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RESEARCH ARTICLE

Migration of humans fleeing conflict in the Lake Chad region may increase pressures on natural resources in Lake Fitri (Chad): A case study on waterbirds

Nicolas Carenton[1] | Pierre Defos du Rau[1] | Abakar Saleh Wachoum[2] | Delphine Ducros[1,3] | Marie Suet[3] | Clémence Deschamps[3] | Maxime Rotoudjimbaye Betoloum[4] | Julien Birard[1,3] | M' Baïti Narcisse Djimasngar[2] | Yves Kayser[3] | Ib Krag Petersen[5] | Jaime Dias[6] | Mahamat Adoum Wachoum[2] | Bruno Portier[7] | Audrey Mbagogo Koumbraït[8] | Sébastien Le Bel[9] | Jean-Yves Mondain-Monval[1]

[1]Office Français de la Biodiversité, Arles, France; [2]Ministère de l'Environnement, de la Pêche et du Développement Durable, N'Djamena, Chad; [3]Tour du Valat, Research Institute for Conservation of Mediterranean Wetlands, Arles, France; [4]Centre Pour la Recherche Humanitaire, N'Djamena, Chad; [5]Department of Ecoscience, Aarhus University, Aarhus, Denmark; [6]Wings for Conservation, Amsterdam, The Netherlands; [7]Food and Agriculture Organization of the United Nations, Rome, Italy; [8]Université des Sciences et de Technologie d'Ati, Ati, Chad and [9]Centre de Coopération Internationale en Recherche Agronomique Pour le Développement, Montpellier, France

Correspondence
Pierre Defos du Rau
Email: pierre.defosdurau@ofb.gouv.fr

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Abstract

1. Sustainable harvest of wildlife is a major food security and conservation issue. In Africa, where wildlife is harvested mainly for subsistence, this remains a challenge. In this study, using waterbirds as model for natural resources, we assessed the sustainability of harvest through fishing bycatch on Lake Fitri (Chad).
2. We estimated the abundance of 24 target taxa through aerial distance sampling over four consecutive years (2018–2021) and in parallel estimated the number of birds harvested through interviews of a sample of 105 out of approximately 5500 fishermen.
3. By modelling their potential excess growth, we found a high risk of overexploitation for four species, including the world-threatened Black Crowned Crane *Balearica pavonina*, likely due to an influx of fishermen to Lake Fitri fleeing the Boko Haram security crisis.
4. *Synthesis and applications*: This work is likely the first quantitative approach of bird harvest sustainability in Africa. It should contribute to fill a methodological and an information gap in the strategic planification of several multilateral environmental agreements like the African-Eurasian Waterbird Agreement and the Ramsar Convention. In particular, this work could help implementing adaptive management of natural resources (including birds) in Ramsar site management

plans. African wetlands such as Lake Fitri may not be able to provide enough natural resources in the medium term for movements of displaced civilians forced by armed conflict into such biodiversity strongholds.

KEYWORDS
aerial survey, bushmeat, demographic invariant method, fishing bycatch, harvest sustainability, multi-covariate distance sampling, security crisis, waterbirds

1 | INTRODUCTION

Causes of global biodiversity loss have been widely described in recent decades (Pimm & Raven, 2000) and are strongly linked to the intensification of human activities (Swanson, 1998). Destruction and degradation of natural habitats, overexploitation of natural resources (fish, game or wood), pollution, climate change and the introduction of invasive species are the main threats affecting ecosystems and species in all regions of the world (Singh, 2002). Overexploitation may affect up to 6241 species globally, of which more than 2700 through hunting or fishing (Maxwell et al., 2016). As food security remains a daily challenge in many areas of the world, including Africa (Madsen et al., 2015), subsistence harvesting is still widely practised. Due to often rapidly growing human populations, these activities could potentially put exploited species at risk of extinction (Bennett et al., 2006).

