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RESEARCH ARTICLE

Planning from scratch: A new modelling approach for designing protected areas in remote, data-poor regions

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Abstract

1. Human pressure on ecosystems has strongly increased over the last decades and now impacts even the most remote regions. To help mitigate these impacts, it is crucial to designate protected areas in regions that retain a high level of ecological integrity. However, ecological data remain scarce for many such areas, making the systematic design of new protected zones challenging.
2. Following a request from local managers, we developed an original methodological approach to help design new zoning for a pre-existing protected area in a remote, data-poor Sahelian wetland of southern Chad, a vast area rich in biodiversity and exploited by diverse human activities. The method involved first collecting extensive aerial survey data (6252 records) on birds and mammals and then analysing this through a combination of distance sampling and density surface modelling. The biodiversity data, combined with ecological predictors, helped model species distribution layers that were then incorporated with socio-economic constraints into the systematic conservation planning tool Marxan.
3. This approach produced an array of protected zoning options that met three levels of conservation objectives set by experts, corresponding to proportions of individuals from given species to protect in the proposed protected area. Frequent exchanges with local managers allowed the analyses to be refined, resulting in seven potential scenarios to be considered for conservation purposes.
4. *Synthesis and applications*. In a context of high data scarcity, lack of access and short-term conservation objectives, this combined approach that optimizes newly

obtained data via a suite of modelling tools can facilitate identifying and protecting natural areas in regions most in need of urgent conservation policy.

KEYWORDS
aerial survey, birds, density surface modelling, distance sampling, Marxan, protected area zoning, wetlands

1 | INTRODUCTION

Protected areas are vital tools to safeguard the remaining strongholds of biodiversity, championed by the High Ambition Coalition for Nature and People and the Post-2020 Global Biodiversity Framework as one of the main instruments to protect nature and help save species from extinction (Jetz et al., 2007) (HAC: www.hacfornatureandpeople.org, Post-2020 global biodiversity framework: https://www.cbd.int/conferences/post2020). However, gaps in quality data on species distribution remain a major challenge in planning protected areas, especially in remote regions that are often biodiversity rich but data poor (Amano et al., 2016). Factors such as political/social insecurity, inaccessibility, language barriers or lack of local expertise prevent the collection of data in many regions around the globe (Amano & Sutherland, 2013). Together with the dynamic nature of many species, these spatial and temporal gaps in ecological data may jeopardize the analyses required to plan new protected areas or their zoning, that is the delineation of land units associated with specific purposes (Ladle & Hortal, 2013).

While birds are often the best documented taxon in databases, with only 0.5% of species data deficient (IUCN, 2021), even they can be very unevenly sampled (Christie et al., 2021). Vast and remote regions such as central Asia and the Sahel in Africa have enormous ecological importance, yet are among the world's most data deficient in terms of birds. The remote nature of these regions makes them less accessible to conduct extensive standardized biodiversity surveys (Amano et al., 2016; Amano & Sutherland, 2013) and to use traditional bird survey methods. The lack of effective methods to estimate the abundance of species in large remote areas (Collen et al., 2008)—such as birds in the tropics (Robinson et al., 2018)—can lead to possible bias in inferred population parameters (Buckland et al., 2008), hampering efforts to identify areas of conservation interest (Girardello et al., 2018).

As these poorly sampled remote places can be among the most threatened by global changes (Christie et al., 2021) and as larger ones can play a significant role in key ecosystem services and the overall maintenance of biodiversity (Watson et al., 2016), conservation efforts need to target them to halt biodiversity loss worldwide (Di Marco et al., 2019). Scientific evidence has shown that the creation and/or reinforcement of protected areas is a particular priority in the tropics (Jetz et al., 2007), where the human footprint is rapidly increasing (Anderson & Mammides, 2020).

In this context, in response to a request from local conservation managers in southern Chad, a data-poor Sahelian country, we developed a relatively rapid approach for the design of protected area zoning targeting birds and mammals, given an almost total lack of standardized quantitative species data. The approach combines distance sampling (DS), density surface modelling (DSM) and the systematic conservation planning software Marxan: a combination that to our knowledge has not previously been used in a peer-reviewed study to delineate protected area zoning (however, see a study combining DS-DSM-Zonation software: Winiarski et al., 2014). As systematic conservation planning approaches require a lot of data (Ball et al., 2009), their use can be challenged in poorly sampled areas (Kukkonen & Tammi, 2019). One way to generate homogeneous data in a systematic and rapid way in regions where observations from the ground are difficult to obtain is aerial DS. The data can then be integrated into Marxan through DSMs.

This study was carried out in the framework of the African-Eurasian Migratory Waterbird Agreement (AEWA) and the Ramsar Convention through the RESSOURCE project ('Strengthening Expertise in South Sahara on Birds and their Rational Use for Communities and their Environment': see https://www.swm-programme.info/ressource-project). The Bahrs Aouk and Salamat floodplains in Chad are remarkable strongholds of vertebrate biodiversity that are under increasing anthropogenic pressure (Brugière & Scholte, 2013; Zwarts et al., 2009), so the RESSOURCE project partnered with the organization African Parks to develop a preliminary design for a new protected area zoning in this region, with the aim to centre the proposed protected area around a vast and relatively pristine wetland area (Lake Iro and its tributary floodplain) sustaining a high concentration of birds, and possibly remaining mammals. To address the lack of geolocated vertebrate abundance data, we conducted systematic aerial surveys, recording both birds and mammals and analysed the collected data using a unique suite of modelling tools to identify potential protected areas and design their zoning, primarily targeting birds and mammals. Our study produced alternative scenarios that were discussed with local managers in view of implementing the most effective measures to protect biodiversity.

2 | MATERIALS AND METHODS

2.1 | Study area

2.1.1 | The Bahrs Aouk and Salamat floodplains

The Bahrs Aouk and Salamat floodplains cover 50,000 km^2 of southern Chad (Figure 1) and are characterized by a tropical dry climate. The landscape of this region is dominated by dense shrubby forests (Raimond et al., 2019) and typical floodplain vegetation such as *Andropogon* sp., *Hyparrhenia* sp., *Cymbopogon* sp., *Echinochloa* sp., *Oryza* sp. and *Acacia* sp. Lake Iro (145 km^2) is supplied by the Bahr Salamat (river) and hosts a high density of resident and migratory birds. This region is of great importance for wildlife, including elephants *Loxodonta africana*, Kordofan giraffes *Giraffa camelopardalis* and hippos *Hippopotamus amphibius*, and has two protected areas: the Zakouma National Park and the Bahr Salamat Faunal Reserve. The latter is a buffer zone around the park where human activities are authorized, except for hunting and the construction of new human settlements, which are theoretically prohibited. One of the largest Ramsar sites in Africa, this area is of great importance for many bird species, including six species of vulture (all either Critically Endangered or Endangered on the IUCN Red List), the black-crowned crane *Balearica pavonina* and the northern ground hornbill *Bucorvus abyssinicus*, which are listed as Vulnerable on the IUCN Red List (IUCN, 2021). The black-crowned crane is particularly threatened by the loss of wetlands caused by increasing human pressure (Zelelew et al., 2020) and is classified as a national heritage species in Chad.

