis macrotis</i>	Amphibian	NT
<i>Leptopelis occidentalis</i>	Amphibian	NT
<i>Leptopelis rufus</i>	Amphibian	LC
<i>Leptopelis spiritusnoctis</i>	Amphibian	LC
<i>Nimbaphrynoides liberiensis</i>	Amphibian	CR
<i>Nimbaphrynoides occidentalis</i>	Amphibian	CR
<i>Petropedetes cameronensis</i>	Amphibian	NT
<i>Petropedetes johnstoni</i>	Amphibian	NT
<i>Petropedetes newtoni</i>	Amphibian	LC
<i>Phrynobatrachus elberti</i>	Amphibian	DD
<i>Phrynobatrachus intermedius</i>	Amphibian	CR
<i>Phrynobatrachus nanus</i>	Amphibian	DD

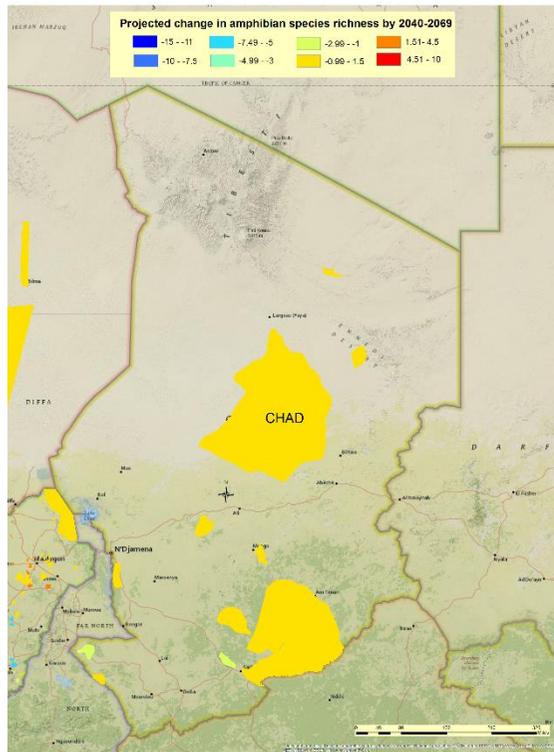
<i>Phrynobatrachus pintoii</i>	Amphibian	DD
<i>Phrynobatrachus plicatus</i>	Amphibian	LC
<i>Phrynobatrachus pygmaeus</i>	Amphibian	DD
<i>Phrynobatrachus sandersoni</i>	Amphibian	LC
<i>Pseudhymenochirus merlini</i>	Amphibian	LC
<i>Ptychadena arnei</i>	Amphibian	DD
<i>Ptychadena retropunctata</i>	Amphibian	DD
<i>Tomopterna milletihorsini</i>	Amphibian	DD
<i>Trichobatrachus robustus</i>	Amphibian	LC
<i>Werneria preussi</i>	Amphibian	EN
<i>Werneria tandyi</i>	Amphibian	EN
<hr/>		
<i>Accipiter badius</i>	Bird	LC
<i>Acrocephalus scirpaceus</i>	Bird	LC
<i>Anthus richardi</i>	Bird	LC
<i>Aquila chrysaetos</i>	Bird	LC
<i>Ardea cinerea</i>	Bird	LC
<i>Ardea purpurea</i>	Bird	LC
<i>Athene noctua</i>	Bird	LC
<i>Bubulcus ibis</i>	Bird	LC
<i>Buteo rufinus</i>	Bird	LC
<i>Butorides striata</i>	Bird	LC
<i>Calandrella brachydactyla</i>	Bird	LC
<i>Casmerodius albus</i>	Bird	LC
<i>Ceryle rudis</i>	Bird	LC
<i>Charadrius alexandrinus</i>	Bird	LC
<i>Ciconia ciconia</i>	Bird	LC
<i>Cisticola juncidis</i>	Bird	LC
<i>Columba livia</i>	Bird	LC
<i>Coturnix chinensis</i>	Bird	LC
<i>Dendrocygna bicolor</i>	Bird	LC
<i>Dendrocygna viduata</i>	Bird	LC
<i>Egretta garzetta</i>	Bird	LC
<i>Elanus caeruleus</i>	Bird	LC
<i>Falco pelegrinoides</i>	Bird	LC
<i>Falco peregrinus</i>	Bird	LC
<i>Falco tinnunculus</i>	Bird	LC
<i>Galerida cristata</i>	Bird	LC
<i>Gallinula chloropus</i>	Bird	LC
<i>Glareola pratincola</i>	Bird	LC
<i>Himantopus himantopus</i>	Bird	LC
<i>Hirundo daurica</i>	Bird	LC
<i>Hirundo smithii</i>	Bird	LC
<i>Ixobrychus minutus</i>	Bird	LC
<i>Lanius excubitor</i>	Bird	LC
<i>Malimbus ballmanni</i>	Bird	EN
<i>Malimbus ibadanensis</i>	Bird	EN
<i>Merops orientalis</i>	Bird	LC

