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Palearctic passerine migrant declines in African wintering grounds in the Anthropocene (1970–1990 and near future): A conservation assessment using publicly available GIS predictors and machine learning

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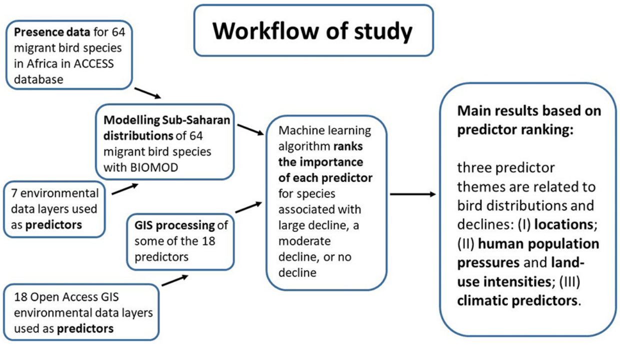
HIGHLIGHTS

- We generated distribution models of migratory birds in Africa.
- We linked their declines with information in Open Access GIS environmental layers.
- Model performance was good for two out of three models describing bird declines.
- Bird declines were linked to locations, human pressures, and climate.
- Models of future changes predicted more intense declines all over Africa.

GRAPHICAL ABSTRACT



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ABSTRACT

The Anthropocene causes many massive and novel impacts, e.g., on migratory birds and their habitats. Many species of migratory birds have been declining on the Palearctic-African flyway in recent decades. To investigate possible impacts on a continental scale, we used 18 predictors extracted from 16 publicly available GIS layers in combination with machine learning methods on the sub-Saharan distributions of 64 passerine migrant species. These bird species were categorized as having experienced a 'Large Decline' ($n = 12$), a 'Moderate Decline' ($n = 6$) or 'No Decline' ($n = 46$) based on European census data from 1970 to 1990. Therefore, we present the first study for these species which uses publically available Open Access GIS-data and a multivariate ($n = 18$) and multi-species ($n = 64$) machine learning approach to deduce possible past impacts. We furthermore modelled likely future human population change and climate change impacts. We identified three predictor themes related to the distributions and declines of these migratory birds: (I) locations, represented by African ecosystems, countries, and soil types; (II) human population pressures and land-use intensities, the latter represented by land-use categories, habitat area, and cropland proportion; and (III) climatic predictors. This is the first study to relate migratory bird declines to human population pressures and land-use intensities using this type of analysis. We also identified areas of conservation concern, such as the Sahel region. Our models also predict that the declining trends of migratory birds will continue into the foreseeable future across much of Africa. We then briefly discuss some wider conservation implications in the light of the increasing drivers of biodiversity change associated with the Anthropocene as well as some possible solutions. We argue that only comprehensive systemic change can mitigate the impacts on the migratory birds and their habitats.

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1. Introduction

Migratory birds face some natural risks (e.g., Walter, 1968; Elkins, 2004) during migration, but nevertheless bird migration has been a successful evolutionary strategy for millions of years (Berthold, 2001; Gill, 2007). However, in recent decades, migratory birds have faced new multidimensional threats deriving from rapid and often unprecedented human-induced environmental changes, which many cannot cope with (Butler et al., 2010; Kirby et al., 2008; Sutherland et al., 2012; Walther, 2016; Yong et al., 2015). The drivers of these changes are ultimately the exponential growth of the human economy and its consequential increase of resource use and waste production (Czech, 2013; Maurer, 1996); this impact has grown so much that this new epoch in which humans drive the relevant processes and ultimately decide the fate of the Earth system has been termed the Anthropocene (McGill et al., 2015; McNeill and Engelke, 2016; Steffen et al., 2018).

The Anthropocene forces ecologists and conservation biologists into a new understanding of their actions in order to assess and possibly mitigate many of its massive and novel impacts, e.g., for migratory birds and their habitats. These novel and severe problems brought about by human-induced changes and especially its relation to socio-economic drivers should be included in analyses of the problems which migratory birds face (e.g., Huettmann et al., 2016, for the Western North Atlantic or Walther, 2016, for the Sahel). As a result of these rapid man-made changes, populations of many migratory bird species all around the world have declined, some precipitously, over the last few decades (Kirby et al., 2008; PECBMS, 2009; Sanderson et al., 2006; Sutherland et al., 2012; Terborgh, 1989; Walther, 2016; Walther et al., 2011; Yong et al., 2015).

In this study, we focus on passerine migrant species which breed in the Western Palearctic region but which have their non-breeding grounds in sub-Saharan Africa (Curry-Lindahl, 1981; Dowsett and Dowsett-Lemaire, 1993; Moreau, 1972; Walther et al., 2010). Many of these migrants have declined during the last few decades predominantly due to human-made impacts. Negative impacts differ for different species and for breeding ranges, overwintering ranges, and migratory stopovers; however, almost all of them are caused by human-made changes to the environment. The main impacts named again and again in the literature cited above (and many others) are: habitat loss and fragmentation, mostly due to agricultural intensification, but also other land-use changes; persecution (especially hunting in the Mediterranean); climate change; and herbicide and pesticide use (Atkinson et al., 2014; Bairlein, 2016; Newton, 2008; Thaxter et al., 2010; Vickery et al., 2014; Walther, 2016; Walther et al., 2011; Zöckler, 2012; Zwarts et al., 2009).

Sub-Saharan migrants have overall declined more than those species that are resident or engage in shorter migrations (i.e. that remain mostly north of the Sahara during the non-breeding season) (e.g., Berthold, 2001; Gregory et al., 2007; Sanderson et al., 2006; Thaxter et al., 2010; but see Voříšek et al., 2010). Among the sub-Saharan passerine migrants, species which overwinter in the Sahel have mostly been declining since the 1970s, while species which overwinter in other parts of Africa have overall declined less or have had stable populations (Walther et al., 2011, but see Thaxter et al., 2010). The question thus arises: what ecological changes brought about by spatially explicit climatic and human drivers may explain these declines?

Part of the answer lies in the severe Sahel drought during the late 20th century, which initially had a negative impact on the populations of some species. Since precipitation has increased again somewhat in this century, some species have actually recovered, at least partially (Walther, 2016). However, Adams et al. (2014), Vickery et al. (2014) and Walther (2016) showed that the important long-term driver of population losses in the migrants' overwintering ranges is not precipitation, but the overall biological impoverishment and ecological degradation of their habitats. These habitat changes are the consequence of local, regional and global economic agendas which have been driving the land-use and land-cover change (LULCC, mostly natural and semi-natural habitats converted to intensive human uses such as agriculture, mining, urbanization, etc.) due to industrialization, agricultural intensification, and the overuse of woody vegetation for timber, firewood and livestock feed (Walther, 2016). Although LULCC has been rapidly progressing across Africa (Lambin et al., 2003; Linderman et al., 2005; Vanacker et al., 2005), it was even more severe in the Sahel than in other African regions (Brink and Eva, 2009) resulting in the “green desertification” (or agricultural intensification) of the Sahel (Herrmann et al., 2014). These changes caused the widespread losses of many species there, including migratory birds. The same process of biological impoverishment seen in the Sahel is repeated in large parts of Africa and the migratory flyways because of humanity's increasing ecological footprint which negatively impacts the habitats which constitute the migrants' stopovers and breeding ranges (see literature cited above).