2.1.2 | Socio-economic context

Human density in the study area is relatively low, with two towns (sub-prefectures) and small villages and hamlets found across the area, as well as nomadic camps during the dry season. In addition to the sedentary and nomadic communities, the major stakeholders include traditional authorities (e.g. territorial and village chiefs, nomad chiefs, sultans), whose influence on resource and tenure management as well as conflict resolution is still very significant, and administrative authorities (e.g. heads of districts and sub-districts, sectoral chiefs and inspectors for fisheries, livestock, wildlife), who are responsible for implementing national laws and provincial regulations, including natural resource management. Administrative authorities often lack sufficient means to fulfil their missions, for example, to regulate land tenure and manage agriculture, to ensure the sustainable and legal management of fisheries or to act against illegal activities. Thus, involving communities and traditional representatives as well as administrative authorities in participatory processes is key in managing land use and resources. Modelling tools can be used as an essential asset to start and to build on this concertation. Other stakeholders involved in the management of protected areas include biologists and experts participating in bird and wildlife censuses, from Chad's Ministry of the Environment or external non-governmental organizations, as well as local managers of the park and reserve where the study site is located. In the specific case of Zakouma's National Park and the associated Greater Zakouma Ecosystem (GZE), where the study area is located, local managers include

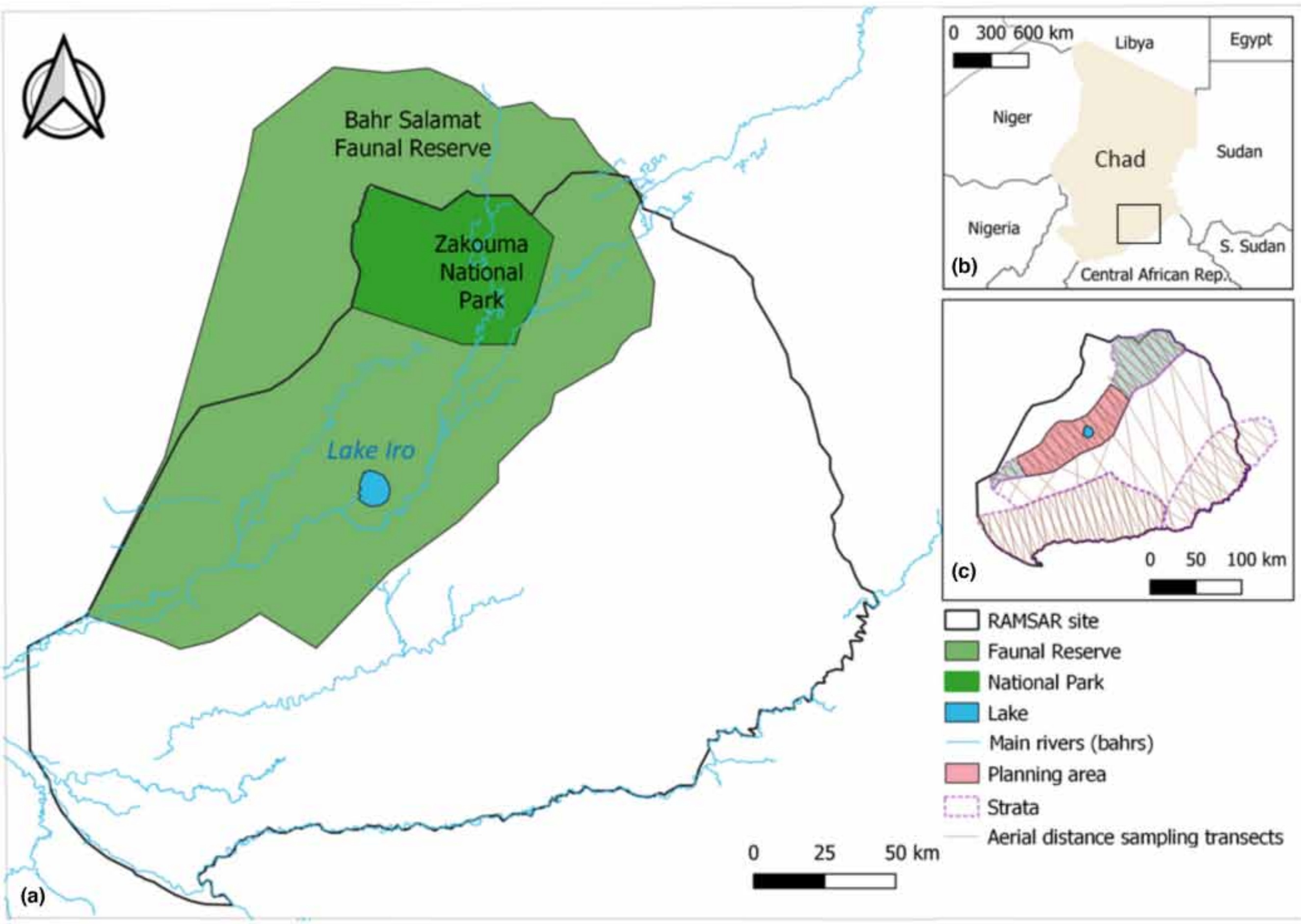

FIGURE 1 (a) Study area in the Bahrs Aouk and Salamat floodplains, Chad; (b) Location of the study area in Chad; (c) Aerial survey design in the four studied strata (sub-regions).

African Parks, a non-governmental organization (NGO) in charge of the management of protected areas and the senior staff from the Chad's Ministry of the Environment, associated with the NGO. Together, they form the Park Management Unit.

An unsuccessful attempt of field survey on the ground in 2020 confirmed the very remote nature of the region, with an extremely limited track network, making most of the area barely accessible by foot only. The local economy is based mainly on livestock rearing, fisheries and agriculture (including single-crop farming of *Sorghum durra*), activities that can all constitute direct or indirect threats to mammal, fish and bird species due to habitat loss or harvesting (Raimond et al., 2019). In recent decades, increasing droughts and conflicts in northern Chad have been responsible for major human displacements within the country, and Lake Iro in particular has become increasingly attractive to migrants (Raimond et al., 2019), putting additional pressure on its ecosystems and further increasing the need for protection.