<i>Merops persicus</i>	Bird	LC
<i>Mesophoyx intermedia</i>	Bird	LC
<i>Milvus migrans</i>	Bird	LC
<i>Monticola solitarius</i>	Bird	LC
<i>Motacilla flava</i>	Bird	LC
<i>Neophron percnopterus</i>	Bird	EN
<i>Nycticorax nycticorax</i>	Bird	LC
<i>Oenanthe deserti</i>	Bird	LC
<i>Passer domesticus</i>	Bird	LC
<i>Platalea leucorodia</i>	Bird	LC
<i>Porphyrio porphyrio</i>	Bird	LC
<i>Psittacula krameri</i>	Bird	LC
<i>Pterocles exustus</i>	Bird	LC
<i>Riparia paludicola</i>	Bird	LC
<i>Rostratula benghalensis</i>	Bird	LC
<i>Salpornis spilonotus</i>	Bird	LC
<i>Sarkidiornis melanotos</i>	Bird	LC
<i>Saxicola torquatus</i>	Bird	LC
<i>Streptopelia turtur</i>	Bird	LC
<i>Sylvia nana</i>	Bird	LC
<i>Tachybaptus ruficollis</i>	Bird	LC
<i>Tadorna ferruginea</i>	Bird	LC
<i>Turnix sylvaticus</i>	Bird	LC
<i>Tyto alba</i>	Bird	LC
<i>Upupa epops</i>	Bird	LC
<hr/>		
<i>Asellia tridens</i>	Mammal	LC
<i>Canis aureus</i>	Mammal	LC
<i>Caracal caracal</i>	Mammal	LC
<i>Cephalophus jentinki</i>	Mammal	EN
<i>Cephalophus zebra</i>	Mammal	VU
<i>Cercocebus torquatus</i>	Mammal	VU
<i>Cercopithecus erythrogaster</i>	Mammal	VU
<i>Cercopithecus erythrotis</i>	Mammal	VU
<i>Cercopithecus preussi</i>	Mammal	EN
<i>Crocidura buettikoferi</i>	Mammal	NT
<i>Crocidura longipes</i>	Mammal	DD
<i>Crocidura virgata</i>	Mammal	DD
<i>Eptesicus platyops</i>	Mammal	DD
<i>Euoticus pallidus</i>	Mammal	LC
<i>Felis margarita</i>	Mammal	NT
<i>Felis silvestris</i>	Mammal	LC
<i>Genetta cristata</i>	Mammal	VU
<i>Genetta poensis</i>	Mammal	DD
<i>Gerbillus nanus</i>	Mammal	LC
<i>Gerbillus nigeriae</i>	Mammal	LC
<i>Glauconycteris superba</i>	Mammal	LC
<i>Hipposideros lamottei</i>	Mammal	CR

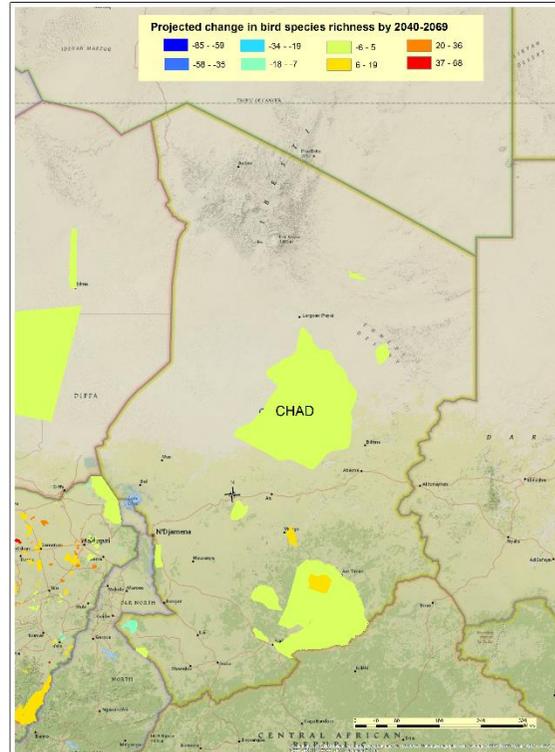
<i>Hyaena hyaena</i>	Mammal	NT
<i>Leimacomys buettneri</i>	Mammal	DD
<i>Meriones crassus</i>	Mammal	LC
<i>Meriones libycus</i>	Mammal	LC
<i>Miniopterus schreibersii</i>	Mammal	NT
<i>Monachus monachus</i>	Mammal	CR
<i>Myosorex rumpii</i>	Mammal	EN
<i>Myotis morrisi</i>	Mammal	DD
<i>Panthera pardus</i>	Mammal	NT
<i>Pipistrellus eisentrauti</i>	Mammal	DD
<i>Rhinolophus ziama</i>	Mammal	EN
<i>Rhinopoma microphyllum</i>	Mammal	LC
<i>Steatomys jacksoni</i>	Mammal	DD
<i>Sylvisorex pluvialis</i>	Mammal	DD
<i>Taphozous nudiventris</i>	Mammal	LC
<i>Trichechus senegalensis</i>	Mammal	VU

Annex 2: Country Level Species Turnover Maps

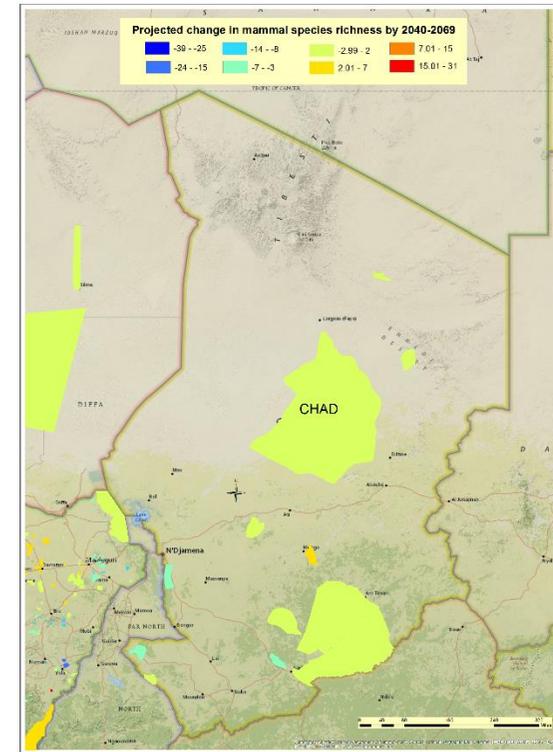
Chad



Median projected change in amphibian species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.

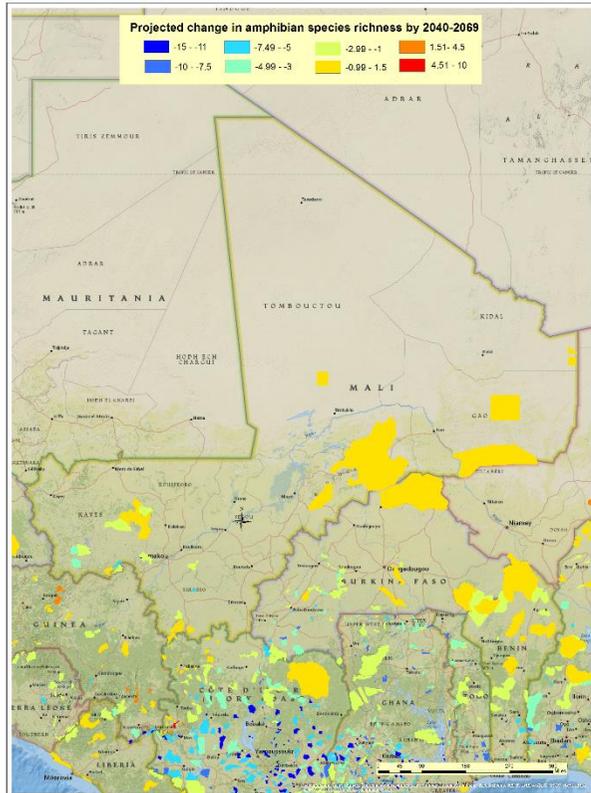


Median projected change in avian species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.