While many studies have used some environmental metrics and data to explain changes in African migrant populations in order to infer the possible causes for their declines, especially those in the Sahel (summarized in Walther et al., 2011, and Walther, 2016), studies which focused on widespread environmental changes in Africa and its landscapes remain relatively few. They were further hampered by the considerable inaccuracy of the distributional maps available for Palearctic passerine migrants overwintering in sub-Saharan Africa (Chernetsov and Huettmann, 2005; Walther et al., 2010). For this reason, a comprehensive database on the geographical distribution of migratory passerine bird species in sub-Saharan Africa was assembled which is more detailed and reliable than any other available database (Walther et al., 2010, *contra* Vickery et al., 2014). This database containing ~250,000 georeferenced data points is well accepted by now and has already been used in a series of biogeographical and conservation studies (Walther et al., 2004, 2007, 2010, 2011), including the possible effects of future climate change on the African distributions of migrant passerines (Barbet-Massin et al., 2009) and the determination of conservation priority areas for these species (Walther and Pirsig, 2017). Arguably, the establishment of such a comprehensive database represents valuable progress for helping to investigate environmental questions on this migratory flyway.

This Africa-wide multi-species database of migratory birds in combination with various publicly available environmental data layers thus offers a ‘Big Data’ cube and a unique chance to data-mine, model-predict, and quantify each species' ecological niche using the latest multivariate statistical techniques (Cushman and Huettmann, 2010; Drew et al., 2011). These techniques can effectively describe the environmental hyperspace within which a species is predicted to exist, but also highlight areas where they decline and where they should be protected (Walther and Pirsig, 2017; Walther et al., 2010; Walther et al., 2011).

To further illustrate the use of these high-resolution distribution data and powerful machine learning techniques for the analysis of possible reasons for population declines, we here used this database of Western Palearctic migrant passerine birds (Walther et al., 2010) and machine learning software (1) to better determine environmental changes related with population declines, and (2) to predict how future changes may impact these species spatially. Previous studies (Huettmann et al., 2011; Humphries and Huettmann, 2014) showed that this approach allows for reliable and meaningful predictions of spatial distributions, inferences of correlates of population, as well as relevant forecasting of the near future on a large scale. As argued in Huettmann and Czech (2006) and Huettmann (2015), our approach provides progressive solutions and new insights explicit in space and time that are highly relevant to a better understanding why these migratory species have been declining for decades and how to conserve them in the complex habitat and human-coupled landscape setting of Africa and beyond.

2. Materials and methods

2.1. Bird data

Data acquisition, entry, verification and technical restriction for use in subsequent niche modelling of species distributions are described in detail in Walther et al. (2010); see Drew et al. (2011) for the underlying concept. Briefly, data for each of the modelled 65 passerine species were acquired from field ornithologists working in Africa, ringing schemes, ornithological atlases, field-guides, check-lists, internet sources (e.g., Kenya Birdfinder, Ornis Net) as well as museum sources (including the Global Biodiversity Information Facility website GBIF.org). Data were entered until 2015, while the oldest record is a museum-based record from 1818. However, most records are recent, with >70% from 1980 onwards and covering all parts of Africa (see Table 2 and Fig. 1, respectively, in Walther et al., 2010). To avoid erroneous or unreliable data, data were vetted for dubious or obviously erroneous coordinates, for vagrant records, and for possible spatial and temporal errors as suggested by their associate EURING (1979) data codes. With currently ~250,000 records (of which most are associated with geographical coordinates), this database presents without doubt the most comprehensive database on Western Palearctic migrant passerines in Africa. Different species were represented by different number of records. Numbers ranged from 13 records for the Bimaculated Lark *Melanocorypha bimaculata* to 68,092 records for the Barn Swallow *Hirundo rustica*, but most species were represented by >100 records (see Table 1 in Walther et al., 2010).

2.2. Niche modelling to obtain species distributions in Africa

2.2.1. Environmental data layers

With the help of a Geographic Information System (ArcGIS), we used seven environmental data layers to model each species' ecological niche which was then used to predict its current sub-Saharan distribution (the entire modelling and prediction procedure is graphically displayed in Fig. S1). Specifically, we divided the African continent into grid cells of 10-min resolution (10′ × 10′). Each data layer was generated at the same resolution and overlaid perfectly with the other layers (i.e. had the same extent, borders, and geographic datum). We first used the CRU CL 2.0 dataset (New et al., 2002) at a resolution of 10′ × 10′ to generate six layers which represent the African long-term climate without climate change (generated from climate data averages spanning the years of 1961 to 1990). We used these six layers which represent the major climatic gradients in Africa, namely: annual growing-degree days, minimum temperature of the coldest month, maximum temperature of the warmest month, mean annual temperature, annual precipitation, and mean annual potential evapotranspiration. Potential evapotranspiration estimates were calculated using the FAO 56 Penman Monteith combination equation (Allen et al., 1998). We also generated a layer on land transformation which we resampled from the 0.5′ resolution "Human Footprint" dataset (Sanderson et al., 2002) to the required resolution of 10′ × 10′. The Human Footprint measures human-induced land transformation using four data types as proxies for human influence: population density, land transformation, electrical power infrastructure, and accessibility. The latter was estimated as the distance to roads, major rivers, or coasts because they usually allow humans to access to natural areas. The four data types were combined so that data values for the human footprint range from 0 to 1, corresponding, respectively, to completely natural habitat to completely transformed habitat for wildlife.

2.2.2. Ecological niche modelling

We modelled each species' sub-Saharan distribution using BIOMOD (Thuiller, 2003) and the seven environmental layers described above (namely, annual growing-degree days, minimum temperature of the coldest month, maximum temperature of the warmest month, mean annual temperature, annual sum of precipitation, mean annual potential evapotranspiration, and the human footprint layer). BIOMOD aims to maximize the predictive accuracy of species distributions by combining and comparing different types of statistical modelling techniques. For each species, it computes predictions using the following algorithms: artificial neural networks (ANN), classification tree analysis (CTA), generalized additive models (GAM), generalized boosting models (GBM), generalized linear models (GLM), multiple adaptive regression splines (MARS), mixture discriminant analysis (MDA), Breiman and Cutler's random forests for classification and regression (RandomForest), and surface range envelope (SRE), the last of these being essentially equivalent to the well-known BIOCLIM algorithm (Beaumont et al., 2005; Busby, 1991). SRE identifies minimum and maximum values for each environmental variable from the localities where the species is present, and the predicted distribution then includes any site with all variables falling between these minimum and maximum limits. While SRE only requires presence data, all other models require presence-absence data.

Once each distribution model has been calculated using the different algorithms, BIOMOD compares the performance of each model and chooses the best performing one by using two evaluation techniques, the kappa statistic and the area under the curve (AUC) of the receiver-operating characteristic (ROC) plot (Fielding and Bell, 1997; Manel et al., 2001; Pearce and Ferrier, 2000). In this study, we exclusively used the AUC score because, unlike the kappa statistic, it is not dependent on a probability threshold which differentiates between a site predicted to be occupied and a site predicted to be unoccupied (Manel et al., 2001; Pearce and Ferrier, 2000). The AUC score is calculated with the help of two other measures of model performance: sensitivity and specificity (Fielding and Bell, 1997; Pepe, 2000). Sensitivity is the ratio of positive

