Protected Areas Resilient to Climate Change, PARCC West Africa
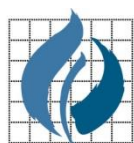
PARCC WEST AFRICA

2015

Integrating species distribution models and traits-based vulnerability assessments to inform conservation planning

ENGLISH

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Durham University

1/1/2015

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Integrating species distribution models and trait data to inform conservation planning, prepared by Durham University, with funding from Global Environment Facility (GEF) via UNEP.

Citation: Durham University. 2015. Integrating species distribution models and trait data to inform conservation planning. *UNEP-WCMC technical report*.

Available From: UNEP World Conservation Monitoring Centre (UNEP-WCMC)
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Executive Summary

In this report, we explore the potential for combining climate impact projection from species distribution models (SDMs) and trait-based vulnerability assessments (TVAs) to produce integrated assessments of the potential threat of climate change to species of conservation concern in West Africa.

TVAs use species trait data to inform the exposure, sensitivity and likely adaptability of species to changes in climate. SDMs, by relating the occurrence of a species to climate, can be used to assess the sensitivity of a species to projected changes in climate, with climate exposure being informed by projections of changes in climate. Typically, such static models do not consider the ability of a species to respond to changes in areas of suitable climate as a result of their biological traits.

Here, we combine SDM and TVA methodologies in two ways:

Firstly, we use climate suitability projections for individual species (from SDMs) under scenarios of future climate to replace the simpler climate exposure metrics more usually included in trait-based analyses. We then estimate the likely vulnerability of species to climate change by combining these exposure projections with sensitivity and adaptability information from trait-based analyses, resulting in a genuine integration of SDM and TVA approaches, which we term 'Modified TVAs'.

Secondly, we incorporate relevant trait data into species distribution models, both as a dynamic element within models of species responses to climate change and, for traits that cannot be incorporated within dynamic distribution model, using dichotomous trait-based queries. This results in a mixed approach to the combination of traits and spatially modelling, which we term 'Modified SDMs'.

Modified TVAs, using SDMs to inform climate exposure in traditional TVAs, are more akin to simple, algorithmic trait-based analyses. We find that the degree to which these two methods differ is greatly affected by how species are treated that have no consensus in their future climate impact (i.e. no consistent trend in their response to predicted changes). However, we advocate this combined approach over simple TVAs as it incorporates changes in climate suitability for each species, and permits site-level climate vulnerability to be evaluated.

Spatial modelling with traits, combines climate suitability from SDMs with demographic and dispersal information in dynamic models of potential responses to climate change, and provides a realistic assessment of how species might respond. Additional traits that cannot be incorporated into dynamic models, such as species interactions and habitat relationships, are evaluated using dichotomous queries. This approach is probably most useful to inform potential management actions for individual species.

We produce maps of differences in the vulnerability to climate change of species assemblages in protected areas across West Africa, using modified TVAs (see above). We also

use spatial modelling with traits to produce management recommendations for individual species based on their potential to respond to forecast changes.

NOTE: Many of the methods used in this project have already been presented in detail in Willis *et al.* (2015) and Baker *et al.* (2015), from both of which some of the methodological summary text of this report is taken.

1. Introduction

Biodiversity loss is occurring across much of the world (Butchart *et al.* 2010, Secretariat of the CBD, 2010, WWF, 2014) and anthropogenic climate change has been identified as one of the main drivers of these trends (Parmesan and Yohe, 2003). This threat is predicted to become more severe over the next century owing to accelerating global warming, and changes in precipitation patterns and timings, as well as alterations in climatic extremes (IPCC, 2007). Various predictions have been made of the impacts of climate change on the world's habitats and species, generally indicating that more species will become threatened with extinction, and that their distributions will move substantially, often shrinking (Sala *et al.* 2000, Midgley *et al.* 2002, Thomas *et al.* 2004, Bagchi *et al.* 2013). Climate change is not only additional to other direct threats to biodiversity, such as land-use change, over-hunting, and invasive species, but can also act synergistically with these threats (Benning *et al.* 2002, Hof *et al.* 2011). There is, therefore, an urgent need to assess the potential consequences of future climate change on species, and to initiate adaptive management planning that helps shape current and future conservation decisions. The need to produce adaptive management plans has stimulated considerable research in recent years, resulting in various approaches to assessing climate change-driven risks (Game *et al.* 2011, Hole *et al.* 2011, Gardali *et al.* 2012, Bagchi *et al.* 2013, Foden *et al.* 2013, Garcia *et al.* 2014).

To date, the majority of climate change vulnerability assessments have used Species Distribution Models (SDMs), which correlate data on species' contemporary distributions with observations of recent climates and then apply these correlations to climate projections to predict the location(s) of suitable climatic conditions for a species in the future (Beaumont and Hughes, 2002, Phillips *et al.* 2006, Huntley *et al.* 2008, Jensen *et al.* 2008, Harrison *et al.* 2006). Consequently, in predicting species responses to projected future climate change, SDMs use future exposure of a species to climate change (i.e. the extent to which the species' physical environment will change) to climate change as an input parameter and assess the sensitivity of the species (the potential for the species to persist, *in situ* or elsewhere) to that change. However, such SDMs take no account of the potential capacities of species to adapt to such changes by dispersal, behavioural change or evolutionary adaptation. For example, a species might have ample climatically-suitable habitat in the future, but its inherent dispersal

limitations may make reaching this habitat unlikely. The shortcomings of using basic SDM approaches to simulate future species changes are well recognised (Seo *et al.* 2009, Sinclair *et al.* 2010, Wiens *et al.* 2009), and include their lack of consideration of biological information about the likelihood of species realising distribution changes projected by SDMs (Pearson and Dawson, 2004). This shortcoming has led to the development of next-generation, dynamic (or process-based) SDMs that include relevant biological traits such as dispersal ability, habitat requirements and other key parameters to assess the likelihood of population changes being realised over space and time (Kearney and Porter, 2009, Conlisk *et al.* 2013). However, to parameterise such models requires quantitative data for a species or system; something that is lacking for many species. An alternative approach, which we term 'Trait-based Vulnerability Assessment' (TVA) (Foden *et al.* 2013, Carr et al. 2014, Willis *et al.* 2015, Pacifici *et al.* 2015) considers the vulnerability of species to potential climate change based on the best available current knowledge of the species' ecology and life history. Unlike process-based models, TVAs use composite indices (as opposed to modelling) to characterise the vulnerability of species to climate change.

TVA approaches identify, for a species, the traits that are known or presumed to render it vulnerable to climate change impacts. This often entails consideration of three aspects of vulnerability: exposure to climate change, sensitivity to changes in climate, and capacity to adapt to such changes, with the latter two aspects benefiting from the consideration of traits. Species that combine high exposure, a high degree of sensitivity, and low capacity to adapt will be most vulnerable to climate change. These methods provide a relatively rapid approach to score species according to their likely vulnerability to future climate change (Rowland *et al.* 2011). Several variants on the TVA approach have recently been developed, and are being applied to increasing numbers of taxa (Williams *et al.* 2008, Chin *et al.* 2010, Dawson *et al.* 2011, Graham *et al.* 2011, Thomas *et al.* 2011, Young *et al.* 2011, Foden *et al.* 2013).

To date, however, there have been few explicit comparisons of SDMs and TVAs in terms of their objectives, the conceptual frameworks underpinning them (Rowland *et al.* 2011), and the results they produce (Garcia *et al.* 2014). Furthermore, little attempt has been made to demonstrate how their outputs can be applied at scales relevant for conservation

decision making (national and smaller). We seek to address remaining gaps of these two approaches by considering how elements of each could be used to strengthen the other, and propose how they can be integrated to provide improved climate change vulnerability assessments. Our resultant framework also indicates how both approaches can feed into adaptive management planning and spatial conservation prioritization at scales where conservation decisions are made (Margules and Pressey, 2000, Moilanen *et al.* 2009, Ladle *et al.* 2011). As part of the PARCC project, systematic conservation planning systems were indeed develop to identify priority areas for conservation based on the representation of broad elements of biodiversity (landcover types, ecoregion types and elevation zones), the conservation of the current distribution of particular species (amphibians, birds and mammals), as well as the conservation of the future distribution of species that may be vulnerable to climate change based on SDM and TVA results (Smith 2015). We finish by outlining some of the challenges in using the results of climate change vulnerability assessments within the framework of systematic conservation planning.

2. Background to Species Distribution Modelling and Trait-based Analyses

a) Basic Species Distribution Modelling

Data Sources

i. Regional climate models

Climate projections were derived for the Africa CORDEX domain (longitude range = -24.64, 60.28; latitude range = -45.76, 42.24; (Giorgi *et al.* 2009)) in a two-step process. Firstly, a Perturbed Physics Ensemble (PPE), in which uncertain model parameters are systematically perturbed to produce a range of climates, was produced using the HADCM3 general circulation model (GCM) for the SRES A1B scenario (IPCC, 2007). Simulations from the individual ensemble members were compared to observed temperature and precipitation data from across Africa and against climate regimes (e.g. spatio-temporal distributions of precipitation maxima) from the Sahel and Guinea Coast domains, following McSweeney *et al.* (2012). Models that were unable to capture important climate features across these three regions were discarded. From the remaining models a five-member ensemble was selected that represented the breadth of future temperature and precipitation projections across the region (Buontempo *et al.* 2014). Each of the five ensemble members was downscaled to a c. 50km^2 spatial resolution for the period 1949 to 2100, using the Met Office Hadley Centre's physically-based PRECIS (Jones *et al.* 2004) regional climate modelling (RCM) system (Hartley, Jones and Janes 2015). 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, surface pressure, and sea-surface temperature) provided by the five-member PPE ensemble.

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 (coefficient of variation of mean monthly precipitation) and an aridity index (mean precipitation/potential evapotranspiration). Such bioclimatic variables have been shown previously to be good predictors of species distributions across taxonomic groups in tropical and sub-tropical systems (Araūjo *et al.* 2006, Bagchi *et al.* 2013, Barbet-Massin and Jetz, 2014), defining

tolerance to thermal extremes and water availability. 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 these periods. Because the baseline data are derived from the RCM there are five different baseline dataset, each validated against observed climate data. This has an advantage over statistically interpolated observed data in regions where ground climate observations are sparse (Sylla *et al.* 2013), as the dynamic projections are able to capture greater spatial heterogeneity across the region and uncertainty in contemporary climate records.

ii.   Species distribution data

Species distribution data for the breeding ranges were derived from refined species distribution maps of all extant bird (from BirdLife-International and NatureServe, 2013)), mammal and amphibian (both from IUCN, 2014) species, which were gridded onto a 0.44^0 grid (ca. 50 km^2 at the equator). A species was considered to occur in a cell if the distribution polygon overlapped ≥10% of the cell, which is a liberal threshold that helps ensure that species with restricted ranges are represented. All areas beyond the range extent are highly unlikely to contain false absences and, therefore, for modelling we consider all cells beyond the range to be true absences. There is some potential for commission error when using refined distribution maps. However, the availability of reliable unbiased point data here is limited, and refined species distribution maps, when used at conservative spatial resolutions, are likely to be representative of species climate tolerances. Species were only included in the analysis if ≥75% of their breeding range occurred within the full RCM extent, thus, omitting 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.

iii. Producing species distribution models

We used an approach to species distribution modelling that quantified the uncertainty in projected distributions caused by selecting different climate projections and modelling approaches, and due to potential spatial dependency in species' distributions.

For modelling, we divided the dataset into spatially disaggregated blocks, rather than random k-fold partitioning, which allowed us to capture uncertainty due to spatial dependency in our projections. For each of the five RCM climate projections the dataset was divided into five

spatially disaggregated blocks, such that the mean and variance of each bioclimatic variable was approximately equal across the blocks (see Bagchi *et al.* 2013 for details); thus, each block has the potential to capture the species-climate relationship. Importantly, the spatial autocorrelation within each block is higher than between blocks; thus, where spatial autocorrelation is high, models trained on *n*-1 blocks (the jack-knifing approach adopted here), where *n* is the total number of blocks, performed poorly when tested on the withheld block. The variation in predicted probability of occurrence across the withheld blocks can be used to assess the effect of spatial autocorrelation on projected distributions.

We modelled the relationship between a species' baseline distribution (representing the period 1971-2000) and the four contemporaneous bioclimate variables using all combinations of four modelling methods [generalised linear models (GLM), generalised additive models (GAM), generalised boosted models (GBM) and random forests (RF)] and five RCM climate projections (20 combinations in total). We conditioned each of these model combinations using the five *n-1* blocks of cells. Thus, for each species, 100 models were fitted to a subset of the baseline distribution data, i.e. each combination of block (5), RCM climate projection (5) and modelling methodology (4). For all four modelling approaches, the median area under the receiver operating characteristic plot (AUC) from across the five blocks was used to assess final model accuracy. The model cross-validation protocol follows Bagchi *et al.* (2013). Ultimately, species distributions models were developed for 1,296 species across all taxa, from an initial 1,443 species (Table 1). These models were applied to climate data from the three future periods ('2040' = 2011-2040; '2070' = 2041-2070; '2100' = 2071-2100). Our recent findings (Baker *et al.* 2015) suggested that end of century projections of species range changes contain very high uncertainty, rendering conservation actions based on the median outcome of these projections less likely to succeed. Consequently, in this report we present climate change vulnerability assessments for the mid-century period only, which we refer to using its mid-point, 2055.

b) Basic Trait-based Vulnerability Assessments (TVAs)

This approach, referred to as a Climate Change Vulnerability Assessment Framework in Carr *et al.* (2014), provides a series of 'rules' that are used to classify species according to three dimensions of climate change vulnerability (Figure 1.1). Here we describe the protocol of Carr *et al.* (2014), in brief, as we use this as the framework into which we integrate SDMs. For further details of this framework refer to the report of Carr *et al.* (2014). This, in turn, closely follows the processes described in Foden *et al.* (2013) and Carr *et al.* (2013).