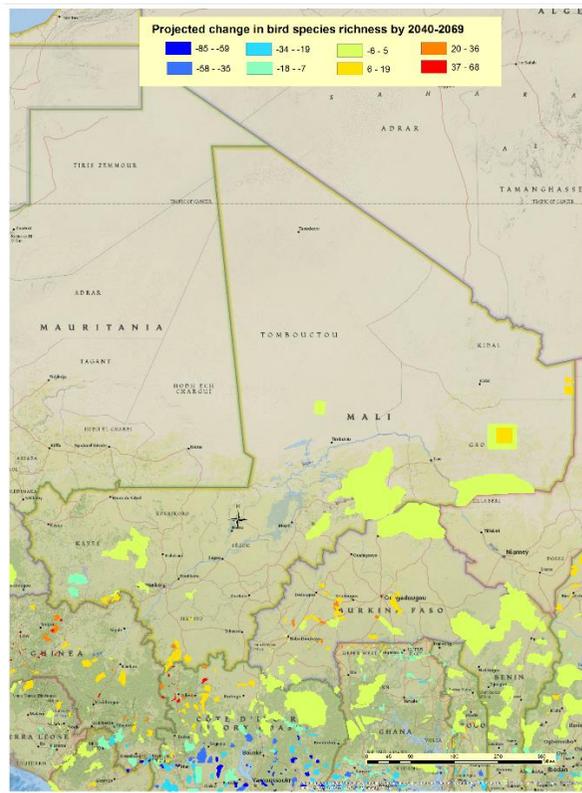


Median projected change in mammalian species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.

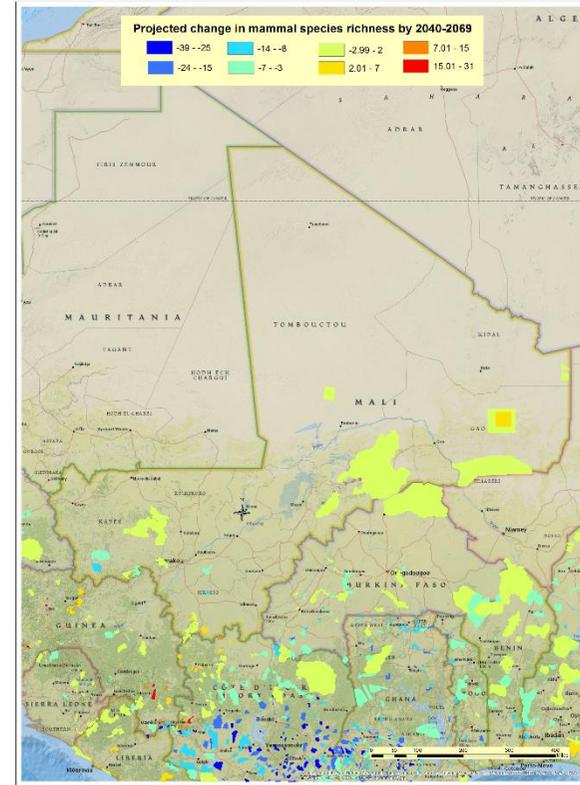
Mali



Median projected change in amphibian species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.

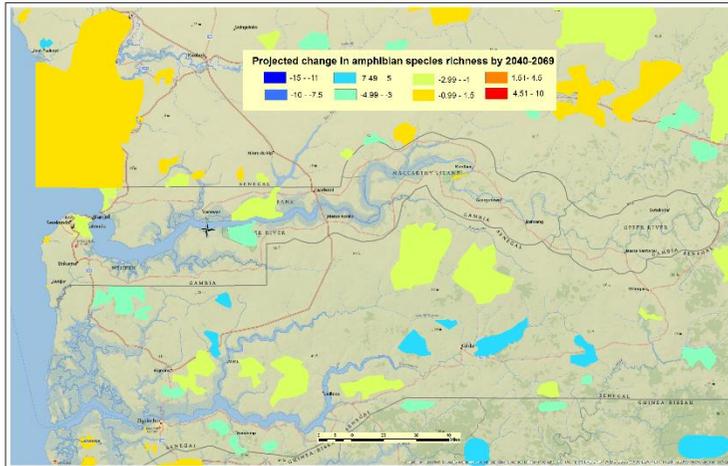


Median projected change in avian species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.

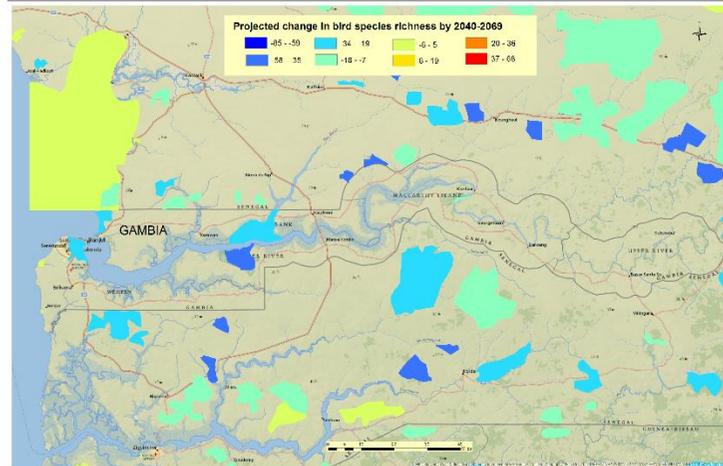


Median projected change in mammalian species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.