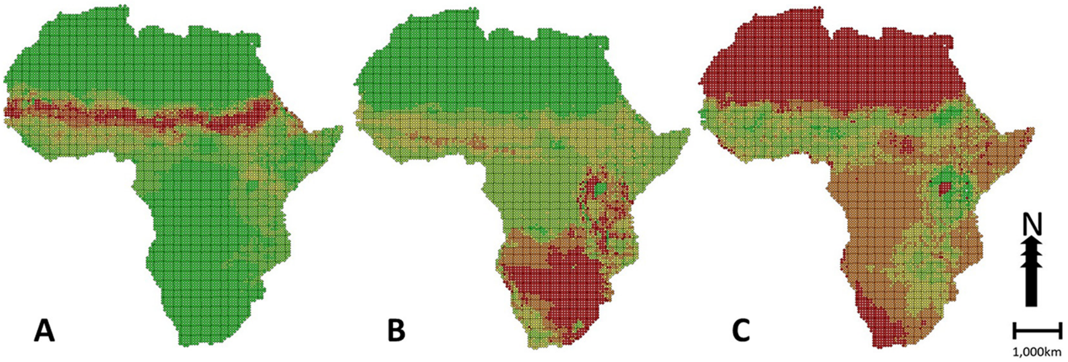

Fig. 1. Pixel-based map of the (A) Large Decline Model, (B) Moderate Decline Model, and (C) No Decline Model of passerine migratory birds for the 1970–1990 period. The map shows the modelled response variable as a relative index of change for the respective model. In all maps, dark-brown colors refer to a large response and green colors refer to a small response. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sites (presence) correctly predicted over the total number of positive sites in the sample, while specificity is the ratio of negatives sites (absence) correctly predicted over the total number of negative sites in the sample. The ROC curve is then obtained by plotting sensitivity versus (1-specificity) for a range of probability thresholds. A 45° line signifies a model that is no better than one generated by chance, while any curve above the 45° line signifies a model that is better than one generated by chance. Thus, good model performance is characterized by a curve that maximizes sensitivity for low values of (1-specificity), i.e. when the curve passes close to the upper left corner of the ROC plot.

Our procedure for modelling species distributions consisted of six steps. Step one was to run the SRE model with the presence-only data (i.e. all the presence localities where each respective species had been observed). Because it is widely acknowledged that presence-only modelling techniques often overpredict species distributions (Brotons et al., 2004; Engler et al., 2004), the second step was to restrict the SRE-prediction to the ecoregions, regions and countries where the respective species had actually been recorded, using the ESRI country shape file and the ecoregion shape file generated by Olson and Dinerstein (Olson and Dinerstein, 2002). For example, the Basra Reed Warbler *Acrocephalus griseldis* has never been recorded in West Africa (Walther et al., 2004), and the Aquatic Warbler *Acrocephalus paludicola* has never been recorded in East Africa (Walther et al., 2007). Because the SRE-prediction predicts the maximum theoretical extension of a species' distribution, it will predict suitable regions in West Africa for the Basra Reed Warbler and in East Africa for the Aquatic Warbler (it would even predict suitable regions in other continents). Therefore, it is paramount to restrict the SRE-prediction to within regions where the species has actually been observed. This procedure was previously used to cut predicted distributions of migrant bird species (Walther et al., 2004, 2007, 2010).

The following four steps were all first presented in Walther et al. (2007). In step three, pseudo-absences were randomly placed inside the African mainland, but outside the restricted SRE-prediction generated in the second step (using an Arcview GIS 3.3 script). We chose a balanced design of equal number of presences and pseudo-absences for each species (e.g., for a species with 20 presence records, we generated 20 pseudo-absences, but for a species with 1000 presence records, we generated 1000 pseudo-absence records) because the performance of AUC scores is best at intermediate sampling prevalence, i.e. an intermediate proportion of data points should be presences (McPherson et al., 2004). The fourth step was to run all model algorithms provided by BIOMOD on the combined presence and pseudo-absence data. In step five, the best of the generated model predictions was chosen, as indicated by the highest AUC score for the evaluation dataset (i.e. the 30% of the initial dataset not used to calibrate each model but used to evaluate the performance of each model, see Thuiller, 2004, for details). In step six, the best prediction was used within the restricted SRE prediction generated in the second step, thus combining the results from the presence-only model with the results from the best model chosen by using the presence/pseudo-absence data.

It should be noted that each resulting species distribution is thus the result of the much more reliable and competing algorithms applied within BIOMOD and only restricted at the boundary by the clipped SRE-prediction, the reason being that, outside of this boundary, the species has simply never been observed. We took great care to double-check every available record in the database as well as each available bird atlas and each distribution map in the *Birds of Africa* series (Brown et al., 1982; Fry and Keith, 2004; Fry et al., 1988; Fry et al., 2000; Keith et al., 1992; Urban et al., 1986; Urban et al., 1997) to ensure that each species distribution is matched by our current distributional knowledge of the respective species (for full list of bird atlas projects entered, see Walther et al., 2010).

Each of the resulting 65 species distribution models were represented as an ArcGIS ESRI grid layer (shown individually in Walther et al., 2010).

2.3. Population trends for 1970–1990

Each bird species was categorized according to its population trend during the period 1970–1990 as either a (1) Large Decline, (2) Moderate Decline, or (3) No Decline (cf. Table 1 in Walther et al. (2011) and Appendix 1) based on the decline status given in Tucker and Heath (1994) except for the Basra Reed Warbler whose population trend was inferred from the information provided by BirdLife International (2016). Note that one species modelled in Walther et al. (2010), namely the Isabelline Shrike *Lanius isabellinus*, was excluded because there was no information on population changes available for it (Walther et al., 2011).

2.4. Data layers as predictors of environmental change

We attempted to use environmental data layers which reflect the environmental changes which we already know to have an impact on migratory bird populations (see Introduction for cited reviews). To determine which environmental changes during the period 1970–1990 may be related to the above population trends, we conducted an intensive search of publicly available GIS-based data layers which contain information on relevant ecological impacts during that period for Africa such as ecosystems, soils, human population, land use and cropland proportion. We also used countries because each country is a ‘container’ in the sense that policies which affect ecology and conservation differ between countries, sometimes dramatically (Doi and Takahara, 2016; Resendiz-Infante and Huettmann, 2015). We were able to obtain 18 predictors for the study area of Africa (Table S4). Moreover, these predictors are publicly available so that their presentation here constitutes value-added information for other researchers. Such a large set of predictors for Africa consistent across time and space has not been used yet to explain avian population trends over time and could be used in future studies for population trends of various taxa and other research topics. Therefore, this study introduces the overall concept to ecologists on which further studies can build upon.

Table S4 summarizes those 18 data layers which we used as predictors in our subsequent machine learning analysis (see Section 2.5). These 18 data layers were selected from a larger set of data layers which we collected (summarized in Appendix 6) because we a priori considered that these 18 predictors reflect the most relevant set of predictors and habitat proxies for environmental change during the selected time period (see Mi et al., 2016, for a similar example using many predictors). In other words, these predictors allowed us to compare the environmental situation of the 1970s to that of the 1990s because the 18 predictors represent environmental changes that occurred within that period and which were captured within a quantified GIS environment. We thus were able to test whether some of the declines which had affected populations of migratory birds in Africa are related to environmental changes captured within our predictor set of environmental predictors (for a similar example of the application of these methods, see also Regos et al., 2016).

2.5. Machine learning analysis to detect signals of population change

We used machine learning to rank the importance of each predictor (or independent variable) and to be able to display non-linear relationships between the predictor and the response (or dependent) variable. The 18 predictor variables are described above, and the response variables are the distributions of the individual species associated with a Large Decline, Moderate Decline and No Decline (see Section 2.3 for details). All these distributions are explained and shown in detail in Walther et al. (2010, 2011) and represent the most detailed and most reliable distribution models for these species that are currently available.