Bushmeat represents a major source of protein for many local communities in the tropics and the Arctic, and its economic value is estimated in billions of euros (Milner-Gulland & Bennett, 2003), yet its consumption is hardly considered in food policy (Chardonnet et al., 1995). Contrary to mammal bushmeat, avian bushmeat remains little investigated despite widespread exploitation in several regions of Africa. From the Inner Niger Delta in Mali to Lake Chilwa in Malawi, few hunting practices on migratory waterbird communities have been documented (Bhima, 2006; Van Zegeren & Wilson, 1999). Most of the harvest is used as a source of food for local communities, especially fishermen, but can also be traded (Deniau et al., 2022; Kone et al., 2002, 2007).

The management of exploited populations of migratory species represents a particular challenge (Madsen et al., 2015). Monitoring and modelling the effects of harvesting activities allow the sustainability of species exploitation to be assessed, necessary for adaptive resource management. However, this approach to ensure sustainable migratory waterbird offtake is seldom applied outside North America, where adaptive management of waterbird harvesting has been implemented since 1995 (Williams & Johnson, 1995), and only recently in Europe (Madsen et al., 2017) under the auspices of the Agreement on the Conservation of African-Eurasian Migratory Waterbirds (UNEP/AEWA Secretariat, 2022a).

Several Afro-Palearctic migratory bird populations have declined along their flyways through Europe and Africa in recent decades (Sanderson et al., 2006; Wetlands International, 2021). This is particularly the case for species wintering mainly in the arid Sahelian zone (Vickery et al., 2014). The main factors for this decline may be anthropogenic alteration of habitats (e.g. drainage of wetlands for irrigation and conversion of habitats) and climatic conditions, in particular the 1970–1991 drought experienced in the region (Zwarts et al., 2012). Overexploitation may also play a role, but its putative impact on the conservation of migratory birds is still largely unknown (Vickery et al., 2014).

This study was carried out in the context of the RESSOURCE project ('Strengthening Expertise in Sub-Saharan Africa on Birds and their Rational Use for Communities and their Environment' coordinated by the United Nations Food and Agriculture Organization). It is one of the first quantified assessments of the sustainability of natural resource exploitation in the context of the Sahelian crisis, developed through the example of the waterbirds in Lake Fitri, a major Sahelian wetland in central Chad. Lake Fitri is representative of the ecological and socio-economic contexts of typical wetlands in the Sahel (Raimond et al., 2019). A productive ecosystem, Lake Fitri, provides local communities with several natural resources (fish, pastures, flood-based agriculture and wood). However, several recent socio-economic changes (population increase and immigration, introduction of new exploitation techniques and increased exportation facilities) have aggravated the tensions around resource sharing. In particular, a large number of fishermen have emigrated from Lake Chad to Lake Fitri due mainly to the security crisis caused by the Boko Haram terrorist organization (Magrin & Pérouse de Montclos, 2018). This has contributed to increase the number of fishermen on Lake Fitri by a factor of 10 compared with the early 2000s, threatening the long-term sustainability of natural resources harvest (Kanu et al., 2019; Raimond et al., 2019).

While there were several aerial surveys of waterbirds in Chad from the 1980s to 2008 (Jarry & Roux, 1987; Trolliet et al., 2008), its biodiversity remains little known (Brugière & Scholte, 2013). In particular, assessment of the numbers of harvested Black-Crowned Cranes *Balearica pavonina* and black-tailed godwits *Limosa limosa*, classified respectively as 'Vulnerable' and 'Near Threatened' by the IUCN (BirdLife International, 2023), are considered a priority for conservation.

In order to determine the sustainability of waterbird offtake in Lake Fitri, an estimate of their abundance was obtained through recent aerial distance sampling (DS) in parallel with an estimate of the catch, based on interviews with fishermen. Both estimates were then integrated into a population dynamics model that was subsequently used to assess the impact of displaced fishermen movements from the Lake Chad conflict area.

2 | MATERIALS AND METHODS

2.1 | Study area

Located in the heart of the Chadian Sahel, in the Batha region, Lake Fitri (12°50′ N; 17°30′ E; Figure 1) is considered as a 'Lake Chad in miniature' (Raimond et al., 2019). The number of waterbirds monitored is highly heterogeneous and depends on flooding and census methods (minimum 3740 waterbirds in 1970, maximum 327,762 in 1999). Designated a Ramsar site in 1990, notably for its waterbird diversity, the water covers a mean surface area of 800 km^2.