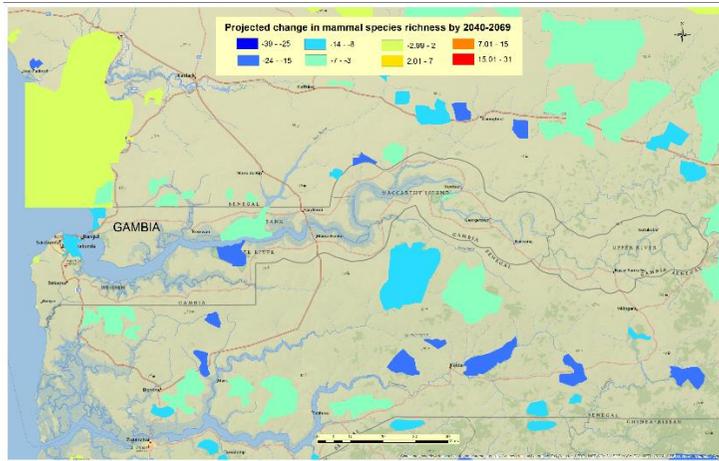
The Gambia



Median projected change in amphibian species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.

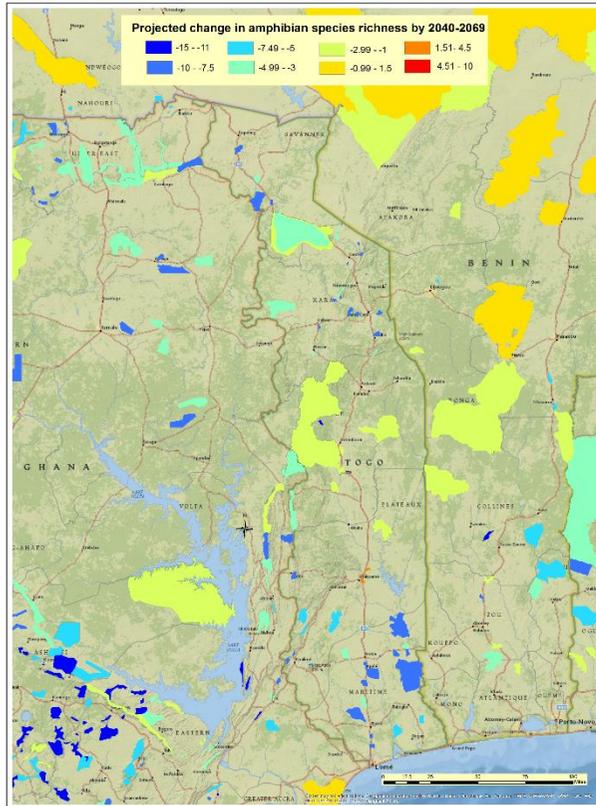


Median projected change in bird species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.

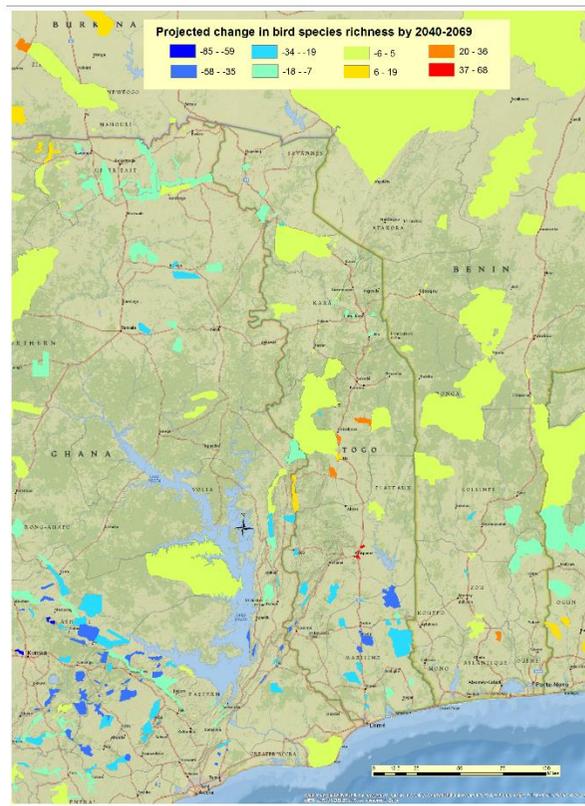


Median projected change in mammal species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.

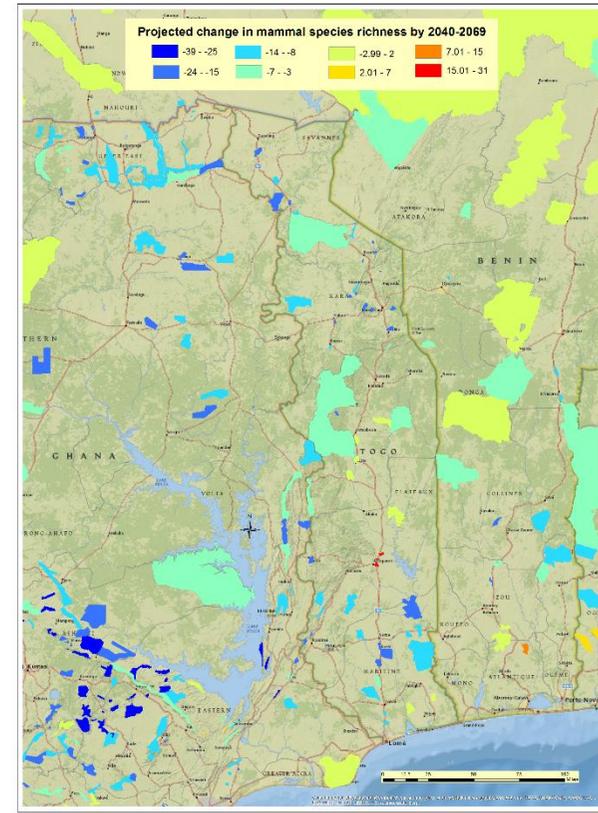
Togo



Median projected change in amphibian species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.