2.2 | Distribution of biological entities

2.2.1 | Aerial survey data

As species data in this region are poor, aerial surveys were conducted over the entire study area, thereafter named 'survey area' (Figure 1a). These were carried out yearly from 2017 to 2020 within four strata (i.e. sub-regions sampled depending on local density of wetlands) along transects following a standardized adjusted-angle zigzag survey design (see Figure 1c for transect locations). This design guarantees equal coverage probability for complex study areas, while being cost-effective compared to other more conventional designs (Buckland et al., 2004). A total of 192 transects (mean length = 44.70 km) were automatically generated using the software 'Distance' v.7.0 (Thomas et al., 2010) and surveyed over the 4 years of the study. Our study was carried out and licensed in the framework of the *Accord de partenariat entre le Gouvernement de la République du Tchad et African Parks Networks (APN) pour la gestion et le financement du Parc National de Zakouma et son Grand Ecosystème Fonctionnel—2017–2027*. One of the aims of the RESSOURCE project is to contribute to the International Waterbird Census (IWC) and to obtain data simultaneously over the major Sahelian wetlands, so data were collected from mid-January to early February, when the importance of wetlands for wildlife is most visible. During the surveys, transects were flown at 90 m above ground level at low speed (~140 km/h) with one observer on each side of the aircraft. Blind side distance of 25 m immediately below the aircraft was right-truncated to represent the minimum observation distance (i.e. distance = 0). The area along the transects was divided into four distance bands (0–80, 80–180, 180–380 and 380–780 m, respectively), materialized by marks on the windows aligned to streamers fixed on the wing struts of the aircraft. Using portable recorders, observers placed on each side of the aircraft recorded for each observation the distance band (one to four), bird and mammal species and size of the observed wildlife cluster, name and position of the observer in the aircraft, transect number, time of day and date. Additionally, opportunistic data (i.e. not associated with any transect) were recorded by the same observers in January 2020 for rarer wildlife species, both during aerial and ground observations (see list of all counted species in Appendix S1). As these opportunistic records were not collected in a systematic way and were too scarce to build even basic species-specific spatial models or too clustered into one single habitat patch (hippos in Lake Iro), they were not used in the planning process, but provided additional biodiversity data that helped to assess the efficacy of protected area designs (PADs).

2.2.2 | DS analysis

We aimed to collect and include in our analysis as much biodiversity information as possible to maximize the comprehensiveness of the scientific data for the future protected area. In total, 71 species (61 birds, including 43 waterbirds, and 10 mammals) were detected from aircraft in our planning area. All species detected during the aerial surveys were recorded and integrated into our analyses, provided they met the following minimum abundance threshold. DS analyses were performed on all single mammal or bird species with at least 40 records (Buckland et al., 2001). Because similar-looking species may share the same detection function, we pooled rarer waterbirds (<40 records) with similar-looking more common waterbird (Buckland et al., 2008). We then performed a single analysis on this pooled dataset of both species to check for similarity in the detection probability and inferred density of the rarer waterbird. In all, 24 waterbird taxa did not meet the sample threshold to be modelled individually but were included in the two following layers on which we put extra emphasis in the Marxan analysis: modelled species richness and total abundance of waterbirds, for a total of 43 taxa (see below).

In addition, DS analyses were also conducted over the four strata on the following biological entities: (1) on some genera with unidentified species or too few observations (genera *Ardea*, *Anas* and *Vanellus*), (2) on the total modelled abundance of all waterbirds and (3) on modelled waterbird species richness. The two latter categories were calculated for each observation point.

We modelled detection probability using 10 covariates generally known to affect detectability (Table S2). Analyses were performed in R software (version 1.1.383, R Core Team, 2021) using the 'ds' function of the 'Distance' package, version 1.0.1.9005 (Miller et al., 2019). For each biological entity, we first selected key functions (from half-normal, hazard-rate and uniform functions) and adjustment terms (from cosine, hermite polynomial and simple polynomial) using AIC (or AICc for sample size <80 observations), providing that the χ^2 goodness-of-fit test was satisfactory (Burnham & Anderson, 2002; Miller et al., 2013, 2019). Moreover, the shape of the detection function was checked at each step of the model selection procedure to verify the assumptions underlying DS analyses (Buckland et al., 2001). We then added each covariate to the most-supported null model and then added remaining non-colinear covariates in a stepwise manner to the retained model until no improvement in the AIC could be obtained.

2.2.3 | DSM analysis

Density surface models associate count data and ecological covariates with a detection function obtained from DS to estimate the density of the population of interest within units (segments) dividing the study area (Miller et al., 2013). We first identified, with the help of local managers, a reduced zone within the larger survey area, referred to as the 'planning area' (see Figure 1c), where we performed DSMs and extrapolated species distributions. Raw species distribution data obtained from the surveyed transects indicated that most species concentrate in the southwest area of Lake Iro, where increased human pressures occur. Moreover, the southern part of Lake Iro already has fishing restrictions (Raimond et al., 2019). As local managers were interested in identifying a protected area that would benefit biodiversity in general, we focused on the large region surrounding Lake Iro, and particularly on its southwest side. Using QGIS software (version 3.16—QGIS Development Team, 2021), we thus selected the restricted planning area around Lake Iro, including a buffer 50 km northeast and 75 km southwest of Lake Iro (Figure 1c). All transects from the planning area were first divided into 3409 segments of 1200 × 1200 m each. Species observations were assigned to a given segment based on their geographical location. We used the R 'dsm' package (Miller et al., 2021) to model the distribution of each biological entity, and used the covariates detailed in Table S3, which all potentially influence the distribution of bird and mammal species (Brito et al., 2014, 2016; Zwarts et al., 2009). All quantitative covariates were standardized prior to analysis.

Density surface models were first fit to various distributions of count data (quasi-Poisson, Tweedie or negative binomial) among segments and compared using AIC or AICc (Burnham & Anderson, 2002). Fit was first checked using qqplots and residual plots. Covariates were then selected in a stepwise procedure using AIC or AICc. Retained models were checked for possible spatial autocorrelation by visual inspection of residuals, and their fit was assessed using explained deviance and coefficient of variation (CV). We discarded models with CV > 50%. We then extrapolated species abundance over a grid dividing the survey area by squares of 1200 × 1200 m (such that the grid unit is approximately twice the truncation distance i.e. 580 m), using the most-supported DS model and DSM for the corresponding species (Miller et al., 2021). To limit extrapolation errors (Fifield et al., 2017), we removed the cells for which predicted values were outside the range of values observed in sampled locations. Although this may lead to false absences, we preferred this option over falsely estimating an abundance that would directly affect the delineation of a protected area.