2.2 | Modelling approach

Lake Fitri is one of the most important Sahelian wetlands for both Afrotropic and Palearctic waterbirds. It is largely used as a staging area where waterbird populations stay for the whole non-breeding period (Zwarts et al., 2012), so we considered it an isolated management unit at the scale of the non-breeding period to conduct harvest sustainability modelling. In order to account for potential local waterbird movements due, for example, to decreased flooding or early migration departure, we replicated our aerial survey in March to provide two abundance point estimates. We then compared these two abundance points to two waterbird bycatch estimating options, resulting in four harvest sustainability modelling replicates. The first and second waterbird aerial counts are referred to as C1 and C2, and H1, H2, and H3 refer to the overall harvest estimated before C1, between C1 and C2, and after C2 respectively. The four corresponding harvest sustainability models were fed with the following inputs:

- **H1 + C1** versus **H1 + H2 + H3**: respectively, the total number of waterbirds assumed to be present in Fitri at the beginning of the fishing season and the total waterbird catch over the entire fishing season.
- **C1** versus **H2 + H3**: respectively, the number of waterbirds present in Fitri at the date of the first aerial count (08/02) and the catch from this date until the end of the fishing season.
- **H1 + H2 + C2** versus **H1 + H2 + H3**: respectively, the total number of waterbirds assumed to be present in Fitri at the beginning of the fishing season and the total waterbird catch over the entire fishing season.
- **C2** versus **H3**: respectively, the number of waterbirds present in Fitri at the date of the second aerial count (16/03) and the catch from this date until the end of the fishing season.

Standard deviations for the population and catch totals were computed by error propagation based on standard deviations of each added component.

2.3 | Estimates of dry season waterbird numbers in Lake Fitri

Following a ground survey over most of the lake in 2018 to inventory the bird community, aerial surveys were conducted every mid-winter from 2018 to 2021 as well as in March 2021 to sample the entire study area and estimate waterbird abundance from DS models. The additional aerial survey conducted in mid-March 2021 aimed at improving adequacy with the concomitant bycatch survey, allowing for a replicated estimate of its sustainability. We opted for a systematic