The latest version of the stochastic gradient boosting classification and regression tree algorithm TreeNet as implemented in the Salford

Systems Data Mining and Predictive Analytics Software (https://www.salford-systems.com/) was used. Through the use of a non-linear and non-parametric machine learning algorithm such as TreeNet, several of the traditional statistical problems, such as how to deal with a mixture of variable types, missing values, and non-normal distributions, heteroscedasticity, and how to extract 'a signal' from complex data and to generalize these patterns from the data (sensu Breiman, 2001; Drew et al., 2011), can be overcome. Furthermore, non-linear relationships can be graphically displayed.

The TreeNet algorithm is described in Friedman (2002, see also https://www.minitab.com/en-us/products/spm/). It is based on a regression tree analysis in which the algorithm recursively partitions the entire dataset into two partial datasets based on the predictors and then optimizes the outcome for best-possible prediction outcome. This is achieved by using an optimized set of predictors in order to create binary trees which try to minimize variation within each dataset, whereby subsequent trees are constructed for the prediction of the residuals from the previous trees, and results are then computed from the entire group of trees (Friedman, 2002). Specifically, the stochastic gradient boosting method was used which further optimizes performance by maintaining a running tally which avoids overfitting, a procedure similar to bagging (Friedman, 2002). The pre-set default settings for TreeNet were used which are known to generally perform very well in most cases (e.g., Kandel et al., 2015). The maximum number of trees to be used was set to 10,000, and the learning rate was set to 0.0005. The maximum number of nodes per tree was set between six and ten (Salford Systems, 2013). We applied 3–10 minimum samples for terminal branches and a 10-fold cross-validation. In our case, we used TreeNet because (1) it focuses on predictions, (2) it assigns a variable importance (VI) score to each predictor which allows one to rank predictors by importance, and (3) it generates one-variable partial dependence plots which graphically display the relationship between one predictor and the response variable.

It is important to note that a one-variable partial dependence plot does not necessarily show the raw relationship between the predictor and the response variable. Instead, the plotted function is more inclusive and depicts how the value of the predictor influences the model predictions (or response variable) after the influence of all other predictors has been "averaged out" (i.e., kept constant). The main advantage of these partial dependence plots is that they can be constructed for any predictive model, regardless of its form or its complexity. Therefore, partial dependence plots do not ignore the effect of all the other predictors; rather, they include and average out the effects of the other predictors from the full model. If the predictor is a categorical variable, a box plot will depict the relationship, with each category of the predictor shown as giving a positive or negative contribution to the relationship. However, if the predictor is a continuous variable, a graph will depict the relationship. Consequently, the resulting plot can look quite different to the simplistic linear scatterplot of the predictor versus the response variable.

The predictions of each model can be displayed in maps in which the magnitude of the modelled response variable should be interpreted as a relative index of change for the respective model developed by the TreeNet algorithm. In all our heat maps, dark-brown colors refer to a large magnitude and green colors refer to a small magnitude of the modelled response variable (or dependent variable).

Following Breiman (2001) we considered that the predictive performance is among the most meaningful metric for inference and benchmarking models (Mi et al., 2016). Therefore, we present four model performance metrics, namely MAD (or mean absolute deviation) for the testing data, RMSE (or root mean square error, see Walther and Moore, 2005) for the testing data, R^2 (or variation explained by model), and the gains curve. Among these, we emphasize the use of the 'gains curve' the most (which is similar to a ROC curve but used for a continuous response; see Pearce and Ferrier, 2000; Huettmann and Gottschalk, 2010).

2.6. Models of future change (~2030)

For our future change models, we used future scenarios based on climate change and human populations as the main drivers.

For future human population change, we used the projected increase in human population density of 38% for Africa from 1990 to 2030 (FAO, 2015; Guyer et al., 2007) as a proxy given the absence of a better future scenario GIS layer for all of Africa. Given that projected population growth in Africa is estimated to be 209% from 2000 to 2050 (Gerland et al., 2014), our proxy estimate of 38% is likely to be on the conservative side. To create this future layer, we multiplied the human population 1990 layer (see Table S4 and HYDE, 2016) by 38% to account for the projected increased human density which we used as the proxy for the associated increase in land-use change resulting from the increased needs of the human population. The future human population layer was generated with the ArcGIS map calculator.

For climate change, we used the WorldClim (2016) database. We a priori chose the temperature and precipitation layers for December because it is a meaningful central month for the wintering period of the migratory bird species. These layers have a 30 s resolution for the greenhouse gas scenario rcp60 (Hadley implementation model for 2050). The temperature minimum and maximum layers were averaged in ArcGIS to obtain the GIS layer which we used. We are aware that this layer is just a proxy for a changing and dynamic factor such as the weather but we are here interested in representing long-term means for which this layer is a useful first approximation for capturing the climatic variation across the African continent during the migrants' wintering period.

While these future climate data are assumed to be an estimate for the climate in the year 2050, we caution that this prediction is likely to be too conservative; see our arguments in Table S5 and other recent information, e.g., Saunois et al. (2016), Peters et al. (2017), Proistosescu and Huybers (2017), Raftery et al. (2017), Shaikh (2017), Brown and Caldeira (2017), Henley and King (2017), Steffen et al. (2018), Watts (2018), Lenton et al. (2019) and Ripple et al. (2020) which all point to more rapid climate change than previously predicted. We therefore argue that our predictions of future change should be interpreted as the 'near future', probably falling into the period 2030 or shortly thereafter, the reason being that many assumptions made by current climate models are rather conservative, parsimonious, and based on earlier scientific knowledge which is now considered to be already outdated. The recent rapid rise in global temperatures further substantiates this assertion. For pro-active decision-making, we consequently consider a shorter time frame to be more realistic.

We used the Salford Systems Data Mining and Predictive Analytics (SPM) Software to project our models for Large Decline species, Moderate Decline species, and No Decline species into the future. The future predictions were then converted into pixel-based shapefiles in ArcGIS. Our GIS-based work (including Figs. 1–2) was done using ESRI ArcGIS version 10.2 and QGIS (www.qgis.org). All the one-variable partial dependence plots in Appendices 3–5 were produced by the automated graphing options implemented in SPM.

3. Results

3.1. Model performances

The internal performance metrics of the three models show that the Large Decline Model and the No Decline Model are rather robust allowing for a reliable inference. The No Decline Model has the best performance except for the gains curve which is higher for the Large Decline Model (Table 1). The Moderate Decline Model has the lowest performance for all metrics except the R^2. This ranks the Large Decline Model and the No Decline Model for powerful inference, whereas the Moderate Decline Model is weaker.

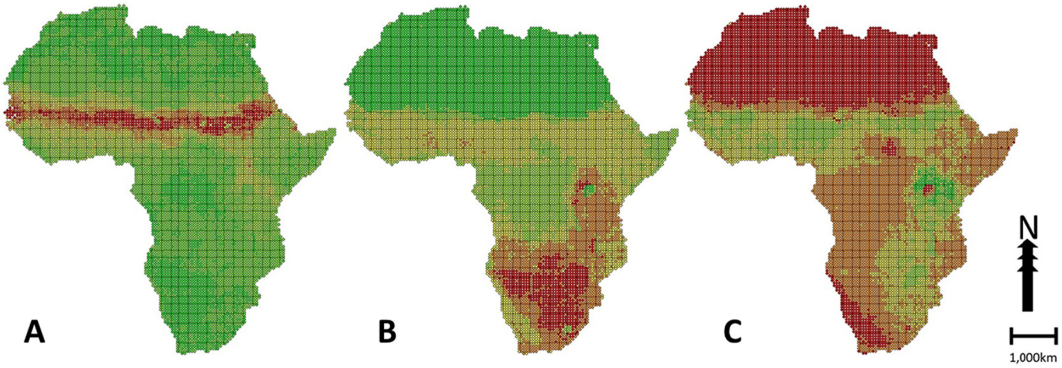

Fig. 2. Pixel-based map of the (A) Large Decline Model, (B) Moderate Decline Model, and (C) No Decline Model extrapolated into the near future (~2030). The map shows the modelled response variable as a relative index of change for the respective model.