2.3 | Conservation planning analysis

We used the systematic conservation planning software Marxan v.2.43 (Ball et al., 2009) and its visualization tool Zonae Cogito v.1.74 (Segan et al., 2011) to design areas that met a set of conservation targets at the lowest possible socio-economic cost (Watts et al., 2017). Marxan uses a simulated annealing algorithm that allows for both flexible and time-efficient computing of the selection of sites to protect, named 'planning units' (Game & Grantham, 2008). Details on the configuration of the Marxan analyses are provided in Appendix S4a.

2.3.1 | Conservation features and objectives

The conservation features used in Marxan (i.e. the biological entities we aim to optimize conservation of) resulted from the modelled distributions of 20 bird entities and 2 mammals (warthog and baboon) for which we could perform DSMs and obtain distributions within the range of the planning area (see Table S5 for the list of species). These features were assigned conservation targets (i.e. numeric objectives to reach for each biological entity) in consultation with local managers (see Section 2.3.3; Table S5). Because the primary focus of this work was to centre the proposed protected area around a wetland area sustaining a high concentration of birds, we put extra emphasis (see below) on three of these conservation features (total modelled abundance of waterbirds, modelled waterbird species richness and the vulnerable black-crowned crane, the latter needing urgent protection) due to their suitability in constructing a comprehensive, sound, science-based protected area. Additionally, Lake Iro currently includes a fishing restriction area (Raimond et al., 2019). Local managers suggested to systematically include this area in any solutions generated by Marxan, using a functionality to automatically include some planning units within the solutions it generates ('fixing' them in). On account of a lack of up-to-date validated data, a natural habitat layer could not be considered. Opportunistic data, although not used for the Marxan analyses, were added to the output maps created by Marxan to check its inclusion within the PADs, as the corresponding species could benefit from the implementation of the PAD.

2.3.2 | Socio-economic constraints

To minimize a protected area's overlap with towns and villages, as well as with the main socio-economic activity (sorghum cultivation), we assigned equally in all scenarios (see below) a cost to each cell that was (1) proportional to the portion of the cell containing socio-economic activities and (2) dependent on the type of area (either core or buffer). The location of villages and towns was provided by local managers. As mobility and road access are limited across the survey area, most crops are located within walking distance from villages, that is within 3 km (Akponikpè et al., 2011). Core area cells belonging to a 3-km radius around each village were assigned a cost proportional to the portion of the cell contained within this radius, from 1 if entirely inside the radius, to 0.01 if entirely outside. For buffer area cells, we assigned half the core area cost value. Marxan also allows the possibility of excluding some planning units from the solutions it generates, so it was set, at the demand of local managers, to exclude from all Marxan solutions the two towns in proximity of the planning area, Boum Kebir and Alako.

2.3.3 | Conservation planning scenarios

We designed three scenarios (with low, moderate or high conservation targets), with increasing levels of protection of biological entities, that is three amounts of protected individuals for each species within the zoning options. Targets were based on Ramsar criteria five and six for waterbirds (Ramsar Convention on Wetlands, 2010) and set arbitrarily for other conservation features to represent a gradient of conservation levels (10%, 25% or 50% of total modelled abundance of a given biological entity within the planning area for a low, moderate or high conservation level, respectively). To set more emphasis on the three aforementioned conservation features (total modelled abundance of waterbirds, modelled waterbird species richness and the vulnerable black-crowned crane), we increased their species penalty factor (SPF) as a way to better reach conservation targets (see below) and doubled conservation targets for the black-crowned crane (compared to the value it should have in regard to criterion six). Table S5 presents, for each level, the different targets used for each conservation feature, the rationale behind each target and the method used to set them.

At the request of the local managers, the proposed designs had to be composed of a core and a buffer area. The core area, where more restrictive conservation measures could be implemented, had to consist of an unfragmented area with high conservation value and low human population. The buffer area, surrounding the core, aimed to reinforce the conservation objectives set in the core without requiring additional strong conservation measures, possibly allowing human activities. Note here that the buffer area includes the core area (i.e. the buffer area is not a spatial addition, but it is an enlarged version of the core area). Hence, simply because it is larger, the buffer area should meet higher conservation targets than the core area alone. Because higher conservation targets tend to lead to bigger protected area, higher targets were set for buffer areas to capture conservation targets in both core and buffer areas.

Potential PADs were created in two steps: (1) first, core areas based on low or moderate conservation targets were designed to identify an unfragmented central (core) area of reduced size for each scenario, and then (2) buffer areas were built around these core areas using moderate or high conservation targets respectively. Each Marxan analysis was preceded by a calibration of the Species Penalty Factor (SPF), a weight improving Marxan's performance in meeting a given target, and the boundary length modifier (BLM), a weight scaling the compactness of solutions (see Ball et al., 2009). We selected the 10 solutions with the lowest cost that included only a unique core area. Local managers were then asked to select three or four different core areas among those 10 solutions for each protection level, based on the total surface area of the solutions, their shape and the number of villages inside the PAD. Marxan offers a functionality to automatically include some planning units within the solutions it generates ('fixing' them in), which we used for the design of buffer areas. For each retained core area, we first fixed the corresponding planning units in order for buffer areas to contain and be built around the core area. We used medium and high conservation targets when fitting buffer areas encompassing fixed core area designs obtained from low and medium conservation targets, respectively. We then selected the 10 solutions with the lowest cost that had a unique buffer area. Concertation between local managers and scientists led to the selection of final PADs among these 10 solutions.

We performed a sensitivity analysis following the approach of Ardron et al. (2010) to assess the sensitivity of Marxan to input data by removing the conservation targets for the four less reliable layers (species richness, hadada ibis, northern ground hornbill and purple heron) and running Marxan again to evaluate whether their lower quality might have detrimentally affected simulation outputs (see details on method and results in Appendix S6).