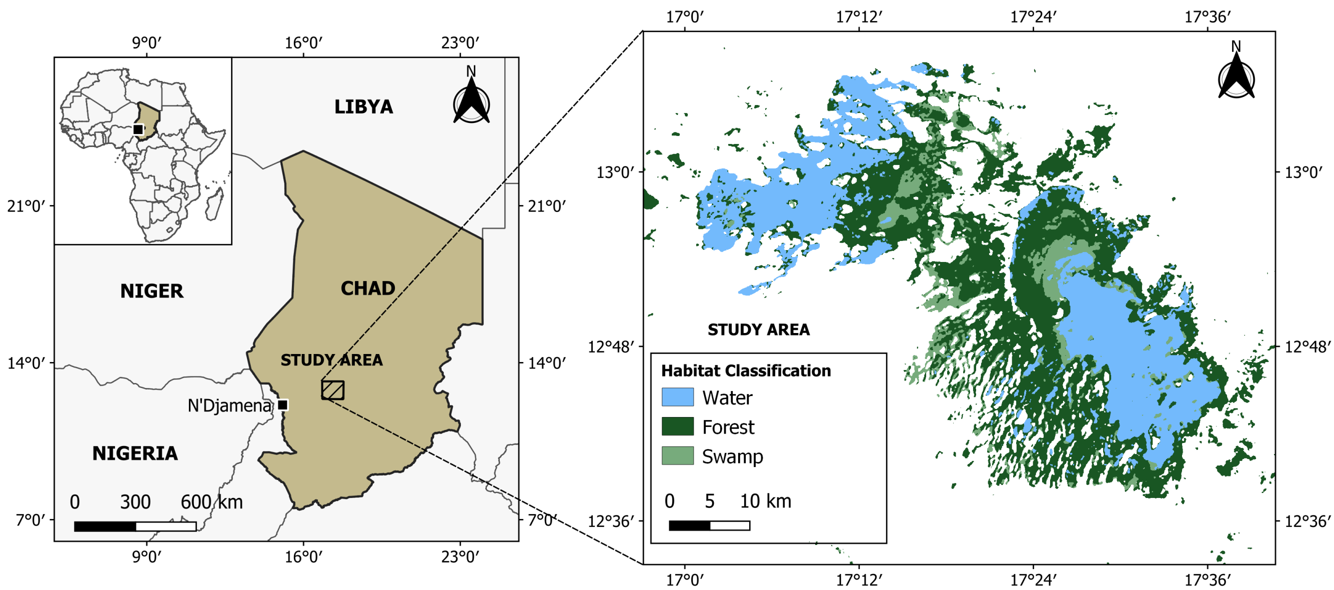

FIGURE 1 Location of the study area (for more details, see Appendix A: 'Habitat classification method').

'zigzag adjusted angle' design (Strindberg & Buckland, 2004) to ensure an equal probability of sampling coverage of the irregular study area and to minimize costly flights between transects. The aircraft flew every transect at 90 m above ground level with one observer on each side of the aircraft. The area along the transects was divided into four parallel bands (0–80, 80–180, 180–380 and 380–780 m, respectively), materialized by window markings aligned to rods positioned on the wing struts. Using digital audio recorders, the observers recorded the species name and count as well as the distance band (A–D). The time, date and exact location were recorded by GPS to which the audio recorder was synchronized. In addition to the distance category, we used the following detection covariates: individual observer, year, month, flight duration, remote-sensed habitat (Appendix A), sampling strata, animal cluster size and general appearance of the waterbird (Appendix B). Estimates of waterbird abundance were modelled using the 'distance' R package (v.1.0.3; Miller et al., 2019). Methodology for waterbird abundance estimation is further detailed in appendices B and C as well as in Ducros et al. (2023).

2.4 | Waterbird bycatch estimation for the sustainability assessment

2.4.1 | Data collection

Field survey

In order to assess the sustainability of waterbird harvesting, we estimated the total species-specific waterbird catch for Lake Fitri and compared it to the corresponding population size estimates using the demographic invariant method (Niel & Lebreton, 2005).

We identified fishermen, both local and from other regions of Chad or other countries, as the main wetland users likely to regularly catch waterbirds (primarily as bycatch) during the fishing period in the dry season. Shooting is prohibited and strictly controlled, especially in the dry season when it is easier for law enforcement officers to move around the area. Fishing is mainly carried out on Lake Fitri during the dry season from November to June, when the birds also concentrate on the lake as the peripheral wetlands dry up.

We sampled fishermen's camps over most of the shores and main islands of the lake during the 2021 dry season so that our sampling scheme would target every regions of the lake (Appendix D). Two sets of interviews (Appendix E) of individual fishermen were conducted between January and March 2021 by a multidisciplinary team (anthropologist, fishing and hunting specialists, and biologists). In the first set of interviews, 96 individual hunting bags were collected, and in the second set, 105 bags were collected, of which 91% were respondents from the first set.

The data collected included number of birds taken by species, by fisherman and by unit of time, and the time spent fishing, hence potentially bycatching/collecting waterbirds. During the first interview session, fishermen were asked to recall their species-specific waterbird catch from the preceding week and month by memory. To that end, a simple illustrated logbook was specially produced to help identify and record the 10 most caught waterbird species, and was provided and explained to each respondent. Several bird identification guides were also provided to each settlement and the study objective was explained to the respondents, local authorities and representatives.

Following the first interview, respondents were asked to record their future bird bycatches directly in the logbook in order to limit the bias linked to memory for the second interview. During the following field session, we aimed to meet the same respondents again in the field, and their waterbird bycatch per time unit was recorded directly from their logbooks. We received verbal consent from all interviewed participants and they were free to withdraw at any time. Consents were verbal rather than written as participants could not write and/or originated from different ethnic groups hence speaking different languages.