In summary, species are assessed in terms of their vulnerability to climate change by assessing the degree with they are exposed to changes in climate (exposure), the degree to which they are sensitive to such changes (sensitivity) and their ability to cope with any changes (adaptability). Exposure is defined by Carr *et al.* (2014) as the extent to which a species' physical environment will change due to climate change, sensitivity as the lack of potential for a species to persist *in-situ,* and adaptability as the ability of a species to avoid the negative impacts of climate change through dispersal and/or micro-evolutionary change.
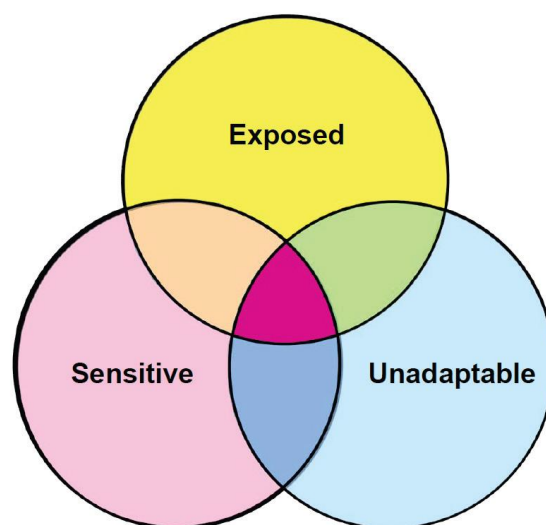
Figure 1.1 Greatest climate change vulnerability occurs when species that possess biological traits or characteristics that confer low sensitivity and adaptability are exposed to substantial climatic change. From Foden *et al.* (2013).

Species that are most highly exposed, sensitive and unadaptable are considered most vulnerable to climatic change. These species, represented by the intersection in the centre of Figure 1.1, are flagged as being of greatest conservation concern. Important information

can also be gained from species scoring highly in other combinations of the framework's vulnerability dimensions.

Carr *et al.* (2014) suggest five traits that render species of particular sensitivity to climatic change. These are: (1) specialized habitat/microhabitat requirements, (2) narrow environmental tolerances or thresholds that are likely to be exceeded due to climate change at any stage in the life cycle, (3) dependence on a specific environmental trigger that is likely to be disrupted by climate change, (4) dependence on interspecific interactions which are likely to be disrupted by climate change, and (5) rarity. They additionally suggest two traits that indicate a reduced likelihood of a species to be able to adapt to climatic change: (1) poor dispersal ability and (2) inability to evolve rapidly to cope with climatic change.

Species were assigned scores of 'unknown', 'low' or 'high' for each of the seven traits above, based on a broad range of information sources. While in some cases, thresholds of risk were considered clear (e.g. 'occurs only on mountain tops'), in many cases no *a priori* basis for setting a particular extinction risk threshold could be defined. In such cases (e.g. tolerance of exposure to projected temperature changes), Carr *et al.* (2014) used an arbitrary threshold to identify the top quartile of most affected species within the group, and categorize them as 'high' for this element.

Trait data for amphibians and birds were made available by Foden *et al.* (2013), who conducted a global analysis of amphibians and birds. For the other taxonomic groups data were collected in two regional species assessment workshops, held in Lomé, Togo, within the framework of the PARCC project, and through consultations with species experts

Assessments of *Exposure* were conducted by overlaying projected changes in taxon-relevant climatic variables on refined species range polygons to obtain simple measures of climatic change to which each species will be exposed. Species range polygons were gridded and the gridded range refining by removing cells that containing elevations and habitats deemed unsuitable for the species.

Because the identification of thresholds that represent significant exposure to climatic changes for individual species have seldom been established, scores were derived by ranking species according to the climatic change within their range and then assigning those in the highest quartile of exposure values as highly exposure. Species were therefore scored

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as potentially being at 'high' not high' or of 'unknown' risk of exposure under projections of future climate change.

Carr *et al.* (2014) considered species' exposure to changes in temperature and precipitation for the same three 30-year future time periods as described in the species distribution models section above, and using the same future climate projections. For all cells in a species' range, overall baseline means (OBM) for temperature and precipitation were calculated. The differences between the baseline OBM's and those of the three future time periods were used as measures of projected change in the means of temperature across each species' current range for respective future period. For projected changes in mean precipitation, the absolute ratio between the baseline and future OBM values was used. In addition, the average absolute deviation (AAD), a summary statistic for dispersion, was calculated for all species and for both climate variables. The differences between the baseline and three future AAD's, and the absolute ratios of the baseline and projected AAD's, were used as measures of projected change in the variability of temperature and precipitation, respectively, across each species' current range. Outputs were ranked and the top quartile identified as 'high' risk.

Sensitivity, adaptability and exposure scores for each species were used to calculate overall vulnerability scores using two simple logic steps: species were assigned a high score under each vulnerability dimension if they have any contributing trait (e.g. considered sensitive due to being a habitat specialist). They were considered highly vulnerable overall, however, only if they scored as 'high' under all three criteria of exposure, sensitivity and adaptive capacity. To account for missing trait data, each of the previous steps was run twice, once replacing missing trait information with a low vulnerability score and once with a high score. This provided best-case (or optimistic) and worst-case (pessimistic) scenarios, respectively.

It is extremely important to note that, since many of the trait thresholds are simply relative cut-offs for continuous variables (e.g. 25% of species of greatest exposure to changes in mean temperatures), rather than empirically tested thresholds of vulnerability, this approach provides a relative, not absolute, measure of climate change vulnerability. The actual numbers and percentages of species emerging as vulnerable through this approach represent only the degree of overlap between the three vulnerability dimensions rather than

a measure of vulnerability overall. It is therefore not appropriate to use the results to compare degrees of vulnerability between different taxonomic groups. Species identified as vulnerable to climate change should be regarded as estimates of the most vulnerable species, noting that in some taxonomic groups, all species may be at risk from climate change impacts while, in others, far fewer species may actually be seriously negatively impacted.

The following two sections (sections 2 and 3) describe the contrasting methods used to integrate the TVA and SDM data and present the results from the two methods. Section 2 describes our method to incorporate individual species climate suitability data (from species distribution models) into traits-based analyses ('Modified TVAs'), and presents the results in terms of climate change vulnerability. Section 3 presents the methods and summary results of using traits to refine species distribution model projections ('Modified SDMs').

3. Including individual species climate suitability data from species distribution models into traits-based analyses to inform climate change vulnerability ('Modified TVAs')

Integrating modelled climate suitability into TVA

The basic TVA exposure metric (see Section 1) is calculated as the absolute difference (temperature) or ratio of change (precipitation) in climate means across an entire species' range between the future and baseline period (also including average absolute deviation, as a measure of dispersion). This method makes no distinction between changes in different parts of a species range, and cannot account for difference in climate change exposure between, for example, the range margins and the range centre. For example, changes in climate in different parts of the range, e.g., large scale drying in the west but increased precipitation in the east of a species range would have no impact on the original exposure metric. Here, as an alternative to the rather simplistic exposure measures used in the basic TVAs, we instead assess species-specific exposure, based on spatially explicit changes in modelled climate suitability from correlative SDMs, and based on multiple interacting climatic variables (see methods in Section 1 but see Baker *et al.* (2015) for full methodology and for estimations of protected area and species-specific change in climate suitability).

It is important to understand whether integrating SDM derived-climate suitability values into the trait-based analyses markedly alters our projections of climate change vulnerability. If the two approaches do not differ, then there is little reason to advocate the additional computational complexity of producing SDM models as a replacement for the more straightforward estimation of climatic anomalies across a range. The latter approach renders TVA analyses more accessible for application by non-specialists, as it does not demand complex modelling capability. By contrast, if the two approaches do differ markedly, this strongly suggests that the more nuanced estimates of climatic suitability, and change in suitability, from SDMs, could be providing refined estimates of the exposure of individual species to climate change. We present an exploration of the relative performance of basic versus modified TVAs in Annex 2.

Figure 2.1 shows conceptually how the SDM suitability data are incorporated into the trait-based analyses.
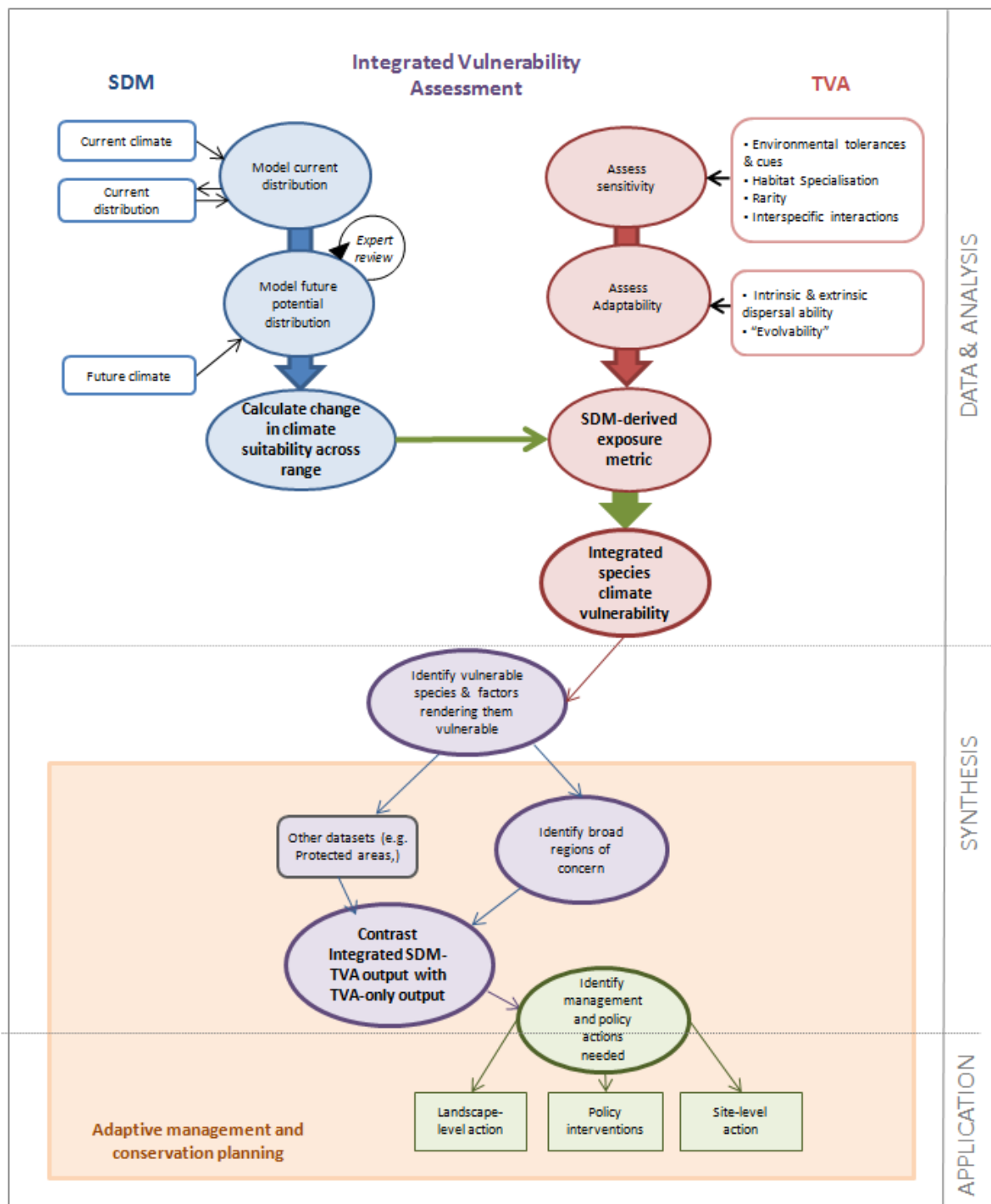
Figure 2.1. Conceptual model demonstrating the ways in which SDM data were integrated into the TVA modelling framework and links to the subsequent application. Green arrows and bold text indicates the components of the model influenced by integrated approach. Figure adapted from Willis *et al.* (2015).

a) Methods

We use the SDM-derived estimates of climate exposure as a direct replacement for the basic climate exposure metrics used in the TVA of Carr *et al.* (2014). If mean modelled climate suitability increases for a species at a site, it is classified as experiencing low climatic exposure, and if suitability decreases it is classed as experiencing high climatic exposure. The other two vulnerability trait types (adaptability and sensitivity) are used exactly as estimated by Carr *et al.* (2014), and the three metric combined using the approach of Carr *et al.* (2014) to assign species as being of high or low climate vulnerability (see Methods section below for further detail).

For each of the species assessed in the TVA of Carr *et al.* (2014) as having 'high' climate change vulnerability, we calculated the relative change in modelled climate suitability (from SDMs) for each species in each protected area in which it occurs, as follows:

$$CLIM\ Change\ i,j\ = \frac{CLIM_{Future}\ ij}{CLIM_{Baseline}\ ij}$$

where *CLIM$_{Future}$* is the future climate suitability for species i in protected area j, and *CLIM$_{baseline}$* is the contemporary climate suitability for species i in protected area j. This was done across each of 100 projections (5 blocks x 5 RCMs x 4 GCMs; which represent a range of uncertainty). Where there was directional consensus among the 100 projections (95% quantile does not overlap unity), the directional change in climate suitability was considered to be 'likely' (see Baker *et al.* 2015 for more details). These were recorded as either 'increasing' or 'decreasing' climate suitability. Where there was no directional consensus, 'no consensus' (or NC) was recorded.