2.3.4 | Iterative planning with local managers

This study was requested by local managers working for the nearby Zakouma National Park and involved in the development of a more comprehensive regional network of protected areas. In a more general approach to elaborate and implement a Land-Use and Management Plan for the entire GZE, that covers the Bahr Salamat Faunal Reserve as well as other natural areas, local managers had started identifying key ecological areas lacking suitable protection in the GZE region. In previous years, data received from aerial surveys performed within the RESSOURCE project showed high concentrations and diversity of avifauna and other species in the Salamat floodplains, that is a potential key ecological area. The present additional ecological expertise was requested by local managers to support a conservation strategy for these floodplains and management of the future network of protected areas (step 1, Figure 2). In addition to the involvement of local managers in the data collection phase, regular discussions between the local managers and the modelling team were central to the analyses, as recommended by Vogler et al. (2017). From the initial step of conceiving the study to interpreting the results, the partners interacted frequently (steps 3 and 8). Local managers provided the conservation planning context (step 1) and some data layers to the modelling team (e.g. to capture human uses of the area). The modelling team, in turn, made proposals about the conservation planning process (step 2) and methods (step 4) and results that were then discussed and refined following regular feedback from local managers (steps 7 and 8). Local managers also regularly informed local representatives and authorities about the process, in the broader context of the Land Use and Management Plan, particularly during one of the sessions of the Governance Meeting of the GZE (February 2021), one of the two main governance bodies

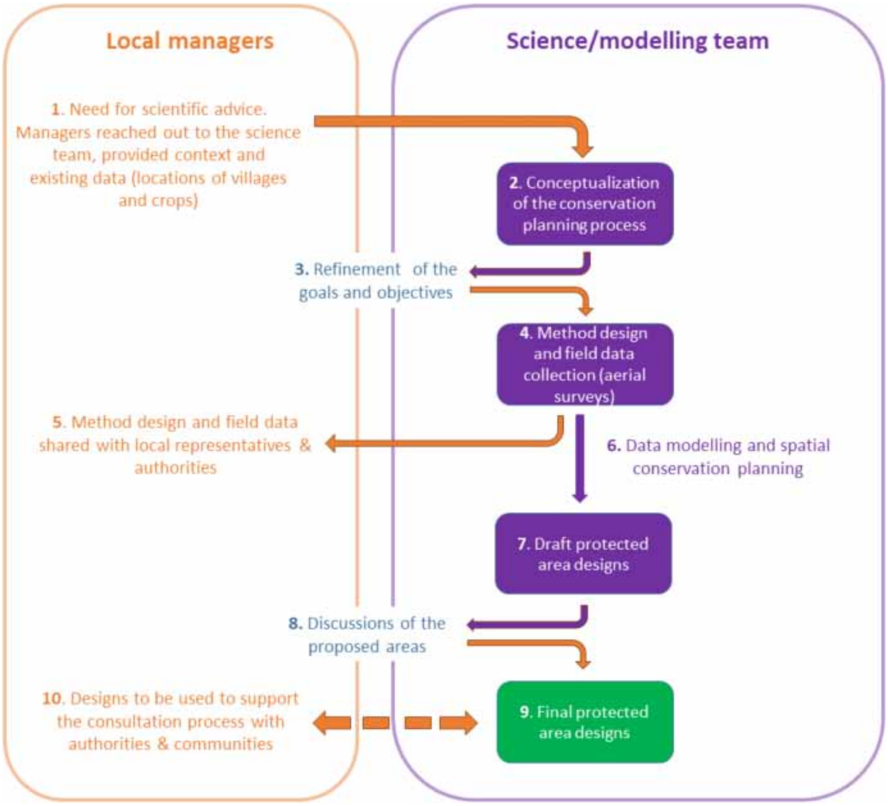

FIGURE 2 Feedback loop of interactions between local managers and scientists throughout the project to develop protected area designs.

of the GZE (step 5). The final solutions for PADs resulted from this concertation between the teams, and prioritized the views of local managers (step 9).

3 | RESULTS

3.1 | Field surveys

The aerial surveys recorded 5506 observations of birds and 635 observations of mammals. Additionally, 443 opportunistic observations were recorded, including 140 observations of birds and 303 observations of mammals.

3.2 | DS and DSM

We derived population estimates for 28 biological entities and distribution maps for 22 of these (see Figure 3 for four example species and Table S5 for the entire list). Most DSMs included geographical coordinates, presence/absence of water or altitude as covariates. We estimated a total of 454,404 (Confidence Intervals: min = 343,984, max = 600,270) waterbirds in the planning area. We could not fit robust DSM models for six biological entities (*Sylvicapra grimmia*, *Redunca redunca*, European ducks, *Spatula querquedula*, *Ephippiorhynchus senegalensis*, lapwings) due to an insufficient sample size. Most models showed a reasonable fit (mean deviance explained = 30.5%, Table S5). Concurvity measures were usually small (mostly <0.5); when above 0.7, we retained the corresponding covariate to limit concurvity. Mean CV across all DSMs was 39.6%. We found some spatial autocorrelation in residuals of several DSMs, which we tried to alleviate by adding an autoregressive function, spatial covariates and ecological covariates (Dormann et al., 2007; Miller et al., 2013). The inclusion of ecological covariates in particular helped reduce the autocorrelation, although the latter remained superior to 0.1 for the hadada ibis and for species richness. Overall, the autocorrelation of both these DSMs was significant but low, so we retained those layers in the Marxan analysis but accounted for their lower quality in the sensitivity analysis (see Appendix S6a). As expected from field observations, we found a particularly high modelled abundance of waterbirds southwest of Lake Iro and around the lake. Both modelled mammals were predominantly distributed in the northern range of the survey area (see Figure 3 for baboons). This was expected due to the proximity of the Zakouma National Park. For more details on DSM results, see Appendix S3c.

3.3 | Marxan analyses

All PADs met all conservation targets, including for the black-crowned crane and northern ground hornbill (both Vulnerable on the IUCN Red List), thus providing the targeted level of protection for all the biological entities of interest. Most PADs proposed by Marxan covered the southwest region of Lake Iro, highlighting the importance of this area for waterbird conservation (see Figure 4). Core area solutions retained for low conservation scenarios had a mean size of 925 km^2 (Figure 4a). When using moderate conservation targets to design a