Estimation of the number of fishermen on Lake Fitri

The local fisheries administration regularly monitors the number of fishing licences. In addition, a special survey of fishing camps was conducted by this administration in 2021 for the purpose of this study, but its precision is unknown as the fishermen constantly move between the lake and other activities, notably agriculture. However, on the basis of fisheries monitoring around the lake, the mean number of fishermen was estimated as the mean (with its associated standard deviation) of uniform distributions with the following parameters: between 2000 and 4000 fishermen in November and December, between 4000 and 6000 in January and February, and between 1000 and 3000 in May and June (Table 1; Dagou et al., 2005; Raimond et al., 2019).

The number of fishermen in March and April 2021 was further corroborated by estimating the number of individual pirogues on the lake by aerial DS.

The estimate μ of the species-specific total waterbird catch per fishing period was obtained by multiplying the mean individual weekly bycatch by the number of fishermen (with their respective associated standard deviations σ and σ') and the number of weeks for each fishing period (H1: the period between the start of fishing and the first aerial survey; H2: the period between the first and second aerial survey; H3: the period between the second aerial survey and the end of fishing; Table 1). The standard deviation for μ was computed by error propagation (Crowder et al., 2020) based on standard deviations σ and σ' of mean individual catch and fisherman population size respectively.

No ethics or fieldwork approval was required for this study.

2.4.2 | Assessing harvest sustainability

We assessed harvest sustainability (Figure 2) for eight waterbird species selected according to their observed bycatch frequency or their conservation status using the demographic invariant method and supported by the 'popharvest' package (Eraud

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TABLE 1 Summary of the different fishing periods with the corresponding number of fishermen and duration in weeks (most of the estimates for the number of fishermen were simulated using a uniform U (min, max) distribution; *see Section 'Estimation of the number of fishermen on Lake Fitri'; **Afrotropical species only).

Fishing period	Number of fishermen	Number of fishing weeks	Fishing period code	
November–December	U(2000–4000)	8	H1*a*	H1
January–8 February *1st aerial survey: 8 February*	U(4000–6000)	5	H1*b*	
8 February–1 March	U(4000–6000)	3	H2*a*	H2
1 March–16 March *2nd aerial survey: 16 March*	2940 (+/– 822) *	2	H2*b*	
16 March–April	2940 (+/– 822) *	6	H3*a*	H3
May–June **	U(1000–3000)	8	H3*b*	