We assume that if, at a species level within a PA, climate suitability is increasing the climate change vulnerability will be low and, conversely, if climate suitability is decreasing the climate change vulnerability will be high. Hence, this approach permits species to have different climate exposure categories in different parts of their range, unlike the original TVA exposure metric.

We then calculated the percentage agreement between species assessed as climate change vulnerable under TVA analysis and those using the SDM change in climate suitability. Following Carr *et al.* (2014), we compared these categorical assessments of local change in

climate suitability to the climate change vulnerability assessment from the TVA using two scenarios: 1) 'Worst case' scenario, where all species with NC in directional trend of climate suitability at a particular PA were assumed to have decreasing suitability; and, 2) 'Best case' scenario, where all such species were assumed to have increasing suitability.

b) Results

Comparing climate vulnerability derived from simple climatic and SDM-derived metrics

Compared to the climate change vulnerability assessment of Carr et al. (2014, Annex 2), the 'modified TVA' approach, which incorporates spatially-explicit modelled climate suitability (Figure 2.2), indicates fewer amphibian species vulnerable to climate change per site and, instead, many more species with little consensus in the degree to which they may be vulnerable to future climate change, dependent upon the future climate projection.

The overall climate vulnerability of birds using the 'modified TVA' approach (Figure 2.3) suggests fewer climate vulnerable species than does the original analysis of Carr *et al.* (see Annex 2) in the southern parts of the region, with around 70 species projected to experience declining suitability in PAs in the South, compared to projection of over 100 species in the original TVA analyses. The 'modified TVA' approach also indicated a large number of bird species for which no climate change vulnerability consensus could be reached.

The number of mammal species considered vulnerable by Carr *et al.* (2014) is broadly similar in its patterning to the totals arising from the 'modified TVA' approach (Figure 2.4) but, again, the totals identified as vulnerable in the individual PAs are smaller than the totals that Carr *et al.* (2014) estimated. The 'modified TVA' approach also highlights less certainty (i.e. a lack of consensus) in parts of SE Nigeria and coastal areas of Ghana, Cote d'Ivoire and Liberia than did Carr *et al.* (Figure 2.4 vs. Annex 2, Figure A2.4).
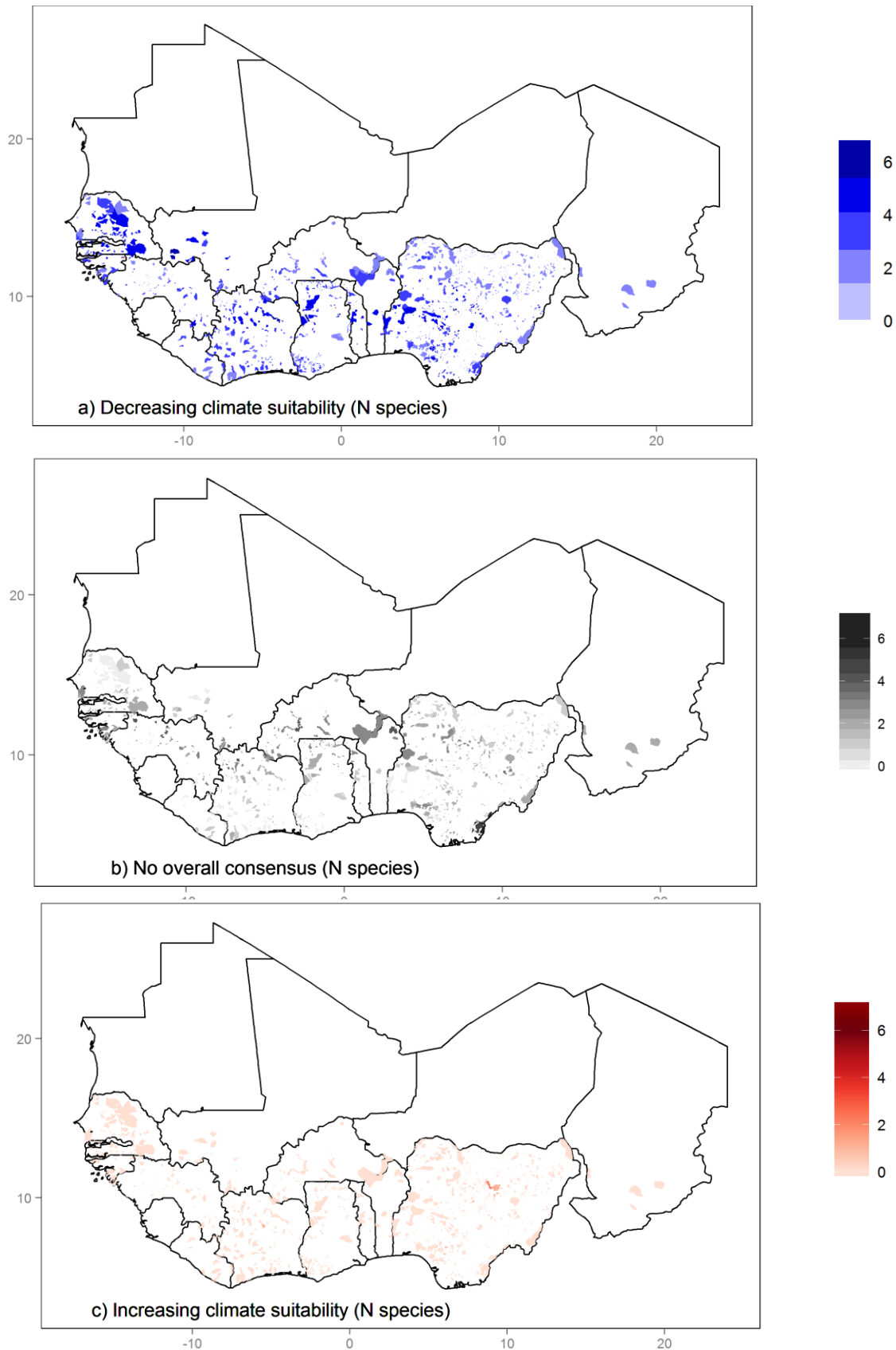
Figure 2.2. The number of amphibian species previously classified as climate change vulnerable by Carr *et al.* (2014) that are assessed as climate change vulnerable by 2055 using the modified-TVA analyses (see text). (a) Shows the number of species experiencing decreasing climate suitability by 2055 in each of the protected areas, (b) shows the number of species with no consensus of future climate impact and (c) shows the number of species for which climate suitability is increasing in protected areas.

Figure 2.3.The number of bird species previously classified as climate change vulnerable by Carr *et al.* (2014) that are assessed as climate change vulnerable by 2055 using the modified-TVA analyses (see text). (a) Shows the number of species experiencing decreasing climate suitability by 2055 in each of the protected areas, (b) shows the number of species with no consensus of future climate impact and (c) shows the number of species for which climate suitability is increasing in protected areas.
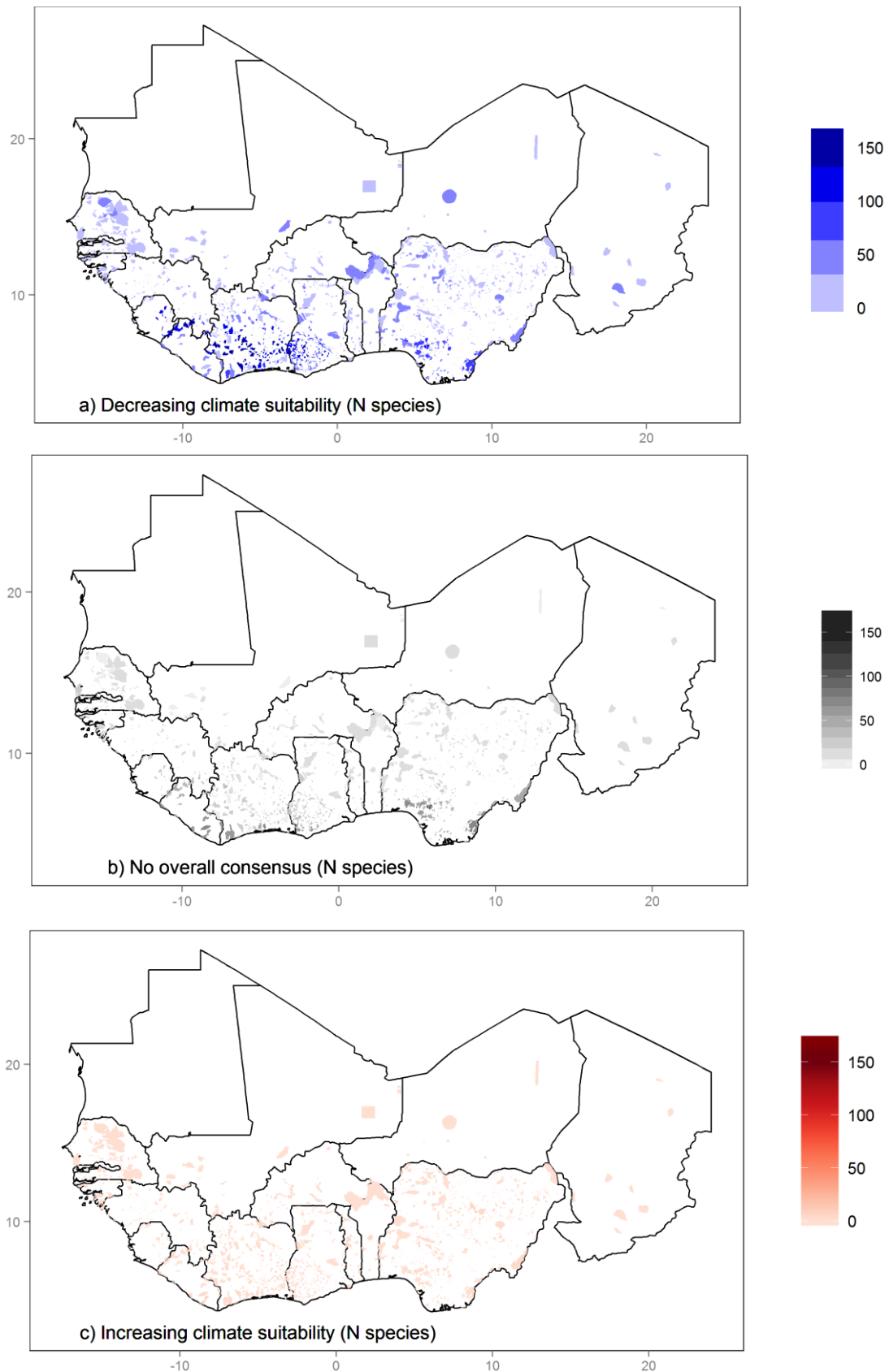
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Figure 2.4.The number of mammal species previously classified as climate change vulnerable by Carr *et al.* (2014) that are assessed as climate change vulnerable by 2055 using the modified-TVA analyses (see text). (a) Shows the number of species experiencing decreasing climate suitability by 2055 in each of the protected areas, (b) shows the number of species with no consensus of future climate impact and (c) shows the number of species for which climate suitability is increasing in protected areas.
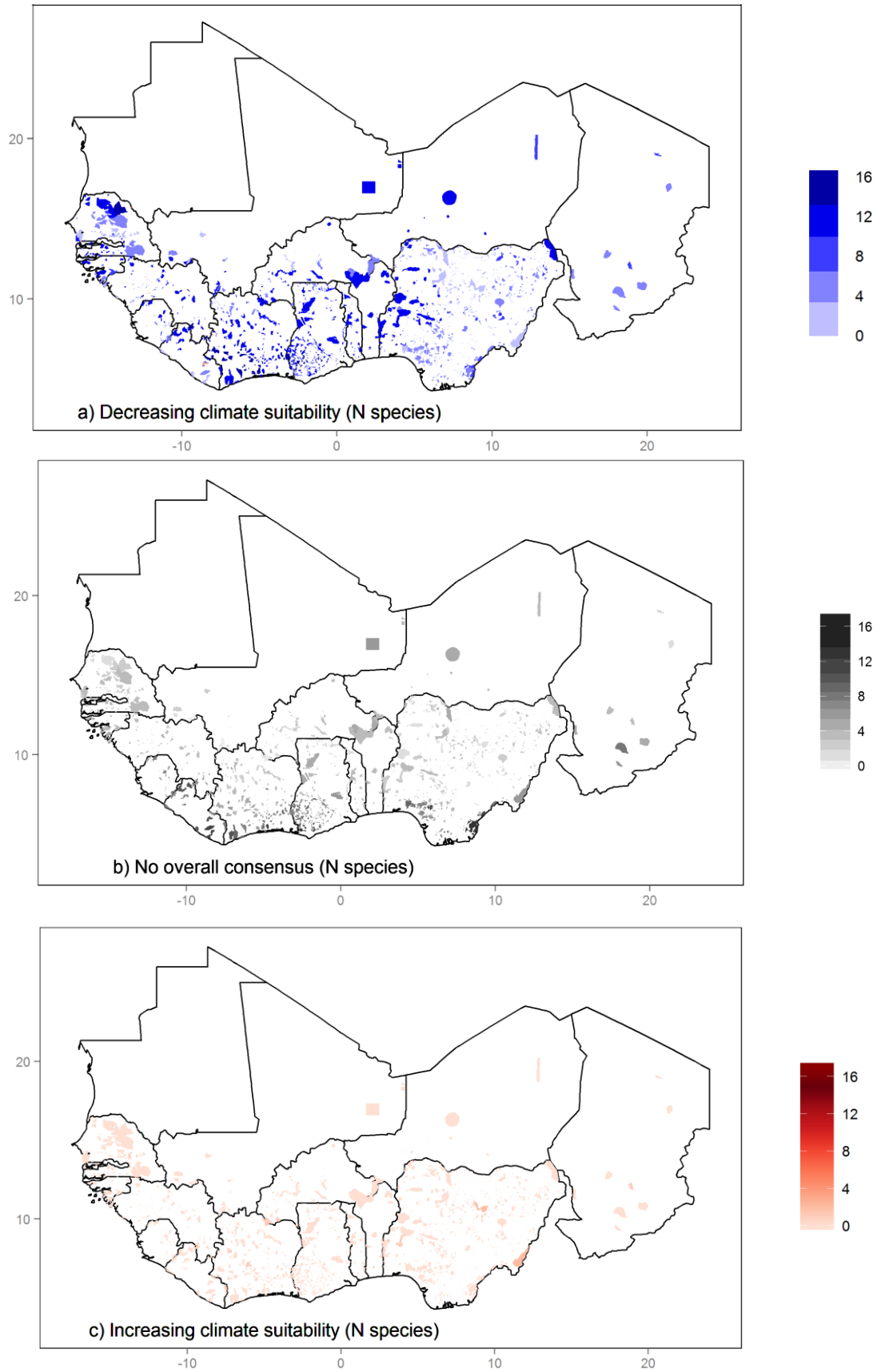
4. Combining traits and species distributions models to inform future management: using traits to refine species distribution model projections ('Modified SDMs')