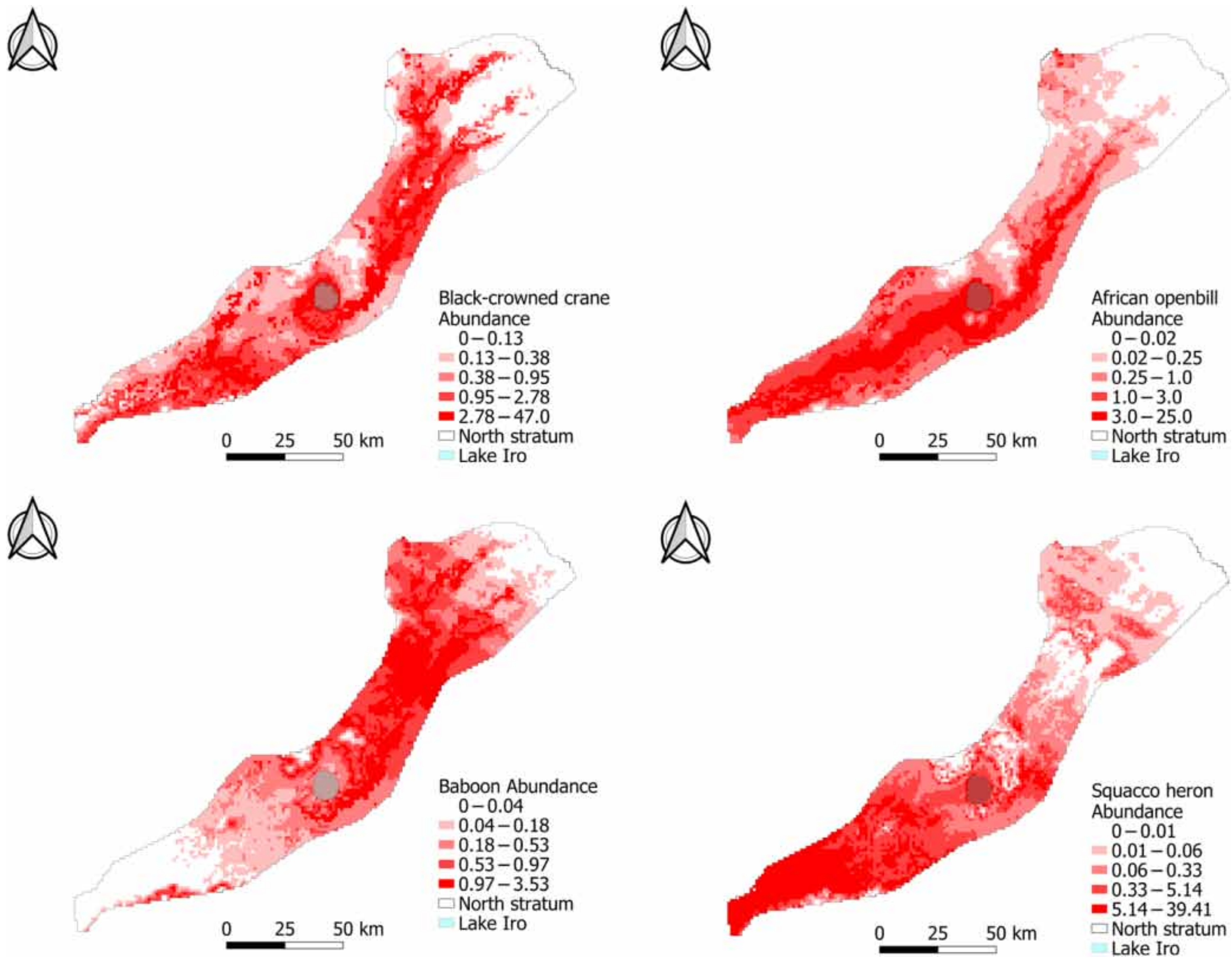

FIGURE 3 Distribution and modelled abundance (N/1.2 km^2) of the black-crowned crane *Balearica pavonina*, african openbill *Anastomus lamelligerus*, squacco heron *Ardeola ralloides* and olive baboon *Papio anubis*, as predicted by density surface modelling runs on aerial distance sampling data from 2017 to 2020.

buffer encompassing the core areas obtained from the low conservation scenario, the mean size of PADs was 1535 km^2 (Figure 4a). Core areas retained for moderate conservation scenarios had a mean size of 1488 km^2 (Figure 4b). When using high conservation targets to design a buffer encompassing the core areas obtained from a moderate conservation scenario, the overall size of PADs averaged 2286 km^2 (Figure 4b). While PADs did not avoid all villages, most only included one or two, and avoided the towns. While some threatened species such as the hippopotamus or vultures were not used as conservation targets because of the lack of systematic data, the PADs were found to potentially contribute to the protection of these species, as well as the three species listed in Column A of the AEWA appendix (see Figure 4; Table S6). Indeed, 66% of the surveyed species of conservation concern (IUCN or AEWA) were included in the PADs when considering a low conservation scenario, and 100% were included when considering a moderate conservation scenario (see Table S6). Of course, additional data would ideally be useful to assess their occurrence in the PADs. Sensitivity analyses suggested that layers of lower quality did not substantially change the solutions, as most planning units were selected in a similar way by Marxan in simulations with and without layers less reliable (see Appendix S6).

4 | DISCUSSION

In this study, we combined three analytical methods to attempt to develop a robust and comprehensive approach for designing protected area zoning in a remote region with an absence of quantitative biodiversity data. The use of DS and DSM allowed the estimation of the abundance of 28 biological entities and the distribution of 22 of these. Given the scarcity of data within the Sahelian region and nearby sub-Saharan areas (Brito et al., 2014), this new information can contribute to national and international conservation databases such as that of Wetlands International. By incorporating the data layers into Marxan conservation planning software, we were able to provide, in a relatively short time span, local managers and decision-makers with