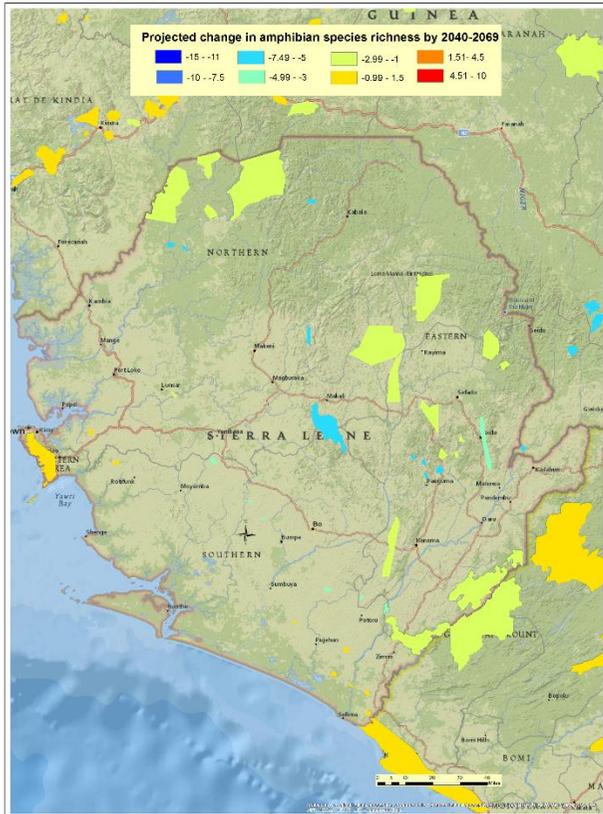


Median projected change in avian species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.

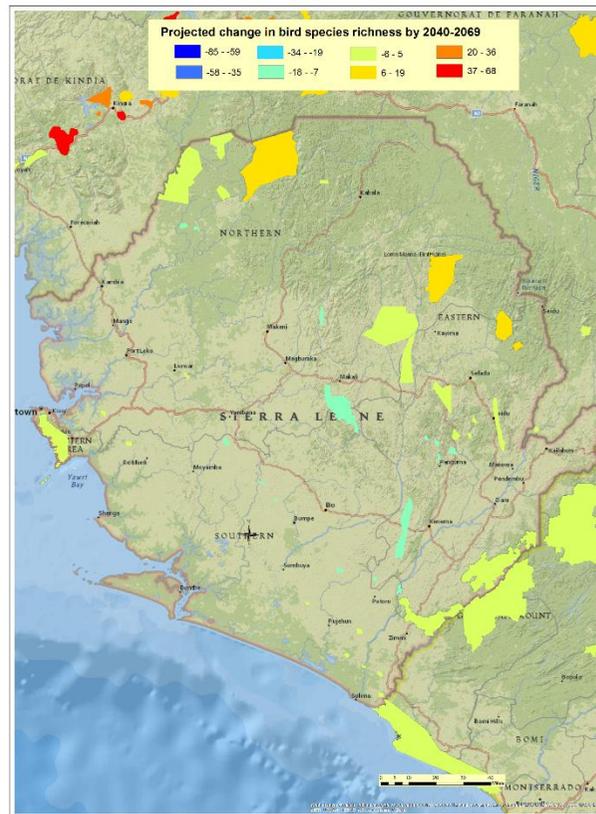


Median projected change in mammalian species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.

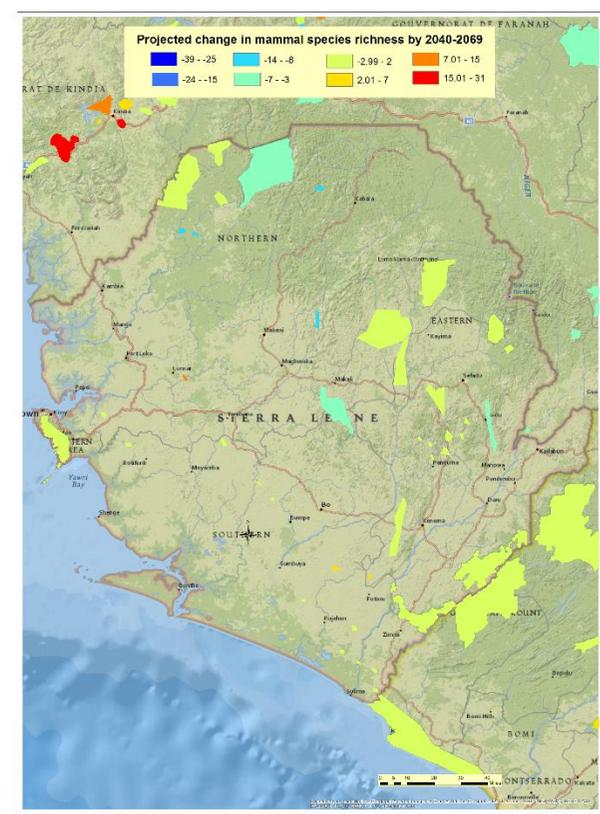
Sierra Leone



Median projected change in amphibian species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.



Median projected change in avian species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.



Median projected change in mammalian species richness in individual protected areas between the present and the period 2040-2069. Median projections are derived from multiple species distribution modelling and climate projection scenarios. Negative values denote declining species richness compared to current levels, and positive values denote increasing species richness.

Annex 3: Change in climate suitability across the network for red listed species

This table presents for each taxonomic group the species that are classified as either critical (CR), endangered (EN), vulnerable (VU) or data deficient (DD) and their categorical change in climate suitability across the region’s PA network. Species are classified as ‘highly likely’ to gain (G) or lose (L) climate suitability where the 95% CI show a unanimous classification; otherwise, species are classified as showing ‘no consensus’ (NC) (see methods and results sections for full details).