3.2. Predictor importance

Specific locations in Africa, mostly located in Western Africa, as well as a set of three predictor themes were most correlated with (1) the distributions and (2) the areas of declines of the migratory birds (the response variables): (I) locations, represented by African ecosystems, countries, and soil types; (II) human population pressures and land-use intensities, the latter represented by land-use categories, habitat area, and cropland proportion; (III) climatic predictors (summarized in Table 2). We use the Roman numerals I-III to identify these three predictor themes more easily in the Results below.

It is noteworthy that all of these predictors are also known to act in synergy, e.g., ecosystems are directly driven by climate which drive many subsequent metrics. Below we present our results in more detail for each of the three models.

3.3. Specifics of the ‘Large Decline Model’

The Large Decline Model identified the following predictor themes and their values of relevance for the large declines in Africa (Table 2; the associated map and figures for this model are shown in Fig. 1A and Appendix 3, respectively, and the numbers and abbreviations below refer to the categories in the respective GIS-based data layers; see also the figures in Appendix 3).

I. a) African Ecosystem: North Sahel Tree'd Steppe & Grassland (#181, 182, 183, 113), Sudano-Sahelian Dry Savanna (#131, 132, 133).

b) Country: Eritrea, Guinea-Bissau, Senegal, Togo, Burkina Faso, Nigeria, Ghana.

c) Soil: Luvic Calcozols (Clvvi), Haplic Luvisols (LVhA), Chromic Luvisols (LVCR), Acrisols (AC), Plinthic Acrisols (ACPL), Brunic Arenosols (ArBR), Eutric Fluvisols (Fleu), Eutric Gleysols (Gleu), Solidic Planosols (Plsc).

II. a) Land-use 1970 categories: Grassland/Steppe (13), Grazing land (2), Cropland (1), Scrubland (15).

b) Human Population 1990: A density of >10 people per km^2 resulted in large bird declines.

c) Human Population 1970: A density of >5 people per km^2 resulted in large bird declines.

III. a) Air Temperature 1974: A range of 19.0° to 27.0 °C describes the climate envelope where the large bird declines occurred.

b) Mean Temperature December: A range of 22.0° to 27.0 °C describes the climate envelope where the large bird declines occurred.

c) Precipitation 1994: <5 units (mm) describes the climate envelope where the large bird declines occurred.

The three predictors under III describe a specific dry climate envelope defined by temperature ranges and a precipitation threshold.

3.4. Specifics of the ‘Moderate Decline Model’

This model was the least robust of the three models (Table 1). It identified the following predictor themes and their values of relevance (Table 2; the associated map and figures for this model are shown in Fig. 1B and Appendix 4, respectively, and the numbers and abbreviations below refer to the categories in the respective GIS-based data layers; see also the figures in Appendix 4).

I. a) African Ecosystem: Moderate decline occurred everywhere except for Saharan Desert Pavement (#206), Saharan Desert Rock Outcrop (#207), Saharan Desert Dune and Sand Plain (#208), Mediterranean Montane Scrub (#606, 607), North Sahel Tree'd Steppe & Grassland (#181, 182).

b) Country: Botswana, Zimbabwe, Zambia, Uganda, Namibia, Tanzania, South Africa.

c) Soil: Umbric Ferrasols (Frum), Plinthic Acrisols (Acpl), Haplic Podzols (Pzha), Eutric Planosols (PLEU), Ferralic Arenosols (Arfl); no moderate bird declines occurred on Eutric Nitisol (NT eu).

II. a) Cropland Proportion 1990: Almost any proportion of cropland resulted in moderate bird declines.

b) Land-use 1970 habitat area: Over 150 units (ha) resulted into moderate bird declines.

c) Land-use 1990 categories: Grazing land (2) and Cropland (1) resulted in moderate bird declines; no moderate bird declines occurred in Hot desert (14) and Tropical forest (18).

3.5. Specifics of the ‘No Decline Model’

We identified a model that can predict the ‘No Decline’ category. This model thus serves as a ‘control’ because it allows us to compare and put the findings into a wider, African and methodological context. The inclusion of such controls is an inherent part of the scientific method (Silvy, 2012). Again, it should be noted that habitats (represented by pixels) can support different species which experienced Large Declines, Moderate Declines and No Declines all at once. The No Decline Model identified the following predictor themes and their values of relevance (Table 2; the associated map and figures for this model are shown in

Table 1
Performance metrics for the three models (for abbreviations, see the Materials and methods section).

	Large Decline model	Moderate Decline model	No Decline model
Metric	Estimate	Estimate	Estimate
MAD (test data)	0.41	0.33	1.23
RMSE (test data)	0.84	0.55	1.96
R^2	0.85	0.89	0.90
Gains curve	~0.83	~0.67	~ 0.70

Table 2
Predictors that are ranked for ≥10% importance for the three models (Large Decline, Moderate Decline, No Decline), with the percentage for importance ranking given in brackets.

Large Decline		Moderate Decline		No Decline	
Predictor	Rank (%)	Predictor	Rank (%)	Predictor	Rank (%)
African ecosystem	1 (100)	African ecosystem	1 (100)	African ecosystem	1 (100)
Country	2 (51)	Country	2 (44)	Country	2 (46)
Soil	3 (38)	Soil	3 (23)	Soil	3 (30)
Land-use 1970 categories	4 (23)	Cropland proportion 1990	4 (13)	Human population 1970	4 (27)
Human population 1990	5 (22)	Land-use 1970 habitat area	5 (10)	Human population 1990	5 (20)
Human population 1970	6 (22)	Land-use 1990 categories	6 (10)	Mean temperature December	6 (19)
Air temperature 1974	7 (19)			Land-use 1970 categories	7 (14)
Mean temperature December	8 (16)			Land-use 1990 categories	8 (13)
Precipitation 1994	9 (10)			Cropland proportion 1990	9 (12)

Fig. 1C and Appendix 5, respectively, and the numbers and abbreviations below refer to the categories in the respective GIS-based data layers; see also the figures in Appendix 5).

I. a) African Ecosystem: Sudano-Sahelian Dry Savanna (#132, 131, 133), North Sahel Tree'd Steppe & Grassland (#183), Zambezi Mopane (#122), Moist Combretum - Terminalia Woodland & Savanna (#101), Wet Miombo (#96), Western African Mesic Woodland & Grassland (#112), Eastern African Bushland & Thicket (#176), Southern African Scarp Forest (#9), Southern Mistbelt Forest (#27), African Tropical Freshwater Marsh (Demos) (#246), Dry Acacia Woodland & Savanna (#117), Southern Kalahari Dunefield Woodland & Savanna (#119); no matching categories: Mediterranean Montane Scrub (#606, 607), Saharan Desert Pavement (#206, 207, 208), 2.B.1 Mediterranean Scrub & Grassland (#147), Sperregebied Succulent Karoo (#157), Bushmanland Semi-Desert Scrub & Grassland (#196), Upper Karoo Semi-Desert Scrub & Grassland #197), Southern Namibian Semi-Desert Scrub & Grassland (#199).

b) Country: Uganda, Senegal, Guinea-Bissau, Kenya, Ghana, Togo, Ivory Coast, Eritrea, Guinea.

c) Soil: Plinthic Acrisol (ACpl), Eutric Histosols (HSEU), Eutric Plaosols (PLEU), Haplic Podsols (PZHA), Haplic Solonetz (SNha), Dystric Nitisols (NTdy), Cambisols (CMBaye), Chromic Cambisols (CMcr), Acrisol (AC); no matching categories: Lixisol (LXal), Petric Plinthosol (Ptpt).