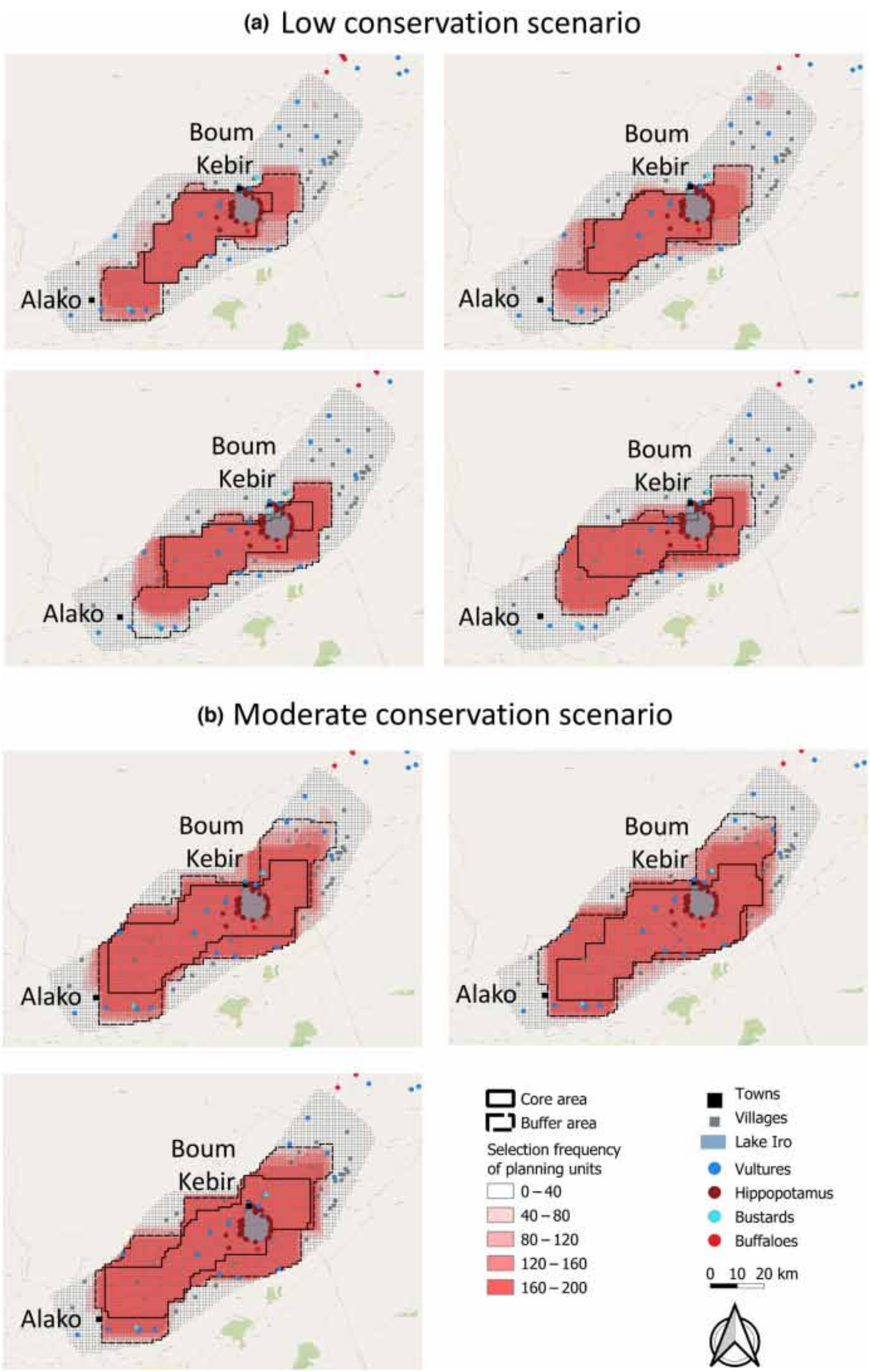

FIGURE 4 The final protected area designs (PADs) selected by local managers from 200 runs of a scenario with core and buffer areas for low (a) and moderate (b) conservation targets. Low and moderate conservation targets correspond to two amounts of protected individuals for each animal species within the zoning options (see Section 2). Selection frequency corresponds to the number of times a planning unit was selected in the 200 runs. Final PADs covered similar areas, including the southwest region of Lake Iro, highlighting the importance of this area for conservation.

potential PADs that balance the needs of biodiversity conservation and human society. The results confirmed the importance of the floodplains southwest of Lake Iro for waterbirds, and helped design several alternative scenarios to be discussed by local partners.

4.1 | The relevance of using DS and DSM outputs in conservation planning

As far as we know, this is the first attempt to combine DS and DSM-derived layers as input data for Marxan analyses to design protected area zoning. The information layers typically input into Marxan mostly originate from: species distribution models (Lawler et al., 2020) such as Maxent (Esselman & Allan, 2011), traditional knowledge or expert information from local stakeholders (Game, Lipsett-Moore, Hamilton, et al., 2011), species distribution records from databases or museums (Game, Lipsett-Moore, Saxon, et al., 2011), phylogenetic data (Asmyhr et al., 2014) or habitat maps (Proudfoot et al., 2020). However, most of this information is hard to obtain in regions where funding and access are limited or where security issues prevent field work. Due to the remoteness of our study area and its almost total lack of a road network, aerial DS allowed large vertebrates to be monitored more comprehensively, accurately and cost-effectively than ground sampling. In remote regions where biodiversity data are most lacking, the tested suite of aerial survey and modelling tools appears a potentially suitable approach to design a sound-protected area zoning proposal, as it can provide and analyse in a relatively short time span an array of systematically surveyed biodiversity layers.

While this approach may be the only option in remote regions, it should be noted that aerial DS has certain limitations. These include:

- Uncertainty in large flock size estimation (Frederick et al., 2003)
- Detection of objects at zero distance (Buckland et al., 2001). To ensure 100% detection in the closest distance band, aerial observers (who were all experienced birders with previous experience in both aerial surveys and Sahel fauna) had to prioritize detection of all target objects from this band. We recommend conducting mark–recapture DS in future studies to control for this and the above bias (Hamilton et al., 2017), which could, for instance, be caused by fatigue or the number of species, potentially generating underestimation in modelled abundance estimates. While it is not currently possible to accurately identify many vertebrate species (e.g. birds), particularly in movement, with the exception of larger mammals from digital images at a reasonable cost and over vast areas (Wang et al., 2019), methodological advances (e.g. based on deep learning algorithms) could make this possible in the future.
- A detection gap for a multitude of smaller or more cryptic species. In line with Rodgers et al. (2005), we ideally recommend standardized ground surveys to sample these species; however, these might prove extremely costly in time, personnel and funds.
- An incomplete removal of spatial autocorrelation in the models, possibly because of undetected ecological drivers (although we brought residual autocorrelation to minimal levels in our DSMs).

In our case study, these limitations were mitigated by the fact that most threatened species in southern Chad are readily detectable from aircraft, such as the black-crowned crane, the northern ground hornbill, and more generally, vultures and large mammals (IUCN, 2021). Using DS and DSM methodology contributed to avoiding common pitfalls in estimating species distribution (Muscatello et al., 2020) by using a systematic sampling design, by not converting quantitative responses into binary ones, and by selecting DS and DSM models through an information-theoretic approach. Most model fits were satisfactory, based on the reasonably satisfying values obtained for deviance explained and the CV. As we suspected that four models of lower quality might bias PAD selection, we performed sensitivity analyses as recommended by Fischer et al. (2010). These demonstrated a relatively robust identification of PADs.