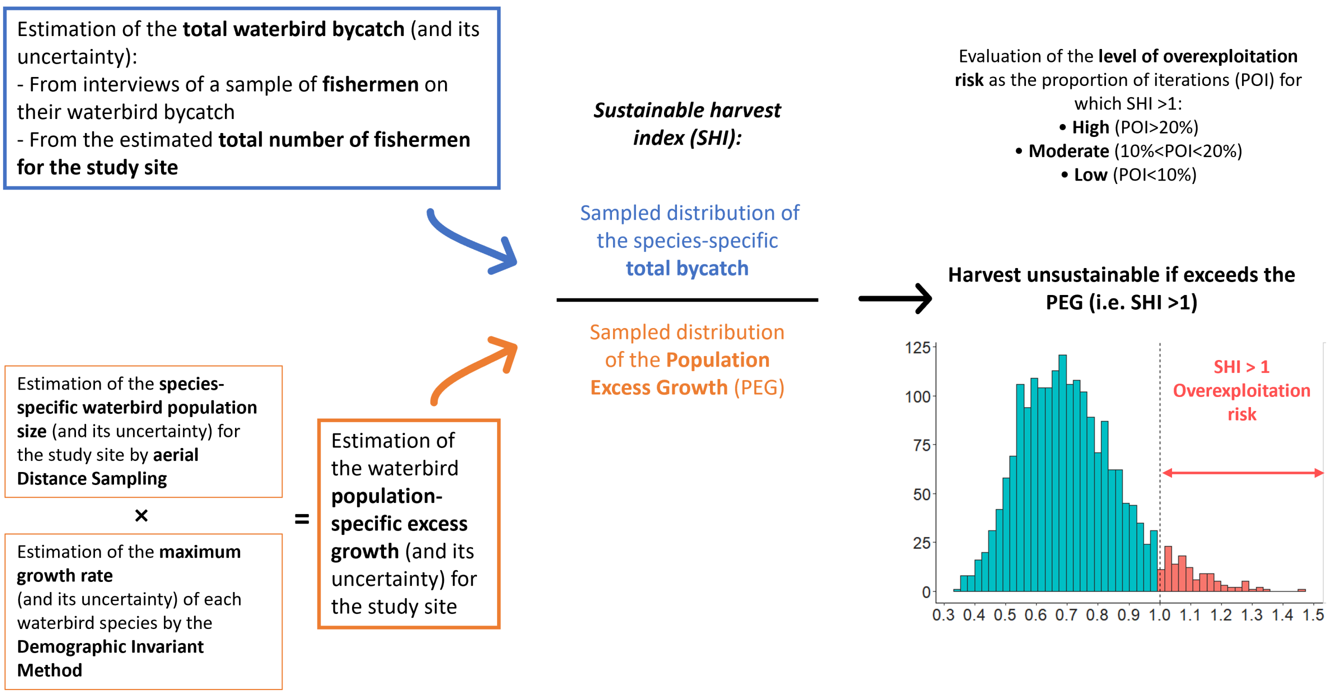


FIGURE 2 Summary of the popharvest approach (Eraud et al., 2021) to assess harvest unsustainability of waterbird bycatch in lake Fitri.

et al., 2021). This recent modelling tool diagnoses harvest unsustainability by comparing the estimated distribution of the total harvest exerted on a given population to the distribution of its potential excess growth (PEG). PEG is estimated as $N(\lambda max-1)F$ (Niel & Lebreton, 2005), that is the maximum number of individuals that can be potentially removed annually from a population of size N given its maximum growth rate (λmax) without putting it at risk of decline. To further minimize the risk of decline, F is used as a safety parameter comprised between 0 and 1, aiming at integrating either density dependence or a precautionary conservation approach (Eraud et al., 2021). We computed a sustainable harvest index (SHI) as the ratio of the sampled distribution of the species-specific total harvest for Fitri divided by the sampled distribution of the PEG of the corresponding species. The maximum annual growth rate λmax can be approximated with the demographic invariant method, only using survival rate and age at first reproduction (Niel & Lebreton, 2005). As recommended by Eraud et al. (2021), population size, survival rate, age at first reproduction and harvest level were sampled using 2000 Monte Carlo simulations from their observed, estimated or reported (Bird et al., 2020) probability distribution (log-normal for population size and harvest level, uniform for age at first reproduction and beta for survival rate). Both survival rate and age at first breeding are summarized in Appendix F.

A harvest was considered unsustainable if it exceeded the PEG (i.e. SHI >1) and was rated by the proportion of iterations (POI) for which SHI >1 over 2000 Monte Carlo simulations. As recommended by Eraud et al. (2021), we considered three levels of overexploitation risk: high (POI > 20%), moderate (10 < POI < 20%) and low (POI < 10%).

2.4.3 | Sensitivity analyses

In order to investigate how uncertainty in PEG and SHI estimates can be attributed to uncertainty in the demographic parameter estimates input into the model, we ran sensitivity analyses on four highly captured species: Spur-winged Goose *Plectropterus gambensis*, White-faced Whistling Duck *Dendrocygna viduata*, Sacred Ibis *Threskiornis aethiopicus* and Black Crowned Crane. We simulated a 10% variation in four demographic parameters (bird population size, age at first reproduction, harvest size and adult survival rate). Distributions of PEG and SHI submitted to a 10% variation in one input parameter at a time were sampled by 100 random draws from the initial and modified input parameter distributions.

2.4.4 | Assessment of the indirect impact of the security crisis on fishing activity on Lake Fitri

To assess the impact of the current immigration of fishermen fleeing Lake Chad on the current level of waterbird catch in Lake Fitri, we re-ran our exploitation models using numbers of fishermen based on historical estimates before the start of the security crisis in 2012. These historical estimates were 500–550 fishermen over the whole fishing period from November to June, except January and February when it reached 620–700 fishermen (CIMA et SOGEC International, 2002). The historical numbers of fishermen were simulated under a uniform *U*(min, max) distribution. The PEG, SHI and POI were estimated using the same values for the other parameters as in the first analysis for the three highly captured species: Spur-winged Goose, White-faced Whistling Duck and Sacred Ibis. The SHI distributions before and during the crisis were compared by chi-squared tests.