II. a) Human Population 1970: A density of >6 people per km^2 resulted in no bird declines.

b) Human Population 1990: A density of >5 people per km^2, and especially >20 people per km^2, resulted in no bird declines.

c) Land-use 1970 categories: Grazing land (2), Tropical Woodland (17), Savanna (16), Scrubland (15), Tropical forest (18), Grassland/Steppe (13), Cropland (1) resulted in no bird declines; no matching categories: Hot Desert (14).

d) Land-use 1990 categories: Cropland (1), Grazing land (2), Tropical Woodland (17), Savanna (16) resulted in no bird declines. No matching categories: Hot Desert (14).

e) Cropland Proportion 1990: A cropland proportion of >0.05 (ha), and especially >0.1 (ha), resulted in no bird declines.

III. a) Mean Temperature December: A range of 21.5° to 27.0 °C describes the climate envelope where no bird declines occurred and thus covers almost the entire temperature range of sub-Saharan Africa (cf. Fig. 1C).

3.6. General results from all three models

From the perspective of the three different populations, the results of the three models (Table 2, Fig. 1) reveal a major emphasis on ecosystems and areas south of the Sahara. For each of the three models, the highest ranked predictors were always African ecosystem > country > soil (Table 2). Furthermore, the highest ranked predictor themes were always Theme I > Theme II > Theme III except for (1) the Moderate Decline model which lacks Theme III and (2) the No Decline Model in which the predictor 'Mean temperate December' has a different trend.

While countries such as Eritrea, Guinea Bissau, Senegal, Togo, Burkina Faso, Nigeria, and Ghana stand out as areas of major declines, additional regions of regional importance were identified around Lake Tanganyika (mainly in Kenya, Uganda and Tanzania) (Fig. 1).

3.7. Future predictions (~2030)

Using our prediction of a future human population and climate change, our three future models (Fig. 2) predict an overall more intense decline for species within regions already identified as having pixels associated with declines. Therefore, no large deviation from the existing spatial patterns is currently predicted. We do not predict large shifts of ecosystems and associated additional bird declines. Overall, our results support that the ongoing decaying trend of winter habitat locations will continue into the near future with no sign of betterment for migratory birds, especially for those already declining because of ongoing changes which have negatively impacted their populations in the past and will likely continue to do so in the near future.

4. Discussion

4.1. Predictors associated with declines

The availability and use of publicly available GIS layers (as predictor variables) for population changes (as response variables) is an underdeveloped area of macroecological and conservation research which should be urgently expanded (Huettmann et al., 2011; Ohse et al., 2009). It should be kept in mind that this is the first time a complex data cube and many categorical predictors were used for this particular research topic. This research problem cannot be resolved well with linear traditional methods. Therefore, we here present a first-time analysis using data mining and machine learning to resolve these research questions. Specifically, we present an example for migratory passerine bird species in sub-Saharan Africa which may facilitate the use of these approaches in ornithology, conservation, and management (Huettmann, 2015; Zuckerberg et al., 2011).

Our main finding from this first-of-its-kind study for this particular system is that we identified three predictor themes which were consistently associated with the distributions and the areas of declines of the migratory birds from 1970 to 1990 (Table 2). Ranked as most important was theme I which identified specific locations, represented by African ecosystems, countries, and soil types. Naturally, these represent the species' ecological niche as represented by their distributions which include mostly open savanna-type habitats and exclude almost entirely desert and rainforest habitats (Walther et al., 2010).

The next highest ranked theme II identified human population pressures and land-use intensities (represented by land-use categories and habitat area, and cropland proportion) as important for bird declines (see Discussion below). Finally, only for the Large Decline model, theme III identified a specific dry climate envelope defined by temperature and precipitation.

Specific locations (or regions) of large decline were the Sahel zone (as emphasized in Walther et al., 2011) but also countries just south of it (Ghana, Guinea-Bissau, Togo, as pointed out in Thaxter et al., 2010). Regions of moderate declines were most of the southern African region (including Botswana, Namibia, South Africa, Zambia, Zimbabwe), as well as the Lake Malawi region, Lake Tanganyika region and Lake Victoria region (especially in Tanzania and Uganda). The large declines in the Sahel occurred in the North Sahel Tree'd Steppe & Grassland and the Sudano-Sahelian Dry Savanna for which Walther (2016) summarized their strong rates of land conversion from natural or semi-natural land-cover to man-altered land-cover, with the vast majority due to agricultural expansion (other causes of LULCC in the Sahel were also reviewed in Walther, 2016). Meanwhile, moderate declines occurred in many different ecosystems (see Section 3.4 and Fig. 1 in Appendix 4). Atkinson et al. (2014) also pointed out that declines occurred in different wintering habitats.

The control model (No Decline) overlaps in many areas with the decline models (Large and Moderate) which indicates 'mixed' pixel results. Habitats can of course support different species which experienced Large Declines, Moderate Declines, or No Declines. In other words, large and moderate declines occurred for some species but no declines occurred for other species within the same locations or habitats. One possible explanation is that these diverging trends are complementary because each species has of course a different life history and specific habitat needs that result in different population outcomes in the same pixels, similar to the notion of 'winners and losers' when environmental changes occur (Bateman et al., 2016; Mace et al., 2010). For our study species specifically, there were winners and losers in the past (Walther et al., 2011), and there will be winners and losers due to future climate change. Barbet-Massin et al. (2009) predicted range expansions for some species, but range contractions for most of our study species in response to predicted future climate change. It should be noted, however, that extreme climate change will be detrimental for most of biodiversity, especially in Africa (Dike et al., 2015; UNEP, 2016; Soultan et al., 2019).

Apart from the large declines found within specific regions (the Sahel and the humid West African forests and savannahs), we find it worrisome that moderate declines are found in most of sub-Saharan Africa and many different ecosystems. Only hot desert and rainforest areas which do not harbor any of the migratory species of this study anyway (Walther et al., 2010) exhibited no relevant trend in our data.

Very importantly, large and moderate declines were also associated with human population pressures and land-use intensities (theme II). Large declines were associated with four land-uses (specifically, grassland/steppe, grazing land, cropland, scrubland) which cover large parts of the Sahel and have suffered precipitous biodiversity loss such as the widespread loss of woody vegetation and agricultural expansion and intensification (Walther, 2016). Supporting this observation, Atkinson et al. (2014) showed that those species which showed the strongest declines during 1970–1990 were associated with more open habitats. In our study, high human population densities in 1970 and 1990 were associated with large declines, thus suggesting that negative pressures on these bird populations increase with human population densities (e.g., Anadón et al., 2010; Brashares et al., 2001; Buij et al., 2013; Lhoest et al., 2020; Marzluff, 2001).