4.2 | Contribution of PADs to conservation and socio-economic objectives

The areas proposed by Marxan contained the floodplain southwest of Lake Iro, which experts empirically predicted to be species rich. This would clearly be a priority area for protection as it could host between 66% and 100% of the systematically or opportunistically sampled species considered threatened by the IUCN and AEWA. As previously mentioned, this latter result would benefit from additional systematic surveys on those species. Opportunistic data are intrinsically biased (Fletcher et al., 2019) and because we collected too few (or too clustered) opportunistic data, we did not model them. Thus, more surveys would be necessary to assess and integrate the distribution of these species in the PADs. Because the shape and zoning of a protected area can impact its effectiveness (Cantú-Salazar & Gaston, 2010), the design followed recommendations from local managers (e.g. a rounded shape was suggested to ease implementation). Solutions retained for the low conservation scenario had a mean size of 1535 km^2 (including the buffer zone). For high conservation targets, the size increased to a mean of 2286 km^2. Although this is quite large compared to other protected areas worldwide (Leroux et al., 2010), it is consistent with both the size of the Zakouma National Park (3050 km^2) and the ecosystems in the planning area, which is a huge natural floodplain covering more than 5000 km^2. It also responds to the pressing need for natural area conservation in the tropics (Jetz et al., 2007). Our methodological approach thus appears to provide a good compromise between PAD shape and size, meeting conservation targets at minimal socio-economic cost.

Our PAD solutions fulfilled our three main objectives for the design of protected area zoning in the Bahrs Aouk and Salamat floodplains. First, all PADs allowed the protection of the entire list of modelled species. This is particularly important, as Sahelian birds, including the vulnerable black-crowned crane, need urgent protection of their habitat (Brito et al., 2016; Zelelew et al., 2020). Additionally, the PADs could benefit other taxa that are currently not represented in our analysis, as bird species richness is very generally linked to habitat heterogeneity, hence quality, therefore providing good quality habitat to any other indigenous species (Tews et al., 2004). Second, the proposed PADs minimize interference with key human activities, a fundamental issue requesting dedicated management (Kaimowitz & Sheil, 2007). They avoid most villages, towns and crops, as most agricultural activities in the region are found within 3 km of villages. In the context of increasing human migration, the implementation of a new protected area zoning and current knowledge of local biodiversity concerns should help local land use planning, as well as new settlement. Third, the opportunistic sightings of eight taxa not studied by DSM (hippos, buffaloes, bustards and five species of vultures classified as Endangered or Critically Endangered on the IUCN Red List, BirdLife International, 2017) were all recorded within the proposed PADs, suggesting these may protect additional species to the 22 used for their delineation. Our methodological approach should thus enable local managers, administrations and decision-makers to contribute in a relatively short time span to the conservation of Sahelian wildlife, many species of which are endangered or on the brink of extinction (Brito et al., 2016).

4.3 | Involvement of local stakeholders: A priority in conservation planning

In addition to a robust approach, concertation with local managers greatly increases the chance of success of a protected area (Vogler et al., 2017). Over the course of the entire project, we exchanged with local managers and biologists. If new zoning for the protected area is to be implemented in the region, public consultations should be carried on as well to take into account the needs and requests of the local population and facilitate its acceptance, as shown in Figure 2 earlier (Binot et al., 2009). Local managers of the Bahr Salamat Reserve and the GZE would need to co-construct the goals and the zoning through concertation and dialogue, taking into account socio-economic data. The maps produced by our approach could serve as scenarios on which to base the zoning alternatives. Since the solutions differ in terms of total surface area, shape, locations included, presence of villages, etc., they could provide flexible options for discussion and offer choices to local stakeholders.

Rules applying to core areas would significantly limit human activities to those compatible with the conservation of wildlife, preventing any further damage: no new settlements, infrastructure or villages; strictly limited expansion of agriculture and degradation of natural habitats; state-led and/or community-led surveillance; community-level sustainable harvesting of fisheries or other natural resources; limitation of other uses. These core areas would benefit species very sensitive to human presence, including the black-crowned crane (Zelelew et al., 2020) and vultures (BirdLife International, 2017).

In the buffer area, where settlements are present, strong efforts to raise awareness, set up community land use and resource management mechanisms, improve the sustainability of agriculture (including alternatives to illegal or harmful agrochemicals), and promote sustainable alternative livelihoods should help decrease pressure on the core area while allowing for coexistence with species less sensitive to human presence.

New protected area zoning in this region could have a significant impact on biodiversity conservation by strengthening a comprehensive corridor of protected and restricted-hunting areas. Such a vast network would help to attract international attention and potentially sorely needed resources to threatened Sahelian ecosystems (Scholte et al., 2004).

This work illustrates how the cooperation between local managers and a modelling team can generate zoning alternatives to design protected areas in remote regions without pre-existing data. The creation of zoning alternatives was strongly guided by the needs and feedback from local managers. The vision of local managers was a critical asset in our study, and building upon their requests and knowledge was essential to create a sound set of conservation area design proposals that have more chances to be adopted in regional public policies. We thus stress the outmost importance in engaging in an open permanent dialogue between local managers and modelling team to build conservation project, which may favour their acceptance by local partners and communities.

AUTHOR CONTRIBUTIONS

Pierre Defos du Rau, Jean-Yves Mondain-Monval, Antoine Messager, Babakar Matar Breme, Rodolphe Devillers, Jocelyn Champagnon, Bruno Portier and Delphine Ducros conceived the ideas and methodology; Abakar Saleh Wachoum, Pierre Defos du Rau, Jean-Yves Mondain-Monval, Ib Krag Petersen, Babakar Matar Breme, Yves Kayser, Nicolas Vincent-Martin, M'Baïti Narcisse Djimasngar and Antoine Messager collected the data; Delphine Ducros, Pierre Defos du Rau, Antoine Messager, Rodolphe Devillers, Jean-Yves Mondain-Monval, Babakar Matar Breme, Ib Krag Petersen, Marie Suet and Clémence Deschamps analysed the data; Delphine Ducros, Pierre Defos du Rau and Rodolphe Devillers led the writing. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

We declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data available from the OFB data repository https://ged.ofb.fr/share/s/mv2wsi4jToOSJg0N2Co5vg (Ducros et al., 2023).

STATEMENT OF INCLUSION

This study brought together authors from several countries, including conservation managers based in Chad. All authors were involved with the research and study design to ensure that their considerations were fully accounted for during the project. Data collected from local teams were used whenever possible.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Species observed during distance sampling aerial surveys and opportunistic sampling.

Appendix S2. Distance sampling analyses.

Appendix S3. Density surface modelling analyses.

Appendix S4. Marxan analyses.

Appendix S5. Species of importance potentially safeguarded within the proposed PADs.

Appendix S6. Sensitivity analyses.

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