Species (binomial)	Red List category	Taxonomic Group	Time period		
			2011-2040	2041-2070	2070-2100
<i>Agelastes meleagrides</i>	VU	Bird	NC	NC	NC
<i>Apus sladeniae</i>	DD	Bird	L	L	NC
<i>Balearica pavonina</i>	VU	Bird	NC	NC	NC
<i>Bycanistes cylindricus</i>	VU	Bird	NC	NC	L
<i>Campephaga lobata</i>	VU	Bird	NC	NC	NC
<i>Campephaga oriolina</i>	DD	Bird	L	NC	NC
<i>Ceratogymna elata</i>	VU	Bird	L	NC	L
<i>Circaetus beaudouini</i>	VU	Bird	NC	NC	NC
<i>Coccycolius iris</i>	DD	Bird	NC	L	NC
<i>Criniger olivaceus</i>	VU	Bird	L	L	L
<i>Estrilda poliopareia</i>	VU	Bird	NC	NC	NC
<i>Gyps africanus</i>	EN	Bird	NC	NC	NC
<i>Gyps rueppellii</i>	EN	Bird	NC	NC	NC
<i>Jubula lettii</i>	DD	Bird	L	L	L
<i>Melaenornis annamarulae</i>	VU	Bird	NC	NC	NC
<i>Melignomon eisentrauti</i>	DD	Bird	NC	NC	NC
<i>Muscicapa tessmanni</i>	DD	Bird	L	L	L
<i>Necrosyrtes monachus</i>	EN	Bird	NC	NC	NC
<i>Picathartes gymnocephalus</i>	VU	Bird	NC	NC	L
<i>Picathartes oreas</i>	VU	Bird	L	L	L
<i>Ploceus bannermani</i>	VU	Bird	L	L	L
<i>Prinia leontica</i>	VU	Bird	L	L	NC
<i>Psittacus erithacus</i>	VU	Bird	L	L	NC
<i>Psittacus timneh</i>	VU	Bird	L	NC	NC
<i>Sagittarius serpentarius</i>	VU	Bird	NC	NC	NC
<i>Scotopelia ussheri</i>	VU	Bird	NC	NC	NC
<i>Torgos tracheliotos</i>	VU	Bird	NC	NC	NC
<i>Trigonoceps occipitalis</i>	VU	Bird	NC	NC	NC
<i>Balaeniceps rex</i>	VU	Bird	NC	NC	NC
<i>Acinonyx jubatus</i>	VU	Mammal	NC	NC	NC
<i>Addax nasomaculatus</i>	CR	Mammal	L	NC	NC

<i>Aethomys stannarius</i>	DD	Mammal	L	NC	NC
<i>Ammotragus lervia</i>	VU	Mammal	NC	NC	NC
<i>Anomalurus pelii</i>	DD	Mammal	NC	NC	NC
<i>Cercocebus atys</i>	VU	Mammal	NC	NC	L
<i>Cercopithecus diana</i>	VU	Mammal	NC	NC	L
<i>Cercopithecus sclateri</i>	VU	Mammal	NC	NC	NC
<i>Colobus polykomos</i>	VU	Mammal	L	L	L
<i>Colobus vellerosus</i>	VU	Mammal	NC	NC	NC
<i>Crocidura planiceps</i>	DD	Mammal	L	NC	NC
<i>Crocidura tarfayensis</i>	DD	Mammal	L	L	L
<i>Cryptomys foxi</i>	DD	Mammal	L	L	NC
<i>Dasymys foxi</i>	DD	Mammal	L	L	L
<i>Eudorcas rufifrons</i>	VU	Mammal	NC	NC	NC
<i>Felovia vae</i>	DD	Mammal	NC	NC	NC
<i>Funisciurus substriatus</i>	DD	Mammal	L	L	L
<i>Gazella leptoceros</i>	EN	Mammal	NC	NC	NC
<i>Genetta johnstoni</i>	VU	Mammal	L	L	L
<i>Gerbillus nancillus</i>	DD	Mammal	L	L	L
<i>Gorilla gorilla</i>	CR	Mammal	L	L	NC
<i>Grammomys buntingi</i>	DD	Mammal	L	L	L
<i>Graphiurus crassicaudatus</i>	DD	Mammal	L	L	L
<i>Heliosciurus punctatus</i>	DD	Mammal	NC	NC	L
<i>Hippopotamus amphibius</i>	VU	Mammal	NC	NC	NC
<i>Hylomyscus baeri</i>	EN	Mammal	NC	NC	NC
<i>Kerivoula cuprosa</i>	DD	Mammal	NC	NC	NC
<i>Liberiictis kuhni</i>	VU	Mammal	L	NC	NC
<i>Loxodonta africana</i>	VU	Mammal	NC	NC	NC
<i>Lycaon pictus</i>	EN	Mammal	NC	NC	NC
<i>Mandrillus leucophaeus</i>	EN	Mammal	L	L	L
<i>Micropotamogale lamottei</i>	EN	Mammal	L	L	L
<i>Myopterus daubentonii</i>	DD	Mammal	NC	NC	NC
<i>Nanger dama</i>	CR	Mammal	NC	NC	NC
<i>Nycteris major</i>	DD	Mammal	L	L	L
<i>Otomys occidentalis</i>	VU	Mammal	L	L	L
<i>Pan troglodytes</i>	EN	Mammal	L	L	L
<i>Panthera leo</i>	VU	Mammal	NC	NC	NC
<i>Paraxerus cooperi</i>	DD	Mammal	NC	NC	NC
<i>Pipistrellus inexpectatus</i>	DD	Mammal	L	L	L
<i>Poiana leightoni</i>	DD	Mammal	NC	NC	NC
<i>Praomys obscurus</i>	EN	Mammal	NC	NC	L
<i>Procolobus badius</i>	EN	Mammal	L	L	L
<i>Procolobus pennantii</i>	CR	Mammal	NC	NC	NC
<i>Procolobus preussi</i>	CR	Mammal	L	NC	NC
<i>Protoxerus aubinnii</i>	DD	Mammal	NC	NC	NC
<i>Rhinolophus guineensis</i>	VU	Mammal	L	L	L
<i>Rhinolophus maclaudi</i>	EN	Mammal	NC	L	NC
<i>Scotoecus albofuscus</i>	DD	Mammal	L	L	L