a) Methods

To integrate traits in SDMs, a process we term 'spatial modelling with traits', we adopted a two-stage process, following Willis *et al.* (2015). Firstly, for those quantitative traits that can be considered within a dynamic modelling framework, we combined these traits into a dynamic SDM. Relevant traits that could be considered in this way, from the available data for West African species, included generation length and natal dispersal distances (which were only available for birds). Secondly, for qualitative traits, which could not be readily incorporated into a modelling framework for most species, we undertook a post-hoc analyses on the output from SDMs to identify species that might be affected by factors not considered in the dynamic SDMs. To complete this second process, we used outputs from both the dynamic and static SDMs to inform the questions provided in the flow chart in Figure 3.1. Static SDMs inform Q1 in the flowchart, and dynamic SDMs inform Q2. Comparing static and dynamic SMDs informs Q3. Q4 is informed from post-hoc consideration of individual species traits, and Q5 from a consideration of the traits and occurrence of interacting species and/or habitats. From Figure 2.1 we can also identify broad management objectives for individual species.

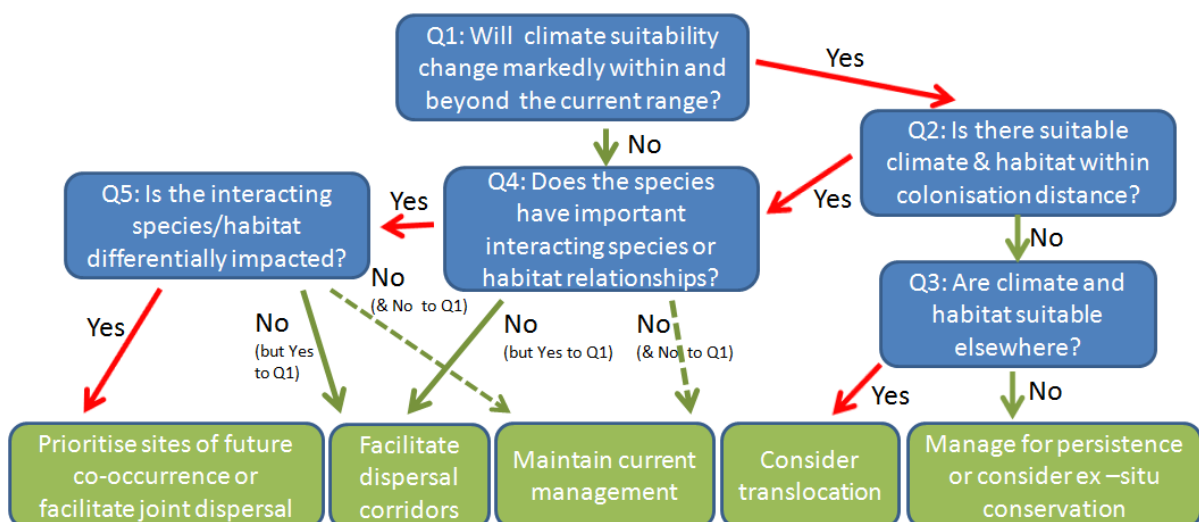**Figure 3.1 Flow chart demonstrating the potential for integration of SDM and TVA approaches in practice. Blue boxes are questions answered from SDM and TVA data; Q1-Q3 can be answered from integrated SDM-TVA models and Q4-Q5 from post-hoc trait considerations. Green boxes indicate the resultant management actions to consider, in addition to continued management within the current range [From Willis *et al.* 2015].**

Figure 3.2 below, adapted from Willis *et al.* (2015), schematically demonstrates how trait data were incorporated into the SDM process and, in the first stage of synthesis, how traits are then considered post-modelling to provide further information regarding species of conservation concern.

The outcomes from the flowchart in Figure 3.1 could provide an alternative approach to classifying species of high climate change vulnerability to more usual TVA approaches (e.g. Carr *et al.* 2014). The management action 'maintain current management' reflects low vulnerability. The two management actions 'prioritise sites of co-occurrence, or facilitate joint dispersal' and 'facilitate dispersal corridors' could be considered to reflect species of intermediate vulnerability, whereas species for which the outcome of the flowchart is 'consider translocation' or 'manage for persistence …' could be considered of highest vulnerability.
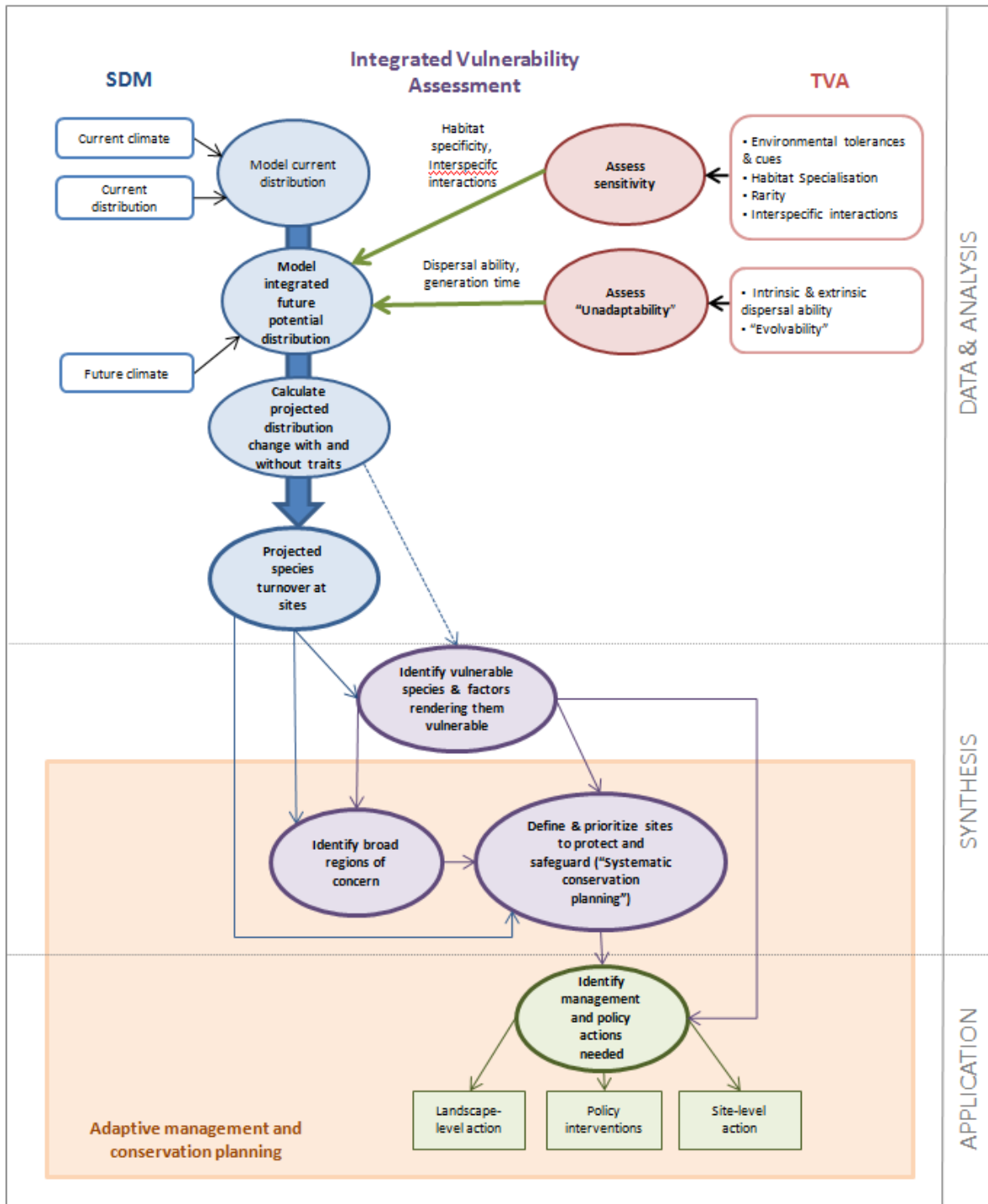
Figure 3.2. Conceptual model demonstrating the ways in which TVA data were integrated into the SDM modelling framework and links to systematic conservation planning and adaptive management. Green arrows linking TVAs and SDMs, and bold text indicates the components of the model influenced by integrated approach. [Adapted from Willis et al. 2015].

We used the following algorithmic rules to dictate the assignment of species through the questions in the flowchart in Figure 3.1.

Q1) To assess whether climate suitability will change markedly within and beyond the current range of a species: Any species that is projected to either lose >10% current range, or to gain > 10% current range was assigned a 'Yes' to Q1.

Q2) To assess whether there was suitable climate and habitat within colonisation distance of a species, we assigned a species a 'Yes' to Q2 if the projected range gain under dispersal was >10% current range.

Q3) To address Q3 in Figure 3.1 and to assess whether climate and habitat are suitable elsewhere for a species, we assigned species into three groups ($Q3_{Losing}$, $Q3_{Unfilled}$ and $Q3_{Maintain}$) using the following algorithms:

i) $Q3_{Losing}$ = After dispersal, are losses still greater the gains (>5% to buffer against very small differences);

ii) $Q3_{Unfilled}$ = After dispersal, is there still uncolonised but suitable areas (>5% of future dispersal mediated occupied extent, to buffer against very small differences);

iii) $Q3_{Maintain}$ = If the species could fill the available suitable space, by any means, could its current range extent at least be maintained (>5% of future dispersal mediated occupied extent, to buffer against very small differences).

In addition, given the complexities of answering Questions 4 and 5 in Figure 3.1 (see Willis *et al.* 2015 for examples), we highlighted those species that are forecast to shift their range into areas that are currently dominated by a different biome than the one(s) they currently occur in. This approach pre-supposes that a species is restricted to a particular biome due to a combination of the species/features of that biome. It also presupposes that the biome (typically predicated upon the underlying dominant plant species types) will be less able to respond to changes in climate than will an individual bird species. For example, using this metric, we would flag as being particularly susceptible an obligate tropical forest species whose suitable future range extends into the savanna biome. By contrast, if an obligate forest species' future range extended into an area of tropical forest that is currently unoccupied, we assume that this range extension is less likely to be limited by important species interaction/habitat effects.

We use these approaches to summarise the number of species of conservation concern that will require various management practices in future. In addition, we identify a

27

sub-set of species that may become extinct in West Africa in future unless assisted colonisation is considered. We provide maps showing potential changes in the ranges of species of conservation concern as supplementary figures.

b) Results

The projected changes in range under future climate change, after considering traits such as dispersal ability, generation length, and age to first breeding, in addition to climatic suitability, were very variable. In Annex 1 we illustrate typical examples of some of the responses along with a table that highlights those species that might potentially be considered candidates for assisted colonisation to maintain important West African populations.