We conducted our analyses with the software R (R 5.3.2; R Core Team, 2018).

3 | RESULTS

3.1 | Estimates of dry season waterbird abundance in Lake Fitri

DS models provided abundance estimates for 24 species/species groups for Lake Fitri in the dry season (Appendix G). For most species, a large number of detections and a reasonably low CV (coefficient of variation) were obtained. In only one species, Black-tailed Godwit, which had only 12 detections, were the estimates considered too imprecise to be used for harvest sustainability assessment despite being pooled with its relative (Ruff *Calidris pugnax*) and sharing the same AIC-selected detection function. All DS models showed satisfactory fit (all GOF test $p(\chi^2) > 0.1$).

We estimated a large number of Palaearctic Anatidae in the study area, mostly Garganey *Spatula querquedula*, with 77,922 ± 35,397 and 130,144 ± 73,537 individuals for January–February 2018–21 (overall) and March 2021 respectively.

As expected, due to the sample size deficit in March, abundance estimates are less precise for this month than for the January–February estimates for most species. Abundance estimates for some species or species groups appear to be accurately estimated for January–February 2018–21 (e.g. Sacred Ibis: CV = 0.1), but others, such as Larus spp. (CV = 0.62), have high uncertainty. The total waterbird estimate of 703,514 (±77,272) for January–February over 2018–21 and 683,893 (±93,096) for March 2021 appears consistent throughout the dry season, with a satisfactory coefficient of variation for both periods: 0.11 and 0.14, respectively (Appendix G).

3.2 | Sustainability of waterbird harvest in Lake Fitri

By extrapolating weekly avian catch levels declared by interviewed fishermen to the total population of fishermen and the whole fishing season, we estimated a season total catch per species: for example 1979 (SD = 366) black-crowned cranes and 19,359 (SD = 1767) spur-winged geese (Appendix H). Although some interviewed fishermen declared they threw away some of their captured waterbirds as they were not slaughtered ritually, a large majority of by-caught waterbirds were declared to have been consumed or sold as bushmeat.

For the estimation of the number of fishermen in March and April based on the aerial DS of pirogues, the most supported model was a key hazard rate function (GOF test: $p(\chi^2) = 0.51$) and included the habitat covariate. This model estimated the total number of pirogues—hence fishermen—on Lake Fitri as 2940 (SE = 812.8; CV = 28%), which is in line with both the literature and fisheries administration estimates.