Meanwhile, moderate declines were associated with cropland proportion, land-use categories, and habitat area. It should be noted that the functional relationship for cropland proportion (cf. Appendix 4) has the shape of a logarithmic threshold function. This result suggests that human agriculture negatively impacts migratory birds in sub-Saharan Africa (Walther, 2016) but also that thresholds may exist where landscapes can rapidly change from sustaining migrant populations to not sustaining them (Kinzig et al., 2006). Moderate declines were also associated with two agricultural land-uses (specifically, grazing land, cropland), further implicating the impact of intensifying human agriculture.

No declines were associated with high human population densities, several land-use categories (specifically cropland, grazing land, savanna, scrubland, tropical woodland; cf. Appendix 5), and cropland proportion. Non-declining species are associated with a variety of habitats and regions (Atkinson et al., 2014; Walther et al., 2011; Walther et al., 2010), which is not a surprising result.

Finally, large declines were also associated with a specific climate envelope (theme III) which represents the naturally prevalent climate of the Sahel (Nicholson, 2013; Walther, 2016) (see Donald et al. (2012) for a similar example). Therefore, climate change will shift climate envelopes across the African continent and negatively affect African ecosystems, including the migratory species studied here (Barbet-Massin et al., 2009) as well as entire African bird communities (Walther and van Niekerk, 2014).

These results, taken together with the results from Walther and Pirsig's (2017) determination of conservation priority areas for these migratory bird species, point to several areas of conservation concern. The main region of conservation concern is the Sahel and the broadleaf savannas and woodlands just south of it. Given the species distributions of these migratory birds, conservation should be especially focused on a western region which encompasses Senegal, southern Mali, Burkina Faso, Guinea, and Côte d'Ivoire and an eastern region which encompasses southern Sudan, Eritrea and northern Ethiopia. The two other main regions which should be the focus of conservation efforts are one region which encompasses southwestern Kenya, Tanzania, and Uganda and one region which includes much of Zimbabwe and southwestern Zambia. These four regions should be priority regions for both research and conservation efforts for the bird species considered here (for concrete suggestions, refer to Section 4.4).

4.2. Forecasting the near future (~2030)

To predict future changes to the migratory bird species of this study, we used predictors from models that follow the latest, but probably conservative forecasting scenarios for future climate change by the IPCC. We assume that the climate science assumptions of this model are already outdated because they do not take into account the recent failures to progress and implement climate mitigation policies and therefore likely underestimate the future speed of climate change (Table S5 and additional references in Methods). Consequently, our predictions will likely come about much earlier, probably in the nearer future (~2030).

Our results suggest that the declining trends of migratory birds will continue into the foreseeable future, assuming that the species are sensitive to the changes which we modelled (see also Barbet-Massin et al., 2009). These future declines will likely be unsustainable for some species, especially for the most endangered and most range-restricted species and those species which have already declined in the past because the past's negative drivers (such as crop land change and climate change) will likely continue to exert similar pressures into the near future.

Furthermore, we predict that these declines will happen in pixels across most of sub-Saharan Africa, reflecting human-induced changes across the entire continent. Scenarios of future biodiversity and climate change in Africa (e.g., Dike et al., 2015; Kehoe et al., 2017; Koch et al., 2019; Soultan et al., 2019; UNEP, 2016) suggest that human-induced changes detrimental to biodiversity will continue well into the future. Our results also suggest that the problems which affect migratory species are not local-scale problems, but regional-scale and even continent-wide problems and need to be addressed as such (see Section 4.4 below).

4.3. Limitations of this study

Our study has some limitations. First, our models did not include additional stressors such as human population growth and the resulting increase in resource consumption (e.g., ongoing land grabs in Africa, Osinubi et al., 2016) and waste production (e.g., UNEP, 2016). This is another reason why our models likely remain on the conservative side and cannot model the full complexity and impact of the real situation. To better investigate conservation problems in Africa, we thus need publicly available and high-quality environmental and socio-economic data layers explicit in space and time to better understand past and future changes (sensu Stéphenne and Lambin, 2001, and Held et al., 2005; see Prentice et al., 1992, Rangel et al., 2006, and Ferrier, 2011, for a model-predicted approach).

We used and benefited from Open Access GIS-based data (sensu Ohse et al., 2009; Huettmann, 2015; see Huettmann, 2005; Huettmann, 2007; Zuckerberg et al., 2011) for best professional practices. These data are made publicly available to enhance scientific progress and to tackle new research questions, such as the ones posed in this study about declining, stable, and increasing bird populations. All the Open Access data used in this study originate from official governmental sources, most of them peer-reviewed and used for research worldwide (see Table S4 and Appendix 6). The use of such data should be the standard for research and data agencies funded by public sources to further public infrastructure and applications in various forms. Metadata are essential to document data processing (e.g., Huettmann, 2005; Huettmann, 2015). Any data on a large scale (e.g., remote sensing data as input) used to create the predictive GIS-layers contain inherent biases and errors, but usually, such errors are corrected using various techniques, which are double-checked by the peer-review process for adequacy. Second, the categorization of the data (e.g., turning remote data into land-use categories) will also create artefacts. However, the GIS-data publishers listed in Table S4 are well-established institutions (e.g., the CRU data were generated from the world-renowned Climatic Research Unit at the University of East Anglia, the HYDE data by the Netherlands Environmental Assessment Agency, and the SAGE data by the Nelson Institute Center for Sustainability and the Global Environment) with well-trained GIS-teams so that the data are error-checked and peer-reviewed, which is the reason that they are used worldwide in thousands of studies. Third, less precise inference may be introduced due to the GIS-data being proxies while better predictor data once created and when made available could prove more effective. The Ecological Niche models which we present operate on the pixel scale of the GIS data, but different scales can of course operate (e.g., microhabitat choices of species). However, because no GIS-data for microhabitats exist yet, here we use the best-available scientific data related to larger ecological features, such as ecosystems and land-use types. Our work is meant to be adaptive (Huettmann, 2007), and here we show a first approach and role model for birds in Africa based on such data and the workflow which we present. The first and second source of error are constantly being improved upon through improved remote sensing data and better algorithms and techniques to improve the categorization accuracy. The third source of error will likely also improve with the advent of fine-scaled and multi-dimensional GIS-data becoming available; this will allow to model microhabitats. Despite the drawbacks of the use of GIS-data, here we present best-available science and state-of-the-art, as we perceive it. In our opinion, the benefits of using this approach to draw new and important ecological and conservation inferences widely outweighs the disadvantages.

Second, our study was limited to the time period 1970–1990 because we were not able to incorporate more recent population trends. Therefore, analyses for the time periods after 1990 are urgently needed which we may pursue in the future using this study as a blueprint.

Third, the linkages between the environmental predictors and the population declines are, of course, correlational. Although they cannot establish causality, they suggest causality (Drew et al., 2011; Manly et al., 2002; see also Thornhill and Fincher, 2013, for an interesting discussion that "all scientific findings are correlational"). For example, the cause-effect relationship between agricultural intensification and population declines is implied because of the ecological knowledge which we have accumulated about this particular relationship through the many studies which have demonstrated it (e.g., Donald et al., 2006; Foley et al., 2005; Green et al., 2005). However, we can of course not rule out additional and synergistic cause-effect relationships.

Fourth, the continent-wide scale of our analysis is important as it constitutes a macroecological-scale study but of course our conclusions may not hold at smaller spatial scales, such as the scale of field studies (e.g., Thorup et al., 2019; Willemoes et al., 2018).