Figure 3.3, below, summarises, using the flow diagram of Figure 3.1, the dominant management strategies that are likely to be most beneficial for the bird species of conservation concern of West Africa, based on consideration of individual species outputs from static and dynamic SDMs. Approximately half of the species will benefit from conservation efforts that facilitate their natural ability to shift their range, in order to track climate (without more direct intervention, e.g. assisted colonisation). Approximately 40% of species will benefit from focussing particular attention on managing the sites within their range where they are forecast to persist. Importantly, approximately 15% of species will benefit from both of these management activities (purple bar below). A smaller proportion (circa 15% of species) will be most effectively managed solely by maintaining current management within their range (i.e. limited opportunity for expansion or threat of decline exists), although this does not consider the possibility of key species on which they depend shifting their range. A small proportion of species considered (9%) have assisted colonisation flagged as one of the key future management objectives to consider, suggesting that this may become a new management option to consider in West Africa in the future.
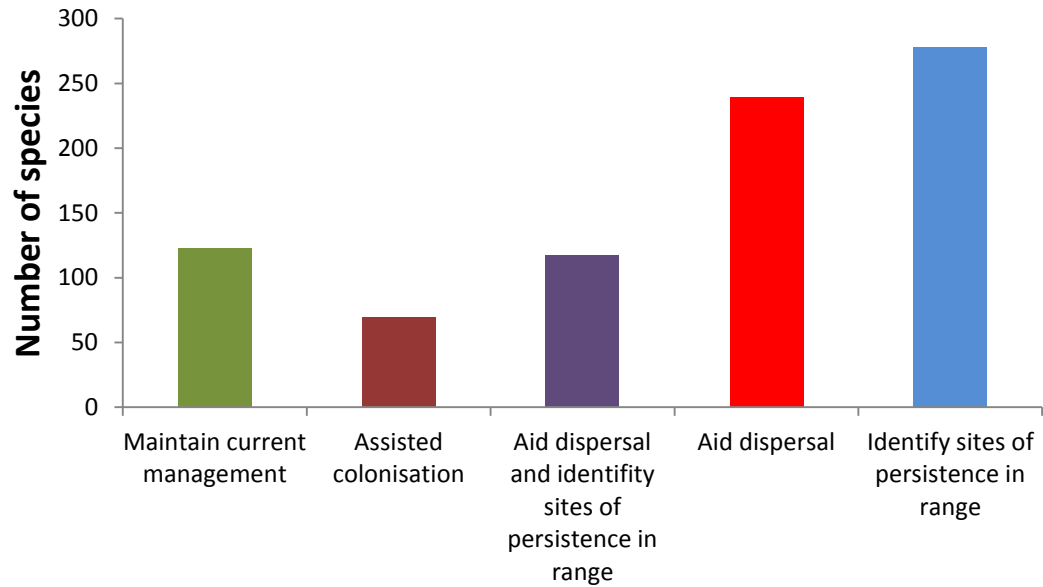
Figure 3.3. A summary of the principal management strategies required for the management of bird species of conservation concern across West Africa. For most species, the dominant management strategy (in addition to maintaining current management within the range) that will facilitate the largest range extent is shown, with up to three management activities selected for species that require multiple management options in different parts of their range. Selection of the category 'maintain current management' indicates that no additional management is necessary to maintain the population. Species for which 'identifying sites of persistence within the range' is a management strategy are those for which future suitability within the current range is variable.

5. Conclusions

The two different approaches adopted here ('modified SDM' and 'modified TVAs') both highlight the benefit that can be gained from integrating trait data into SDMs and vice versa. Incorporating trait data into SDMs provides a better understanding of management strategies that might help species cope with projected climatic changes, while incorporating species-specific modelled climate suitability into TVA analyses not only permits the estimation of site specific projections of climate change risk for individual species, but that these refined TVAs can also highlight different groups of species as being vulnerable to climate change.

The incorporation of traits within dynamic SDMs and post-hoc management considerations provide substantial opportunities for management plans at individual sites to be tailored to individual species movements as a result of climatic changes. Here we demonstrate that for most bird species of West Africa (the only taxa for which we had sufficient traits data to undertake such an assessment), the principal management options that will maximise the occurrence of species of conservation concern will be to facilitate the natural dispersal of species from their current range to areas of suitable climate in future, or to identify sites of suitable climate persisting within their current range. Refugial sites within the current range and potential regions of population expansion can both be identified from the SDMs that incorporate species traits. Maps for all such West African bird species of conservation concern have been produced for their African range (Supplementary Data, which can be provided upon request). Management based on facilitating these two responses to climate change (shrinking or shifting ranges) forms the most common recommendation for West African bird species. A smaller proportion of species (*circa* 100 species) are expected to persist within their current range with limited change as a result of climate change. For a yet smaller proportion (*circa* 60 species) suitable climate becomes so limited within the current range and within natural colonisation distance, such that assisted colonisation might be considered as a conservation strategy. Overall, we find that the best management strategies for the majority of bird species examined in this study are to facilitate movement into novel areas as climate changes and, for species with limited movement projection, to establish (or continue) high quality management at sites within their current range that are projected to remain climatically suitable.

6. References

ARAUJO, M. B., THUILLER, W. & PEARSON, R. G. 2006. Climate warming and the decline of amphibians and reptiles in Europe. *Journal of Biogeography,* 33**,** 1712-1728.

BAGCHI, R., CROSBY, M., HUNTLEY, B., HOLE, D. G., BUTCHART, S. H. M., COLLINGHAM, Y., KALRA, M., RAJKUMAR, J., RAHMANI, A., PANDEY, M., GURUNG, H., TRAI, L. T., VAN QUANG, N. & WILLIS, S. G. 2013. Evaluating the effectiveness of conservation site networks under climate change: accounting for uncertainty. *Global Change Biology,* 19**,** 1236–1248.

BAKER, D. J., HARTLEY, A. J., BURGESS, N. D., BUTCHART, S. H. M., CARR, J. A., SMITH, R. J., BELLE, E. & WILLIS, S. G. 2015. Assessing climate change impacts for vertebrate fauna across the West African protected area network using regionally appropriate climate projections. *Diversity and Distributions***,** in press.

BARBET-MASSIN, M. & JETZ, W. 2014. A 40-year, continent-wide, multispecies assessment of relevant climate predictors for species distribution modelling. *Diversity and Distributions,* 20**,** 1285-1295.

BEAUMONT, L. J. & HUGHES, L. 2002. Potential changes in the distributions of latitudinally restricted Australian butterfly species in response to climate change. *Global Change Biology,* 8**,** 954-971.

BENNING, T. L., LAPOINTE, D., ATKINSON, C. T. & VITOUSEK, P. M. 2002. Interactions of climate change with biological invasions and land use in the Hawaiian Islands: Modeling the fate of endemic birds using a geographic information system. *Proceedings of the National Academy of Science,* 99**,** 14246-14249.

BIRDLIFE-INTERNATIONAL & NATURESERVE 2013. Bird species distribution maps of the world. Version 3.0. Cambridge, UK and NatureServe, Arlington, USA: BirdLife International.

BUONTEMPO, C., MATHISON, C., JONES, R., WILLIAMS, K., WANG, C. & MCSWEENEY, C. 2014. An ensemble climate projection for Africa. *Climate Dynamics***,** 1-22.

BUTCHART, S. H. M., WALPOLE, M., COLLEN, B., VAN STRIEN, A., SCHARLEMANN, J. P. W., ALMOND, R. E. A., BAILLIE, J. E. M., BOMHARD, B., BROWN, C., BRUNO, J., CARPENTER, K. E., CARR, G. M., CHANSON, J., CHENERY, A. M., CSIRKE, J., DAVIDSON, N. C., DENTENER, F., FOSTER, M., GALLI, A., GALLOWAY, J. N., GENOVESI, P., GREGORY, R. D., HOCKINGS, M., KAPOS, V., LAMARQUE, J.-F., LEVERINGTON, F., LOH, J., MCGEOCH, M. A., MCRAE, L., MINASYAN, A., MORCILLO, M. H., OLDFIELD, T. E. E., PAULY, D., QUADER, S., REVENGA, C., SAUER, J. R., SKOLNIK, B., SPEAR, D., STANWELL-SMITH, D., STUART, S. N., SYMES, A., TIERNEY, M., TYRRELL, T. D., VIE, J.-C. & WATSON, R. 2010. Global Biodiversity: Indicators of Recent Declines. *Science,* 328**,** 1164-1168.

CARR, J. A., HUGHES, A. F. & FODEN, W. B. 2014. A Climate Change Vulnerability Assessment of West African Species. UNEP-WCMC Technical Report. Cambridge, UK.

CARR, J. A., OUTHWAITE, W. E., GOODMAN, G. L., OLDFIELD, T. E. E. & FODEN, W. B. 2013. Vital but vulnerable: Climate change vulnerability and human use of wildlife in Africa's Albertine Rift. *Occasional Paper of the IUCN Species Survival Commission No. 48.* Gland, Switzerland and Cambridge, UK: IUCN, .

CHIN, A., KYNE, P., WALKER, T. I. & MCAULEY, R. B. 2010. An integrated risk assessment for climate change: analysing the vulnerability of sharks and rays on Australia's Great Barrier Reef. *Global Change Biology,* 16**,** 1936–1953.

CONLISK, E., SYPHARD, A. D., FRANKLIN, J., FLINT, L., FLINT, A. & REGAN, H. 2013. Uncertainty in assessing the impacts of global change with coupled dynamic species distribution and population models. *Global Change Biology,* 19**,** 858–869.

DAWSON, T. P., JACKSON, S. T., HOUSE, J. I., PRENTICE, I. C. & MACE, G. M. 2011. Beyond predictions: biodiversity conservation in a changing climate. *Science,* 332**,** 53-58.

FODEN, W. B., BUTCHART, S. H. M., STUART, S. N., VIÉ, J.-C., AKÇAKAYA, H. R., ANGULO, A., DEVANTIER, L. M., GUTSCHE, A., TURAK, E., CAO, L., DONNER, S. D., V.KATARIYA, BERNARD, R., HOLLAND, R. A., HUGHES, A. F., O'HANLON, S. E., GARNETT, S. T., ŞEKERCIOĞLU, Ç. H. &

MACE, G. M. 2013. Climate change susceptibility of the world's birds, amphibians and corals. *PLoS One,* 8**,** :e65427.

GAME, E. T., LIPSETT-MOORE, G., SAXON, E., PETERSON, N. & SHEPPARD, S. 2011. Incorporating climate change adaptation into national conservation assessments. *Global Change Biology,* 17**,** 3150-3160.

GARCIA, R. A., ARAÚJO, M. B., BURGESS, N. D., FODEN, W. B., GUTSCHE, A., RAHBEK, C. & CABEZA, M. 2014. Matching species traits to projected threats and opportunities from climate change. *Journal of Biogeography,* 41**,** 724-735.

GARDALI, T., SEAVY, N. E., DIGAUDIO, R. T. & COMRACK, L. A. 2012. A climate change vulnerability assessment of California's at-risk birds. *PLoS One,* 7**,** e29507.

GIORGI, F., JONES, C. & ASRAR, G. R. 2009. Addressing climate information needs at the regional level: the CORDEX framework. *WMO Bulletin,* 58**,** 175-183.

GRAHAM, N. A. J., CHABANET, P., EVANS, R. D., JENNINGS, S., LETOURNEUR, Y., MACNEIL, M. A., MCCLANAHAN, T. R., OHMAN, M. C., POLUNIN, N. V. C. & WILSON, S. K. 2011. Extinction vulnerability of coral reef fishes. *Ecology Letters,* 14**,** 341-348.

HARRISON, P. A., BERRY, P. M., BUTT, N. & NEW, M. 2006. Modelling climate change impacts on species' distributions at the European scale: implications for conservation policy. *Environmental Science & Policy,* 9**,** 116-128.

HARTLEY, A.J., JONES, R. and JANES, T. 2015. Projections of change in ecosystem services under climate change. UNEP-WCM Technical Report.

HOF, C., ARAUJO, M. B., JETZ, W., RAHBEK, C. & : 2011. Additive threats from pathogens, climate and land-use change for global amphibian diversity. *Nature,* 480**,** 516-519.

HOLE, D. G., HUNTLEY, B., ARINAITWE, J., BUTCHART, S. H. M., COLLINGHAM, Y. C., FISHPOOL, L. D. C., PAIN, D. J. & WILLIS, S. G. 2011. Toward a Management Framework for Networks of Protected Areas in the Face of Climate Change. *Conservation Biology,* 25**,** 305-315.

HUNTLEY, B., COLLINGHAM, Y. C., WILLIS, S. G. & GREEN, R. E. 2008. Potential Impacts of Climatic Change on European Breeding Birds. *Plos One,* 3.

IPCC 2007. *Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change,* Cambridge, UK, and New York, NY, USA., Cambridge University Press.

IUCN 2014. The IUCN Red List of Threatened Species. *Version 2014.2.*

JENSEN, R. A., MADSEN, J., O'CONNELL, M., WISZ, M. S., TOMMERVIK, H. & MEHLUM, F. 2008. Prediction of the distribution of Arctic-nesting pink-footed geese under a warmer climate scenario. *Global Change Biology,* 14**,** 1-10.

JONES, R. G., NOGUER, M., HASSELL, D. C., HUDSON, D., WILSON, S. S., JENKINS, G. J. & MITCHELL, J. F. B. 2004. Generating high resolution climate change scenarios using PRECIS. Exeter, UK: Met Office Hadley Centre.

KEARNEY, M. & PORTER, W. 2009. Mechanistic niche modelling: combining physiological and spatial data to predict species' ranges. *Ecology Letters,* 12**,** 334-350.

LADLE, R. J., WHITTAKER, R. J., WATSON, J. E. M., GRANTHAM, H. S., WILSON, K. A. & POSSINGHAM, H. P. 2011. Systematic conservation planning: past, present and future. *In:* LADLE, R. J. & WHITTAKER, R. J. (eds.) *Conservation Biogeography.* Oxford, UK: Blackwells.

MARGULES, C. R. & PRESSEY, R. L. 2000. Systematic conservation planning. *Nature,* 405**,** 243-253.

MCSWEENEY, C. F., JONES, R. G. & BOOTH, B. B. B. 2012. Selecting Ensemble Members to Provide Regional Climate Change Information. *Journal of Climate,* 25**,** 7100-7121.

MIDGLEY, G. F., HANNAH, L., MILLAR, D., RUTHERFORD, M. C. & POWRIE, L. W. 2002. Assessing the vulnerability of species richness to anthropogenic climate change in a biodiversity hotspot. *Global Ecology and Biogeography,* 11**,** 445-451.

MOILANEN, A., WILSON, K. A. & POSSINGHAM, H. P. 2009. *Spatial Conservation Prioritization: Quantitative Methods and Computational Tools,* Oxford, UK, Oxford University Press,.