<i>Scotophilus nucella</i>	DD	Mammal	NC	NC	NC
<i>Sylvisorex camerunensis</i>	VU	Mammal	L	L	L
<i>Tadarida russata</i>	DD	Mammal	NC	NC	NC
<i>Tadarida trevori</i>	DD	Mammal	L	L	L
<i>Crocidura manengubae</i>	EN	Mammal	L	L	L
<i>Crocidura picea</i>	EN	Mammal	NC	L	L
<i>Glauconycteris curryae</i>	DD	Mammal	NC	NC	NC
<i>Hipposideros curtus</i>	VU	Mammal	L	L	L
<i>Hybomys badius</i>	EN	Mammal	L	L	L
<i>Nycteris parisii</i>	DD	Mammal	L	L	L
<i>Pipistrellus flavescens</i>	DD	Mammal	NC	NC	NC
<i>Pipistrellus muscivorus</i>	DD	Mammal	NC	NC	NC
<i>Cardioglossa melanogaster</i>	EN	Amphibian	L	L	L
<i>Cardioglossa pulchra</i>	EN	Amphibian	L	L	L
<i>Conraua alleni</i>	VU	Amphibian	L	L	L
<i>Conraua derooi</i>	CR	Amphibian	L	L	NC
<i>Conraua robusta</i>	VU	Amphibian	L	L	L
<i>Hylarana asperrima</i>	EN	Amphibian	L	L	NC
<i>Hylarana occidentalis</i>	EN	Amphibian	L	L	NC
<i>Hyperolius riggenbachi</i>	VU	Amphibian	L	L	L
<i>Hyperolius torrentis</i>	EN	Amphibian	L	L	L
<i>Kassina arboricola</i>	VU	Amphibian	NC	NC	NC
<i>Leptodactylodon bicolor</i>	VU	Amphibian	L	L	L
<i>Leptodactylodon polyacanthus</i>	VU	Amphibian	L	L	L
<i>Phrynobatrachus annulatus</i>	EN	Amphibian	L	L	NC
<i>Phrynobatrachus cricogaster</i>	VU	Amphibian	L	L	L
<i>Phrynobatrachus steindachneri</i>	VU	Amphibian	L	L	L
<i>Phrynobatrachus villiersi</i>	VU	Amphibian	L	L	L
<i>Ptychadena pujoli</i>	DD	Amphibian	L	L	L
<i>Ptychadena submascareniensis</i>	DD	Amphibian	L	L	L
<i>Wolterstorffina parvipalmata</i>	VU	Amphibian	L	L	L
<i>Amietophrynus djohongensis</i>	EN	Amphibian	NC	L	NC
<i>Amietophrynus villiersi</i>	EN	Amphibian	L	L	L
<i>Astylosternus diadematus</i>	VU	Amphibian	L	L	L
<i>Astylosternus fallax</i>	EN	Amphibian	L	L	L
<i>Astylosternus laurenti</i>	EN	Amphibian	L	L	L
<i>Astylosternus rheophilus</i>	VU	Amphibian	L	L	L
<i>Cardioglossa venusta</i>	EN	Amphibian	NC	NC	NC
<i>Hylarana longipes</i>	VU	Amphibian	NC	NC	L
<i>Idiocranium russeli</i>	DD	Amphibian	L	L	L
<i>Leptodactylodon perreti</i>	EN	Amphibian	L	L	L
<i>Petropedetes perreti</i>	EN	Amphibian	L	L	L

Annex 4: 'High priority' sites identified for two or three taxonomic groups

Protected areas (in alphabetical order) identified as being consistently 'high priority', measured as those sites with projected species turnovers in the upper quartile ($\geq 95\%$ certainty level). See methods and results for full details.

Name	Country	Designation	Amphibians	Birds	Mammals	Taxonomic groups (n)	Time period
Abasumba	GHA	Forest Reserve	1	1	0	2	2011-2040
Abeanou	CIV	Classified Forest	0	1	1	2	2011-2040
Abouderessou	CIV	Classified Forest	1	1	1	3	2011-2040
Adzope	CIV	Classified Forest	1	1	0	2	2011-2040
Agbo	CIV	Classified Forest	1	1	1	3	2011-2040
Ahirasu Blocks I & II	GHA	Forest Reserve	1	1	0	2	2011-2040
Ahua	CIV	Classified Forest	1	1	1	3	2011-2040
Akrobong	GHA	Forest Reserve	0	1	1	2	2011-2040
Amou-Mono	TGO	Forest Reserve	1	1	1	3	2011-2040
Ananguie	CIV	Classified Forest	1	1	0	2	2011-2040
Anhwiaso East	GHA	Forest Reserve	1	1	0	2	2011-2040
Arrah	CIV	Classified Forest	0	1	1	2	2011-2040
Banie	GIN	Classified Forest	1	1	1	3	2011-2040
Besso	CIV	Classified Forest	1	1	0	2	2011-2040
Bodio Doubele	CIV	Classified Forest	1	1	1	3	2011-2040
Boli	CIV	Classified Forest	0	1	1	2	2011-2040
Bong Mountain	LBR	National Park	1	0	1	2	2011-2040
Bongouanou	CIV	Classified Forest	1	1	1	3	2011-2040
Bonsa Ben	GHA	Forest Reserve	1	1	0	2	2011-2040
Classified Forest Name Unknown CIV No22	CIV	Classified Forest	0	1	1	2	2011-2040
Classified Forest Name Unknown CIV No30	CIV	Classified Forest	1	0	1	2	2011-2040
Classified Forest Name Unknown CIV No31	CIV	Classified Forest	1	1	1	3	2011-2040
Classified Forest Name Unknown CIV No36	CIV	Classified Forest	0	1	1	2	2011-2040
Classified Forest Name Unknown CIV No45	CIV	Classified Forest	1	0	1	2	2011-2040