4.4. Conservation implications in the Anthropocene

We now briefly discuss the possible linkages between the ecological system which we studied and the socio-economic drivers of change which we first discussed in the Introduction. We acknowledge that some people will not agree with our views, but we believe the following discussion to be important in order to begin a much needed debate about solutions to the emerging ecological crisis playing out in Africa and beyond. For a similarly relevant broad discussion, see Brito et al. (2018).

Our results emphasized that the declines of migratory bird populations are partly linked to widespread human-made environmental changes on the African continent (as noted in the Introduction, they are of course also partly linked to changes in the breeding ranges and migratory stopovers, but our focus in this study is clearly on the overwintering ranges so we will focus our discussion on Africa, even though several of our arguments below do apply to the entire flyway). Therefore, if we are serious in our ambition to conserve Palearctic-African bird migrants and the ecosystems on which they depend, then we must realize what the underlying drivers of change are, and what solutions are needed to drive change towards a more sustainable future. If we are not honest and forceful about which "major transformations in the ways our global society functions and interacts with natural ecosystems" (Ripple et al., 2020) are urgently needed, the accelerating drivers of change of the Anthropocene will very soon overwhelm our ability to stop the sixth mass extinction event (Barnosky et al., 2012; Ceballos et al., 2015).

First, we note that the main region of large declines in the Sahel zone (Fig. 1A) and specifically in the western part of it are inherently unstable human-climate coupled ecosystems (D'Odorico et al., 2013; Foley et al., 2003) which have experienced both the highest rates of habitat conversion in sub-Saharan Africa (Brink and Eva, 2009; Walther, 2016) and increasing rates of human conflict in the form of civil unrest, terrorism, and war (Brito et al., 2014; Nyong, 2011; Walther, 2016; Daskin and Pringle, 2018). Six out of nine Sahelian countries were involved in armed conflicts in 2012, and conflicts have increased by >500% since 2011 directly resulting in catastrophic biodiversity losses but also losses of the human, financial, organizational and infrastructure resources to stem the biodiversity losses (Brito et al., 2018). This region thus remains stuck in conflict and poverty despite the fact it has received international development aid for many decades (Mann, 2015; Mattelaer, 2016; Somerville, 2019). Instead of promoting ecological resilience, this kind of development has led to widespread biological impoverishment and ecological degradation, including declining migratory bird populations (Walther, 2016).

While the large declines were confined to specific regions, the moderate declines were much more widespread. In our opinion, this finding suggests that, on a finite piece of land, one cannot have both (1) development that removes natural habitat and (2) natural habitat for species conservation (Green et al., 2005; Maurer, 1996; Trauger et al., 2003). Instead, one of the two has to give, and usually that is wilderness and species conservation (Daly and Farley, 2011). Moreover, even protected reserves are now overrun by detrimental human forces and also suffer from increasing isolation (Brito et al., 2018; Ripple et al., 2016; Walther, 2016).

From an avian conservation point of view, changes to economic and environmental policies are therefore urgently required. First, the "growth for growth's sake" mantra of the Anthropocene (Daly and Farley, 2011; Huettmann and Czech, 2006) must be replaced by development which is truly sustainable and does not further harm species, ecosystems and the societies which depend on them. Although desperately needed and fervently advocated by many researchers and conservation practitioners, such a fundamental and radical reorientation of developmental policies is not really in sight (e.g., Brito et al., 2018; Unmüßig, 2015). Because of the lack of truly sustainable development, ongoing biodiversity declines have been identified all over the African continent (e.g., for the Sahara and the Sahel, Brito et al., 2014; Durant et al., 2014; Walther, 2016). While these declines call for immediate action using pre-cautionary decision-making which fully takes the wider framework of coupled socio-economic-environmental systems into account, including online opportunities (Huettmann, 2007), environmental justice (Rosales, 2008), and ecological economics (Daly and Farley, 2011), little actual conservation or development work is currently based on essential sustainability principles such as the steady-state economy (Czech, 2013; Huettmann and Czech, 2006), the precautionary principle (Cooney, 2004), the non-polluting materials economy (McDonough and Braungart, 2008), or biocultural importance (Kronenberg et al., 2017). Furthermore, poverty alleviation, food security, good governance and conflict resolution including arms control are additional core problems which must be resolved (Aloui, 2019; Brito et al., 2018; Davis, 2017; Hendrix and Brinkman, 2013).

Conservation work which does not pose questions and seeks answers within the wider socio-economic-environmental system cannot possibly succeed in the long-term (Brito et al., 2018; Miller and Spoolman, 2012), but will just continue to document the accelerating habitat loss and biodiversity declines without relevant progress (e.g., Ceballos et al., 2015; Walther, 2016). Unless a balanced steady-state socio-economic-environmental system, as very briefly outlined above, is achieved within the next few decades, it is highly unlikely, if not impossible, to halt or reverse the ongoing and massive decay of African biodiversity generally and of many of the bird species of the Palearctic-African migratory flyway. Negative trends will continue because currently all drivers of biodiversity loss are increasing in strength with no reversal in sight (McGill et al., 2015; Pereira et al., 2010; UNEP, 2016).

If our goal is to reverse the declines of migratory birds, conservation biologists should honestly admit that a few relatively small and isolated protected areas will do little for the long-term survival of most species. Given that the wintering grounds of most of the Palearctic-African migrant species are spread across large regions of Africa (Walther et al., 2010) and that protection levels, enforcement, and funding are pitifully low and even absent (Brito et al., 2018), we will not be able to protect them adequately unless we can achieve land-use and management strategies compatible with species survival in large parts of the African continent (Walther and Pirsig, 2017). Therefore, a large-scale and more holistic and sociocultural approach to build resilient societies is required (Brito et al., 2018; Sheehan and Sanderson, 2012). Unless such systemic change in land-use and land management across large regions of the African continent is achieved, the populations of many migrant species will simply continue to decline. While many conservation biologists and decision-makers may call such large-scale changes unrealistic, we assert that the objective of science should be to assert what is necessary, not what is 'realistic' (Rosales, 2008). Consequently, conservation biologists should insist that these species require large areas for their survival, along the lines of Wilson's (2016) assertion that half the planet must be conserved for wild nature in order for most of the biosphere to have a decent chance for survival. To provide real progress, we should not dampen down our conclusions and agendas to fit 'realistic' requirements, whatever they may be.

Our continent-wide conservation analyses strongly advance the notion that a wholesale change in policy priorities is needed, including regulation and enforcement of conservation-based laws on a continent-wide scale (UNEP, 2013; UNEP, 2016) in which the link between biodiversity and human health and well-being is nurtured (Sandifer et al., 2015). Thus, positive conservation outcomes would not just be restricted to protected areas, but be implemented across entire landscapes and regions to sustainably develop the resilient economies and stable societies (Brito et al., 2018).

Without the support and understanding of African governments and civil society and international aid donors and NGOs, analyses such as this one become essentially meaningless ivory-tower exercises in number crunching without affecting any positive change. With their support, however, they could be the launching pads for a sustainable future for the African continent, the migratory flyways, and beyond. Both top-down and bottom-up sustainability initiatives are urgently needed to better inform African societies about the value of biodiversity and sustainability for human well-being and how to incorporate that knowledge into truly long-term sustainable policies and actions, and how to strengthen the adherence to laws and regulations to achieve systemic change. This is the key task we have in order to assure the birds' futures, which goes hand in hand with the future of Africa's people.

CRediT authorship contribution statement

Bruno Andreas Walther: Methodology, Conceptualization, Writing – original draft. **Falk Huettmann:** Investigation, Methodology, Conceptualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices 1-6. Supplementary data

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