PACIFICI, M., FODEN, W. B., VISCONTI, P., WATSON, J. F. M., BUTCHART, S. H. M., KOVACS, K. M., SCHEFFERS, B. R., HOLE, D. G., MARTIN, T. G., AKCAKAYA, H. R., CORLETT, R. T., HUNTLEY, B., BICKFORD, D., CARR, J. A., HOFFMANN, A. A., MIDGLEY, G. F., PEARCE-KELLY, P., PEARSON, R.

G., WILLIAMS, S. E., WILLIS, S. G., YOUNG, B. & RONDININI, C. 2015. Assessing species vulnerability to climate change. *Nature Climate Change,* 5**,** 215-225.

PARMESAN, C. & YOHE, G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature,* 421**,** 37-42.

PEARSON, R. G. & DAWSON, T. P. 2004. Bioclimate envelope models: what they detect and what they hide - response to Hampe (2004). *Global Ecology and Biogeography,* 13**,** 471-473.

PHILLIPS, S. J., ANDERSON, R. P. & SCHAPIRE, R. E. 2006. Maximum entropy modeling of species geographic distributions. *Ecological Modelling,* 190**,** 231-259.

ROWLAND, E. L., DAVISON, J. E. & GRAUMLICH, L. J. 2011. Approaches to Evaluating Climate Change Impacts on Species: A Guide to Initiating the Adaptation Planning Process. *Environmental Management,* 47**,** 322-337.

SALA, O. E., CHAPIN, F. S., ARMESTO, J. J., BERLOW, E., BLOOMFIELD, J., DIRZO, R., HUBER-SANWALD, E., HUENNEKE, L. F., JACKSON, R. B., KINZIG, A., LEEMANS, R., LODGE, D. M., MOONEY, H. A., OESTERHELD, M., POFF, N. L., SYKES, M. T., WALKER, B. H., WALKER, M. & WALL, D. H. 2000. Biodiversity - Global biodiversity scenarios for the year 2100. *Science,* 287**,** 1770-1774.

SECRETARIAT OF THE CBD 2010. *Global Biodiversity Outlook 3,* Montréal.

SEO, C., THORNE, J. H., HANNAH, L. & THUILLER, W. 2009. Scale effects in species distribution models: implications for conservation planning under climate change. *Biology Letters,* 5**,** 39-43.

SINCLAIR, S. J., WHITE, M. D. & NEWELL, G. R. 2010. How Useful Are Species Distribution Models for Managing Biodiversity under Future Climates? *Ecology and Society,* 15**,** e-article 8.

SMITH, R.J. 2013. A Gap Analysis of Climate Change Resilience Areas: A Preliminary Study. UNEP-WCMC technical report.

SYLLA, M. B., GIORGI, F., COPPOLA, E. & MARIOTTI, L. 2013. Uncertainties in daily rainfall over Africa: assessment of gridded observation products and evaluation of a regional climate model simulation. *International Journal of Climatology,* 33**,** 1805-1817.

THOMAS, C. D., CAMERON, A., GREEN, R. E., BAKKENES, M., BEAUMONT, L. J., COLLINGHAM, Y. C., ERASMUS, B. F. N., DE SIQUEIRA, M. F., GRAINGER, A., HANNAH, L., HUGHES, L., HUNTLEY, B., VAN JAARSVELD, A. S., MIDGLEY, G. F., MILES, L., ORTEGA-HUERTA, M. A., PETERSON, A. T., PHILLIPS, O. L. & WILLIAMS, S. E. 2004. Extinction risk from climate change. *Nature,* 427**,** 145-148.

THOMAS, C. D., HILL, J. K., ANDERSON, B. J., BAILEY, S., BEALE, C. M., BRADBURY, R. B., BULMAN, C. R., CRICK, H. Q. P., EIGENBROD, F., GRIFFITHS, H. M., KUNIN, W. E., OLIVER, T. H., WALMSLEY, C. A., WATTS, K., WORSFOLD, N. T. & YARDLEY, T. 2011. A framework for assessing threats and benefits to species responding to climate change. *Methods in Ecology and Evolution,* 2**,** 125-142.

WIENS, J. A., STRALBERG, D., JONGSOMJIT, D., HOWELL, C. A. & SNYDER, M. A. 2009. Niches, models, and climate change: Assessing the assumptions and uncertainties. *Proceedings of the National Academy of Sciences of the United States of America,* 106**,** 19729-19736.

WILLIAMS, S. E., SHOO, L. P., ISAAC, J. L., HOFFMANN, A. A. & LANGHAM, G. 2008. Towards an Integrated Framework for Assessing the Vulnerability of Species to Climate Change. *Plos Biology,* 6**,** 2621-2626.

WILLIS, S. G., FODEN, W., BAKER, D. J., BELLE, E., BURGESS, N. D., CARR, J. A., DOSWALD, N., GARCIA, R. A., HARTLEY, A., HOF, C., NEWBOLD, T., RAHBEK, C., SMITH, R. J., VISCONTI, P., YOUNG, B. & BUTCHART, S. H. M. 2015. Integrating climate change vulnerability assessments from Species Distribution Models and Trait-based Approaches *Biological Conservation***,** in press.

WWF 2014. Living Planet report 2014: species and spaces, people and places. *In:* MCLELLAN, R., IYENGAR, L., JEFFRIES, B. & OERLEMANS, N. (eds.).

YOUNG, B., BYERS, E., GRAVUER, K., HALL, K., HAMMERSON, G. & REDDER, A. 2011. Guidelines for Using the NatureServe Climate Change Vulnerability Index. Release 2.1. April 2011. https://connect.natureserve.org/sites/default/files/documents/Guidelines_NatureServeClimateChangeVulnerabilityIndex_r2.1_Apr2011.pdf.

Annex 1. Examples of climate change impacts on the potential future distribution of West African bird species of conservation concern

For some species (e.g. *Campephaga oriolina*, Figure A1.1), almost the entire region where they currently occur in West Africa is projected to become unsuitable and their continued existence may depend upon assisted colonisation of other areas that are becoming newly climatically suitable. Other species are projected to lose much of their West African range (e.g. *Jubula* lettii, Figure A1.2) but with no climatically suitable areas beyond their dispersal capabilities. For such species, prioritising their conservation in the small areas projected to remain suitable will be vital.
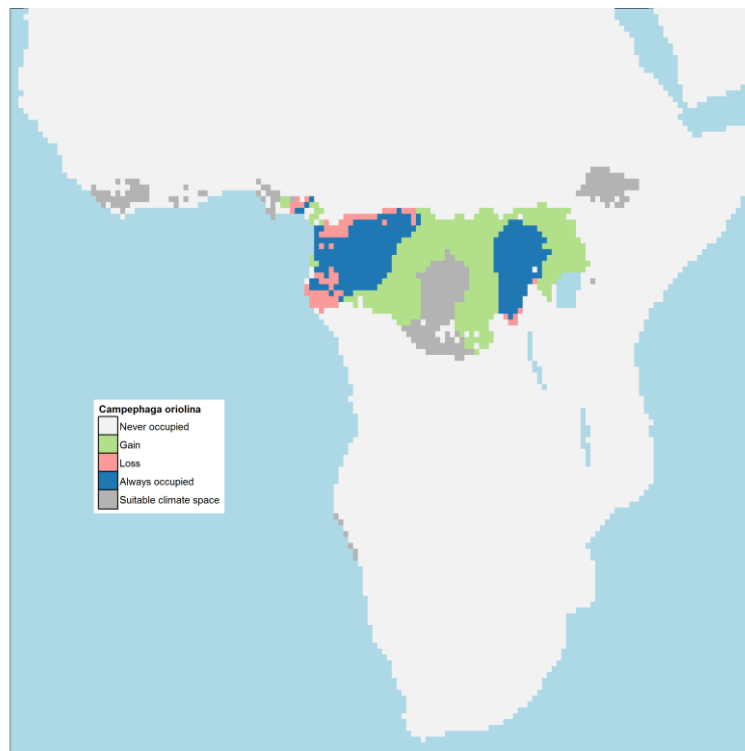

Figure A1.1. The projected change in range extent for *Campephaga oriolina*, showing a marked range contraction in West Africa but some substantial areas of climatically suitable habitat in parts of Liberia and Cote d'Ivoire beyond the species disposal capabilities. In the figure legend, always occupied indicates climate suitability in current and future periods. Gains indicate areas of climate suitability within colonisation capability in the time-frame and losses indicate loss of climatic suitability between the current and future period. Suitable climate space indicates areas that become newly climatically suitable in future but which a species is incapable of colonising in the intervening period.
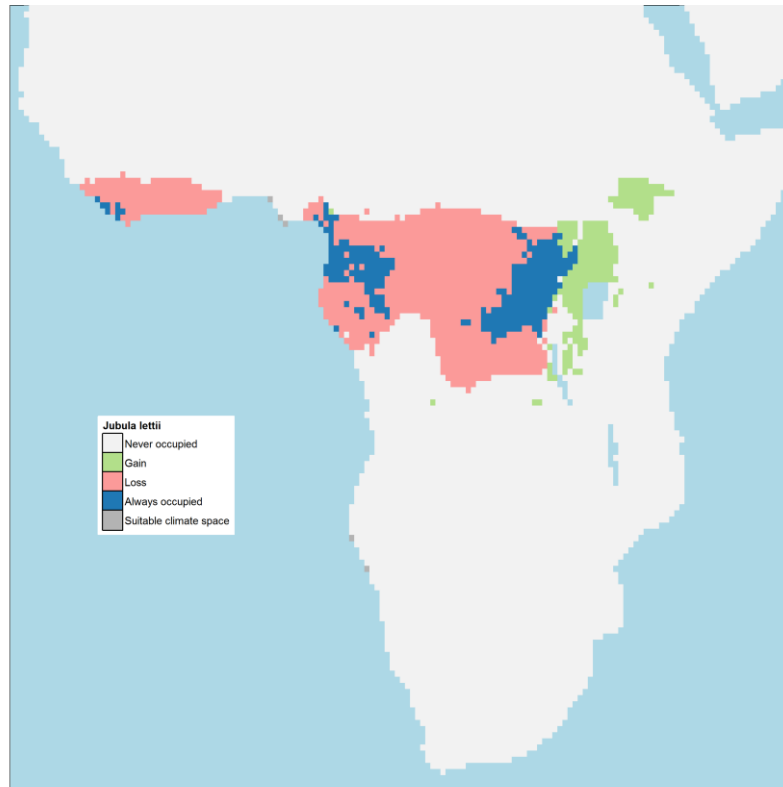
Figure A1.2. The projected change in range extent for *Jubula lettii* showing a marked range contraction in West Africa.

For other species (e.g. *Jynx ruficollis*, Figure A1.3), although there could be scope for assisted colonisation to introduce the species to West Africa, the suitable sites in West Africa are too small and fragmented to be likely to result in a viable population in the longer term, and conservation resources are probably better allocated in parts of the species range where persistence is more likely.
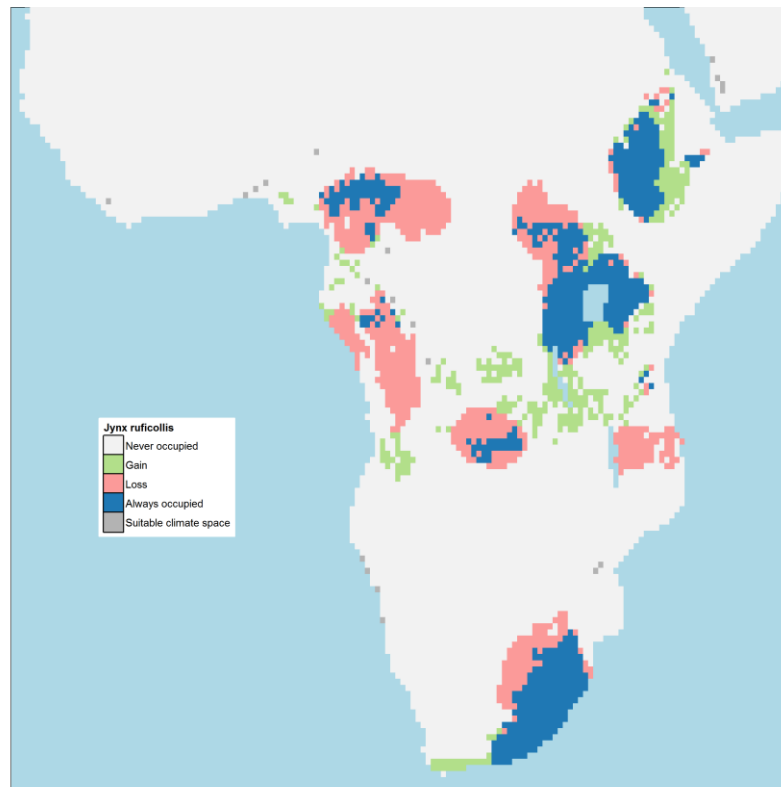
Figure A1.3. The projected change in range extent for *Jynx ruficollis* showing a marked range contraction in west parts of central Africa but a limited scope for suitable climate space to occur in west Africa in the future.