Classified Forest Name Unknown CIV No46	CIV	Classified Forest	1	1	0	2	2011-2040
Classified Forest Name Unknown CIV No49	CIV	Classified Forest	1	1	1	3	2011-2040
Classified Forest Name Unknown CIV No50	CIV	Classified Forest	1	1	0	2	2011-2040
Classified Forest Name Unknown CIV No51	CIV	Classified Forest	1	1	1	3	2011-2040
Classified Forest Name Unknown CIV No55	CIV	Classified Forest	0	1	1	2	2011-2040
Classified Forest Name Unknown CIV No56	CIV	Classified Forest	1	1	1	3	2011-2040
Classified Forest Name Unknown CIV No57	CIV	Classified Forest	1	1	1	3	2011-2040
Classified Forest Name Unknown CIV No64	CIV	Classified Forest	1	1	1	3	2011-2040
Classified Forest Name Unknown CIV No72	CIV	Classified Forest	1	1	0	2	2011-2040
Dan	BEN	Classified Forest	1	1	0	2	2011-2040
De	CIV	Classified Forest	1	1	1	3	2011-2040
Disue River	GHA	Forest Reserve	1	1	0	2	2011-2040
Divo	CIV	Botanical Reserve	0	1	1	2	2011-2040
Draw River	GHA	Forest Reserve	1	0	1	2	2011-2040
Ebrinenou	CIV	Classified Forest	1	1	1	3	2011-2040
Fada Archei	TCD	Faunal Reserve	0	1	1	2	2011-2040
Gboi Hills	SLE	Forest Reserve	1	1	0	2	2011-2040
Gorke	CIV	Classified Forest	1	1	0	2	2011-2040
Goudi	CIV	Classified Forest	1	0	1	2	2011-2040
Inekar	MLI	Hunting Area	0	1	1	2	2011-2040
Jeni River	GHA	Forest Reserve	1	1	0	2	2011-2040
Kambui Hills and Extensions	SLE	Forest Reserve	1	0	1	2	2011-2040
Kassa	CIV	Classified Forest	1	1	0	2	2011-2040
Kavi	CIV	Classified Forest	1	1	0	2	2011-2040
Kravassou	CIV	Classified Forest	1	1	1	3	2011-2040
Lakes of Ounianga	TCD	World Heritage Site	1	1	1	3	2011-2040
Mando	CIV	Classified Forest	1	1	1	3	2011-2040
Marahoue	CIV	Classified Forest	1	1	0	2	2011-2040
Matiemba	CIV	Classified Forest	1	1	1	3	2011-2040
Mkar	NGA	Forest Reserve	1	1	0	2	2011-2040
Monogaga	CIV	Classified Forest	1	1	1	3	2011-2040

Mopri	CIV	Classified Forest	1	1	0	2	2011-2040
Ndokouassikro	CIV	Classified Forest	1	1	1	3	2011-2040
Oasis du Kawar	NER	Ramsar Site, Wetland of International Importance	1	1	1	3	2011-2040
Obotumfo Hills	GHA	Forest Reserve	1	1	1	3	2011-2040
Obrachere 1	GHA	Forest Reserve	1	1	0	2	2011-2040
Obrachere	GHA	Forest Reserve	1	1	0	2	2011-2040
Offumpo	CIV	Classified Forest	1	1	1	3	2011-2040
Opimbo	GHA	Forest Reserve	1	1	0	2	2011-2040
Osomari	NGA	Forest Reserve	1	0	1	2	2011-2040
Otamiri	NGA	Forest Reserve	1	0	1	2	2011-2040
Owabi	GHA	Ramsar Site, Wetland of International Importance	1	1	0	2	2011-2040
Owabi	GHA	Wildlife Sanctuary	1	1	0	2	2011-2040
Plaine des Elephants	CIV	Classified Forest	0	1	1	2	2011-2040
Sab-Sabre	SEN	Not Reported	0	1	1	2	2011-2040
Seguela	CIV	Classified Forest	1	1	1	3	2011-2040
Seguie	CIV	Classified Forest	1	1	0	2	2011-2040
Taabo	CIV	Classified Forest	1	1	0	2	2011-2040
Tchilla-Monota	TGO	Forest Reserve	1	1	0	2	2011-2040
Tete	CIV	Classified Forest	0	1	1	2	2011-2040
Tin Achara	MLI	Hunting Area	0	1	1	2	2011-2040
Tiwai Island Sanctuary	SLE	Game Sanctuary / Non-hunting Forest Reserve	1	1	1	3	2011-2040
Ukpam	NGA	Forest Reserve	1	0	1	2	2011-2040
Vavoua	CIV	Classified Forest	0	1	1	2	2011-2040
Yandev	NGA	Forest Reserve	0	1	1	2	2011-2040
Yoyo River	GHA	Forest Reserve	1	1	0	2	2011-2040
Abasumba	GHA	Forest Reserve	1	1	1	3	2041-2070
Abouderessou	CIV	Classified Forest	1	0	1	2	2041-2070
Ahirasu Blocks I & II	GHA	Forest Reserve	1	1	0	2	2041-2070
Ahua	CIV	Classified Forest	1	0	1	2	2041-2070
Akrobong	GHA	Forest Reserve	1	1	0	2	2041-2070
Banie	GIN	Classified Forest	1	1	0	2	2041-2070
Classified Forest Name Unknown CIV No63	CIV	Classified Forest	1	1	0	2	2041-2070
Classified Forest Name Unknown CIV No64	CIV	Classified Forest	1	1	1	3	2041-2070
Classified Forest Name Unknown CIV No67	CIV	Classified Forest	0	1	1	2	2041-2070

Dechidan Stream	GHA	Forest Reserve	1	1	1	3	2041-2070
Kalakpa	GHA	Game Production Reserve	1	1	0	2	2041-2070
Kassa	CIV	Classified Forest	0	1	1	2	2041-2070
Kavi	CIV	Classified Forest	0	1	1	2	2041-2070
Lakes of Ounianga	TCD	World Heritage Site	1	1	1	3	2041-2070
Monogaga	CIV	Classified Forest	1	1	1	3	2041-2070
Mount Nimba	CIV	National Reserve	1	1	1	3	2041-2070
Mt De	CIV	Classified Forest	1	1	1	3	2041-2070
Ndokouassikro	CIV	Classified Forest	1	0	1	2	2041-2070
Nimba West	LBR	National Park	0	1	1	2	2041-2070
Niouniourou	CIV	Classified Forest	0	1	1	2	2041-2070
Oasis du Kawar	NER	Ramsar Site, Wetland of International Importance	1	1	0	2	2041-2070
Obotumfo Hills	GHA	Forest Reserve	1	1	0	2	2041-2070
Obrachere	GHA	Forest Reserve	1	1	0	2	2041-2070
Opimbo	GHA	Forest Reserve	1	1	0	2	2041-2070
Wologizi	LBR	National Park	1	1	0	2	2041-2070
Yoyo River	GHA	Forest Reserve	1	1	0	2	2041-2070
Zakpaberi	CIV	Classified Forest	1	0	1	2	2041-2070
Banie	GIN	Classified Forest	1	1	1	3	2071-2100
Classified Forest Name Unknown CIV No72	CIV	Classified Forest	1	1	0	2	2071-2100
Dam Makama	NGA	Forest Reserve	1	1	0	2	2071-2100
Kavi	CIV	Classified Forest	1	1	0	2	2071-2100
Kpo Mountains	LBR	National Park	1	1	0	2	2071-2100
Zakpaberi	CIV	Classified Forest	1	0	1	2	2071-2100