For other species, the area of suitable climate within colonisation of the species may lead to large declines in future, even though there are regions of suitable climate beyond the species' dispersal capabilities. For such species (e.g. *Campephaga oriolina*, Figure A1.1), assisted colonisation might be considered as a future conservation tool. Those species for which assisted colonisation might be considered are listed in Table A1.1. Note that this list is predicated solely on substantial loss of suitable climate space within a species current range in West Africa or elsewhere and a corresponding increase in potential climate space within West Africa but beyond the species colonisation abilities. Species that are projected to be able to colonise extensive new areas but which also have areas beyond their colonisation ability in West Africa are not included. This list takes no account of the availability of suitable habitat already being available in newly suitable sites, nor of potential issues with introducing a novel species into an established community. The list should simply be considered a starting point, from which more thorough evaluations of the potential for benefits accruing from assisted colonisation could be evaluated, on the basis of detailed ecological considerations. In the vast majority of cases, assisted colonisation should be considered only as a last option,

if natural range alterations will not be possible for some reason, because there are considerable risks associated with introducing species to novel areas.

Unlike the some of the examples given above, as well as the examples in Table A1.1, for which substantial range contractions occur, there are also a number of species that are projected to remain as widespread in future as they are currently (e.g. *Crysococcyx caprius*, Figure A1.4), whilst other species are project to have the potential to expand their range considerably (e.g. *Colius striatus*, Figure A1.5), perhaps colonising West Africa for the first time.

Table A1.1. A list of 56 candidate species for which assisted colonisation might be considered as a future conservation tool.

| Species Scientific Names	
Acrocephalus gracilirostris	*Lybius leucocephalus*
Agelastes niger	*Malimbus cassini*
Anthreptes aurantium	*Malimbus coronatus*
Apalis binotata	*Malimbus erythrogaster*
Apus batesi	*Malimbus racheliae*
Baeopogon clamans	*Melignomon zenkeri*
Bradypterus baboecala	*Muscicapa tessmanni*
Campephaga oriolina	*Myrmecocichla nigra*
Campephaga petiti	*Nectarinia oritis*
Caprimulgus natalensis	*Nectarinia ursulae*
Chlorocichla falkensteini	*Nesocharis capistrata*
Chloropeta natalensis	*Nesocharis shelleyi*
Cisticola brunnescens	*Ortygospiza locustella*
Cisticola discolor	*Parmoptila woodhousei*
Cossypha isabellae	*Phyllastrephus poensis*
Cossyphicula roberti	*Phyllastrephus poliocephalus*
Crinifer zonurus	*Picathartes gymnocephalus*
Criniger ndussumensis	*Picathartes oreas*
Criniger olivaceus	*Platysteira chalybea*
Dryoscopus senegalensis	*Poicephalus crassus*
Estrilda nonnula	*Poliolais lopezi*
Euplectes hartlaubi	*Prinia bairdii*
Grafisia torquata	*Prinia fluviatilis*
Gymnobucco bonapartei	*Prinia leucopogon*
Kakamega poliothorax	*Terpsiphone rufocinerea*
Lamprotornis purpureiceps	*Thripias namaquus*
Laniarius atroflavus	*Thripias xantholophus*
Laniarius poensis	*Urolais epichlorus*
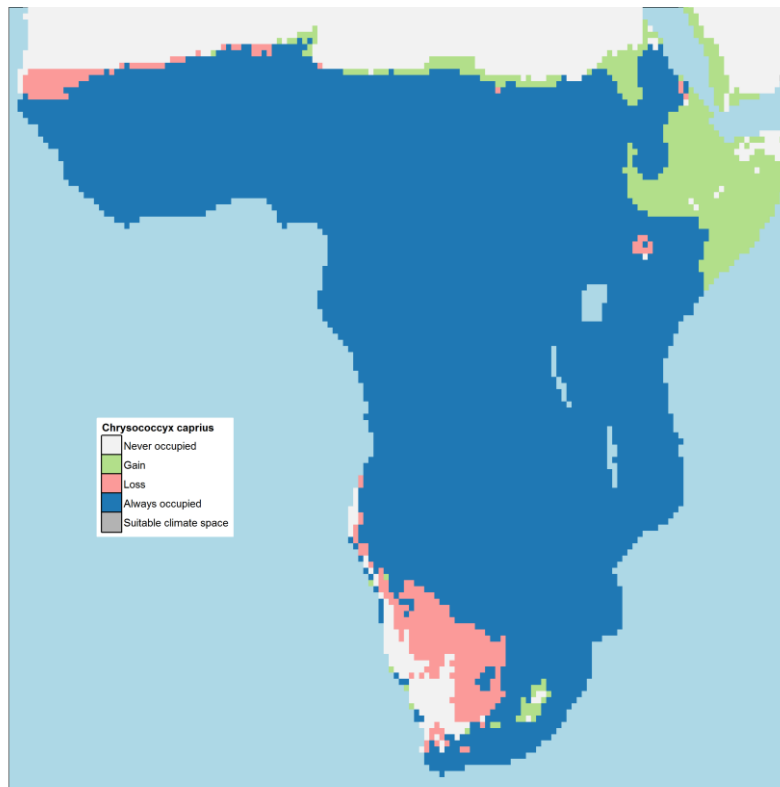
Figure A1.4. The projected change in range extent for *Crysococcyx caprius,* a species with very limited change projected across West Africa in the future.
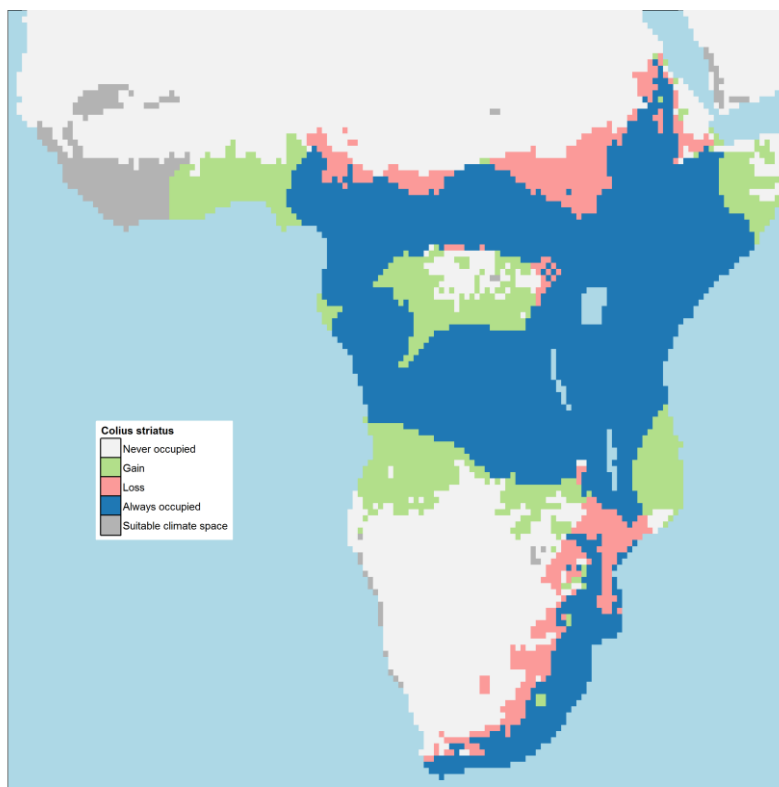

Figure A1.5. The projected change in range extent for *Colius striatus,* a species projected to expand its range further into West Africa (and other areas) in the future.

Annex 2. Contrasting the TVA of Carr et al. (2014) with the 'Modified TVA' approach

Summary

The original TVA flagged 194 species of high overall climate change vulnerability using simple climatic metrics applied across an entire species range (Carr *et al.* 2014, Figure A2.1). Here, we were able to produce a more nuanced measure of climate exposure that varied across space. Consequently, we were able to assign individual climate change vulnerability assessments to each of these species in each protected area.

In the 'worst case' scenario for all three taxonomic groups, there was high consensus in the percentage of species whose climate vulnerability agreed between the TVA and SDM approaches (Figs A2.2a, A2.3a & A2.4a). By contrast, under the 'best case' scenario, there was much lower consensus in the percentage of species whose climate vulnerability agreed between the TVA and SDM approaches (Figs A2.2b, A2.3b & A2.4b). The large number of species with 'no consensus' in the directional trend in climate suitability from the SDM approach means that overall consensus is likely to be lower, although not as low as indicated in the 'best case' scenarios.

Amphibians

Figure A2.2 maps the agreement in climate change vulnerability for amphibians as assessed using the two contrasting approaches. The maps show, for amphibian species, that despite high correlation between the two methods under the best case scenario (Fig A2.2a), there is substantial disagreement, and substantial spatial patterning in the disagreement, under the best case scenario (A2.2b). In particular, there is substantial disagreement in the drier habitats of the north and east of the region, but closer agreement in some of the coastal forest regions.

The close agreement under the worst-case scenario (i.e. where we assume species with unclear trends across sites will have declining suitability) between the modified TVA and the original TVA assessment, suggests that the original methods of assessing climate

suitability (using mean changes in climate) flags many species as being climate change vulnerable. Conversely, under the assumption in the modified TVA that species with unclear trends are not climatically vulnerable, there is much less agreement, and considerable spatial patterning. This patterning suggests climate is affecting species suitability differently across species' ranges, which in turn suggests that using SDM derived climate suitability improves discrimination of areas where species will experience differing degrees of climatic exposure. Note, however, that the low levels of agreement in desert and semi-desert areas will partially be an artifact of the low species richness in such areas, meaning that a change in the categorization of just one or two species will markedly affect the percentage agreement.
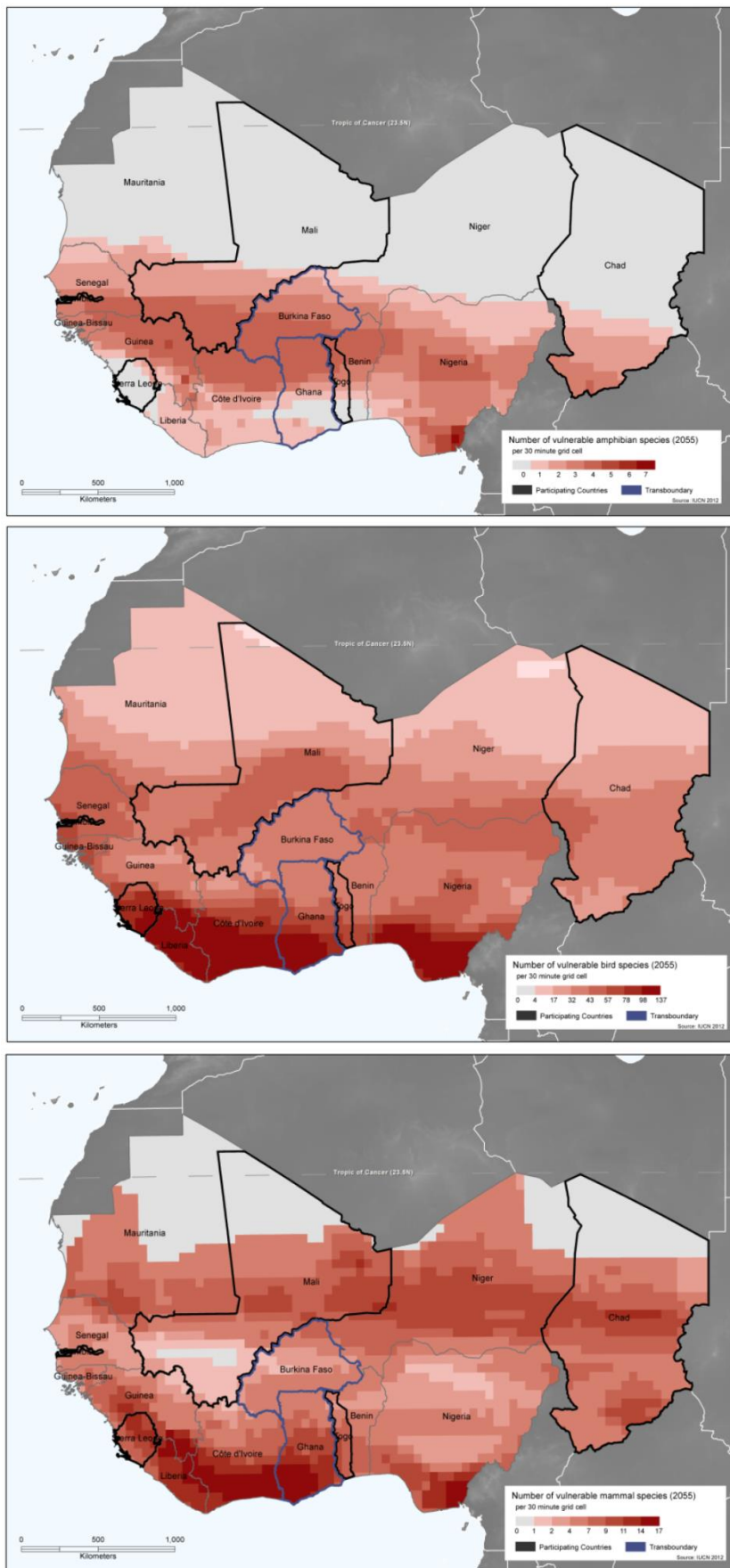
Figure A2.1. Richness of climate change vulnerable West African amphibians (top), birds (middle) and mammals (lower) for the 2040-2069 period from the original methods of Carr *et al.* (2014). Images taken from Carr *et al.* (2014).
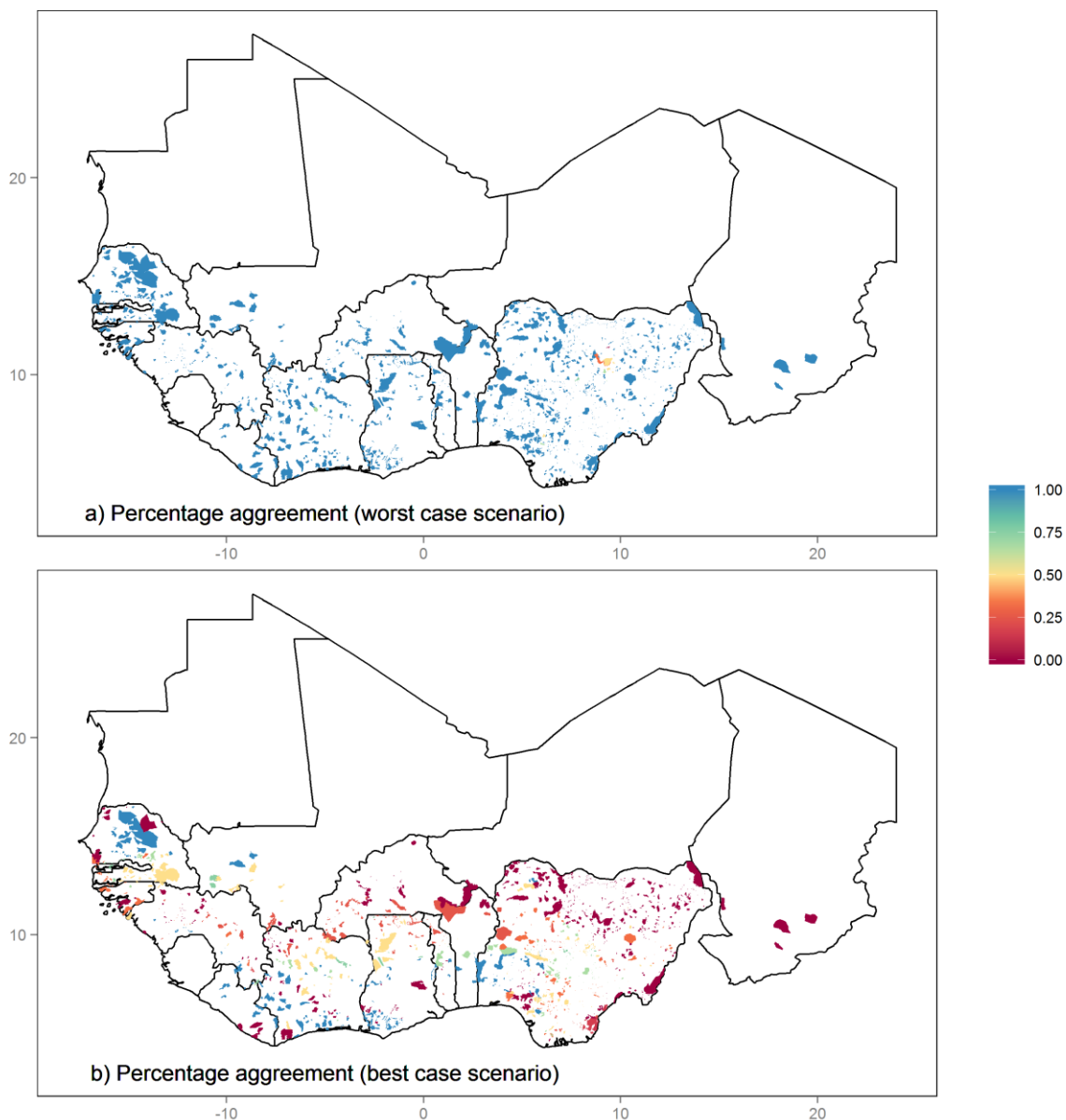
Figure A2.2. The percentage agreement between amphibian species assessed as climate change vulnerable under TVA analysis and those assessed using the SDM change in climate suitability, under a; (a) 'Worst case scenario', where all species with NC in directional trend of climate suitability at a particular PA were assumed to have decreasing suitability; and, (b) 'Best case scenario', where all such species were assumed to have increasing suitability.

Birds

Figure A2.3a shows a similar pattern for bird species (compared to amphibians) under the worst case scenario, with almost complete agreement between the two approaches. Under the best case scenario (Fig A2.3b), as with the amphibian species, there is substantial difference between the two approaches and spatially patterning in these differences. However, unlike in the amphibians, there are almost no regions of high agreement under this scenario and lots of areas of only intermediate agreement. A band of moderate agreement

runs across the Guinea forest-savanna transitional zones in western Africa. As with the amphibians, this contrast in levels of agreement under best and worst case scenarios suggests many birds are assigned as climatically vulnerable under the basic TVA approach, but in many areas the climate suitability signal (as derived from the SDMs) remains unclear. Consequently, when it is assumed in the modified TVA approach that a lack of consensus in changing suitability will result in low climate vulnerability, the differences between the two methods become marked. Again, the spatial pattering in the best-case scenario is indicative of a non-uniform signal in climate vulnerability for species across their ranges in this region.
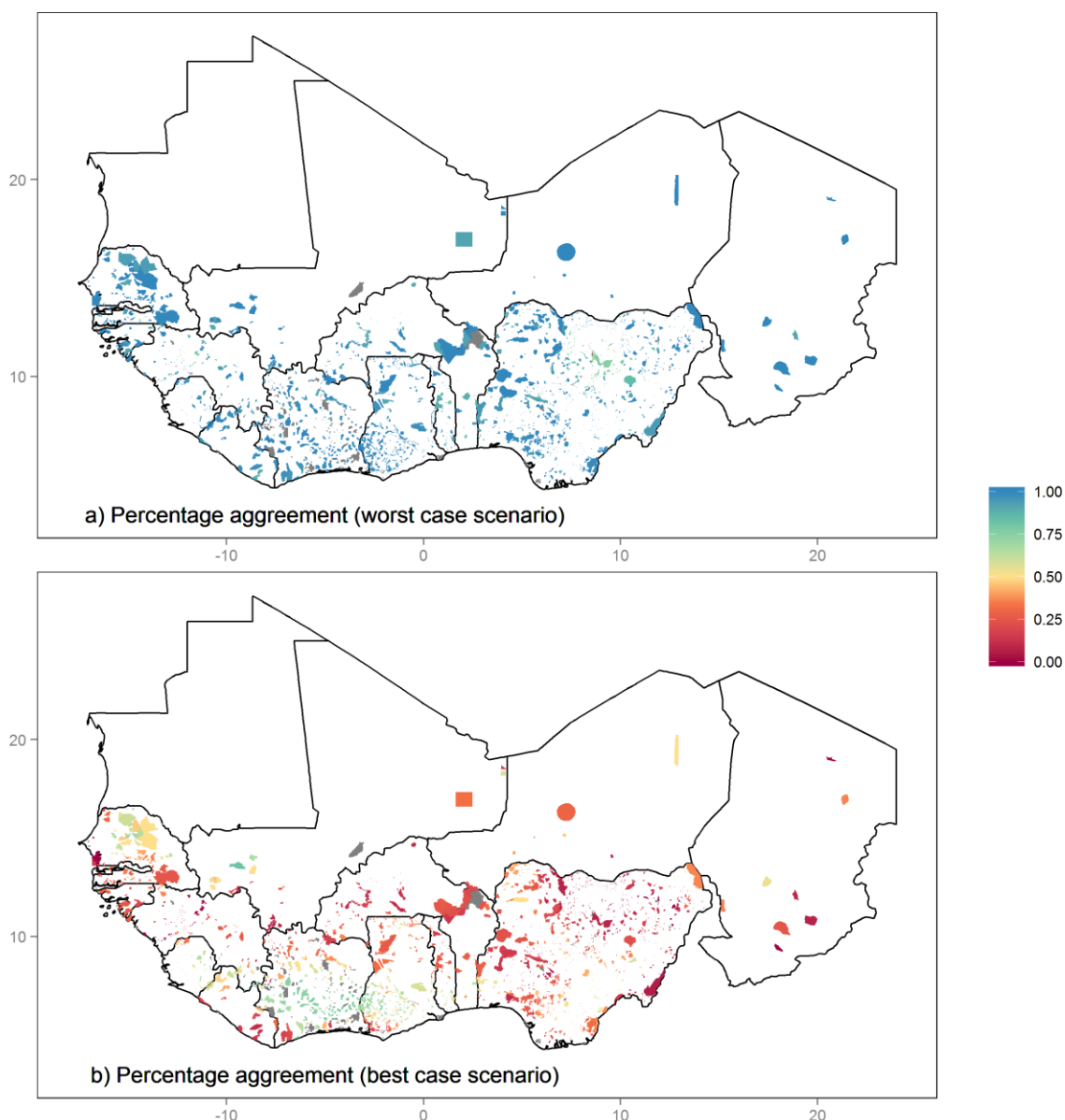

Figure A2.3.The percentage agreement between bird species assessed as climate change vulnerable under TVA analysis and those assessed using the modified TVA approach, where; a) 'Worst case scenario', where all species with NC in directional trend of climate suitability at a particular PA were assumed to have decreasing suitability; and, b) 'Best case scenario', where all such species were assumed to have increasing suitability.

Mammals

The agreement between the two methods of assessing climate change vulnerability is also very high for mammal species, under the worst case scenario (Fig A2.4a). However, again, there are substantial differences between the two approaches under the best case scenario (Fig A2.4b). As with amphibians and birds, there are very few areas of high agreement under this scenario but extensive areas of low to moderate agreement, and strong spatial patterning suggestive of local variability in climate vulnerability.
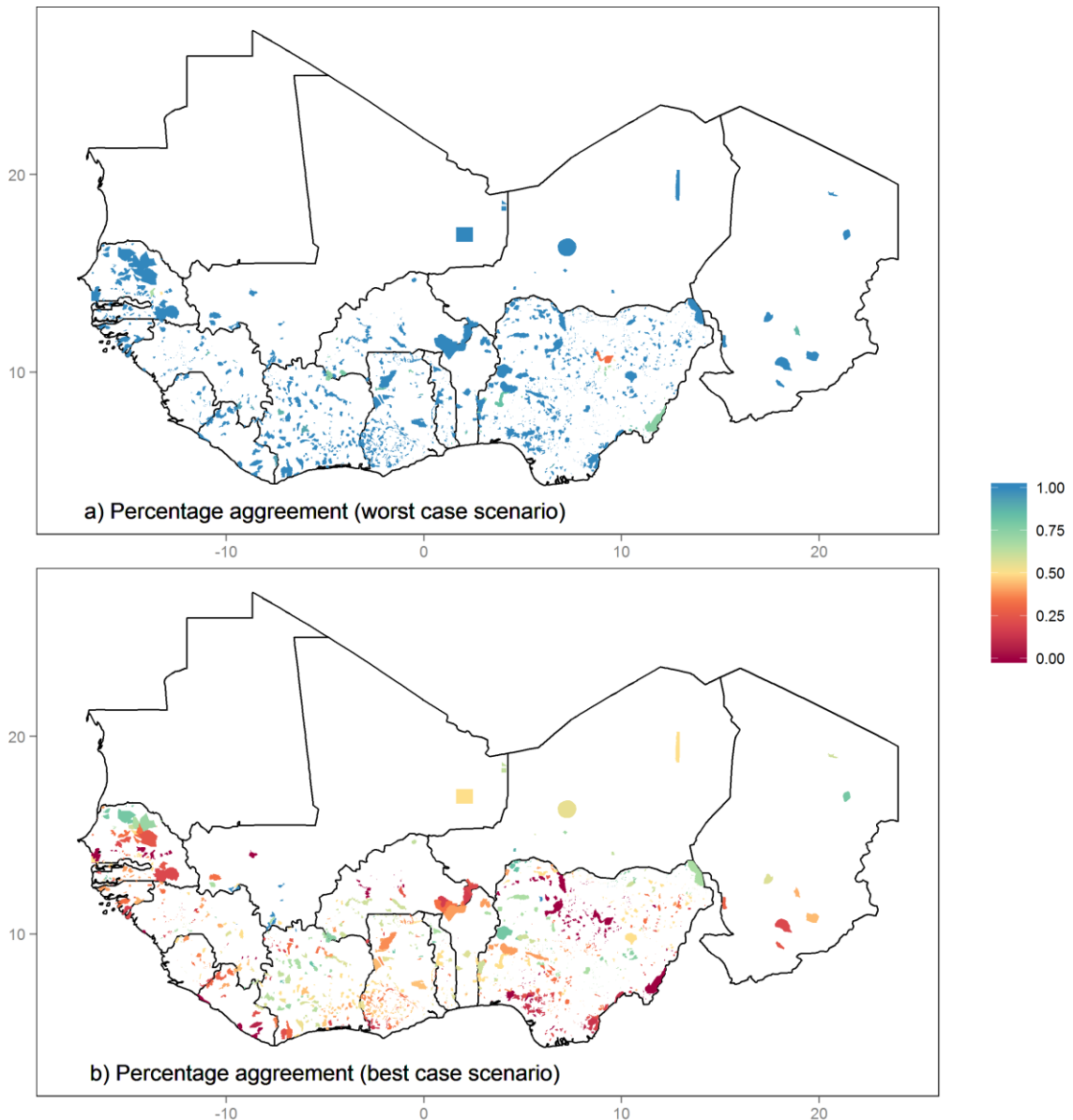

Figure A2.4.The percentage agreement between mammal species assessed as climate change vulnerable under TVA analysis and those assessed using the modified TVA approach, where; a) 'Worst case scenario', where all species with NC in directional trend of climate suitability at a particular PA were assumed to have decreasing suitability; and, b) 'Best case scenario', where all such species were assumed to have increasing suitability.

Durham University. SDM-TVA integration.

Annex 3. Impacts of climate change on the potential future distribution of West African bird species of conservation concern

Maps of potential impacts of future climate change for 756 bird species of conservation concern that occur in, or adjacent to, the West African study region, are included as pdfs on a DVD, and can be provided upon request.