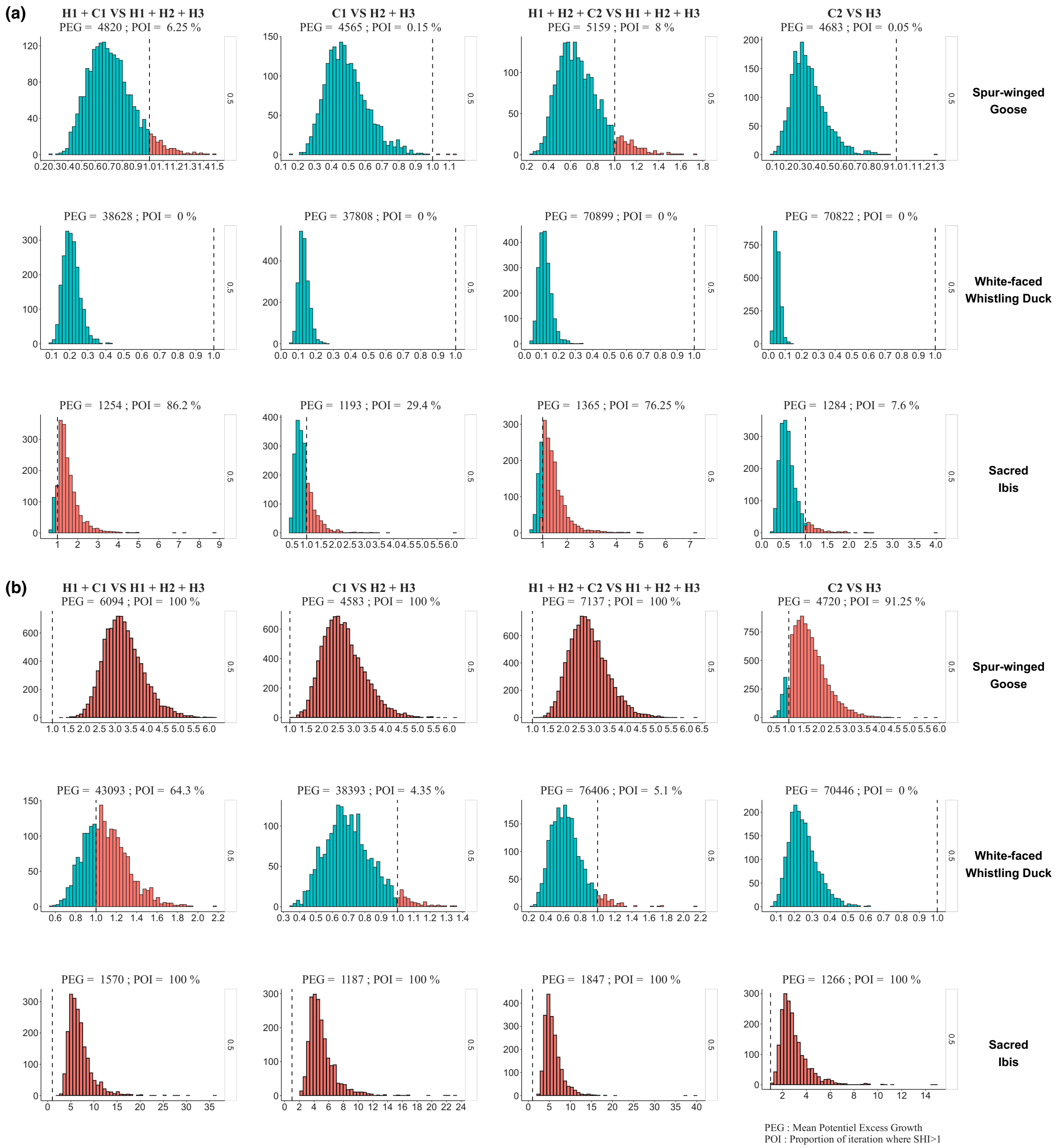


FIGURE 3 Distributions of estimated sustainable harvest index (SHI) for three harvested waterbird species in Lake Fitri under pre-security crisis conditions, that is with the past population of fishermen (a) and in 2021 (b) for Spur-winged Goose (top), White-faced Whistling Duck (middle) and Sacred Ibis (bottom). The *x*- and *y*-axes are respectively the sustainable harvest index and the number of simulations. (PEG: mean potential excess growth; POI >1: proportion of SHI iteration>1).

Mean estimated PEG ($\widehat{PEG}$) and distributions of SHI (Figure 3b and Appendix I) suggest that the bycatch of four out of the eight assessed species would not be sustainable for any of the four sampled periods: Spur-winged Goose, Sacred Ibis, Black Crowned Crane and pelicans Pelecanus spp. In contrast, bycatch does potentially not appear to be unsustainable for two species: Garganey and Ruff. For both these species, none of the 2000 simulations generated a SHI above 1 in any of the four sampled periods. However, without knowledge of other potential sources of non-natural mortality, a SHI below 1 is not definitive proof of sustainability (Eraud et al., 2021; Niel & Lebreton, 2005).

For White-faced Whistling Duck, one bycatch sampling period indicated a strong risk of overexploitation, while the three others indicated a low risk. For Spur-winged Goose and Sacred Ibis, all bycatch sampling periods indicated a high risk of overexploitation (Figure 3b and Appendix I).

3.3 | Sensitivity analyses of harvesting sustainability models

Sensitivity tests of the harvest sustainability models for Sacred Ibis and Black Crowned Crane revealed a strong impact of variation in survival rate or inaccuracy in its estimation on PEG and SHI (Figure 4). For Spur-winged Goose and White-faced Whistling Duck, variation in abundance and harvest or inaccuracy in their estimates showed the strongest impact on harvest sustainability assessment.

3.4 | Assessment of the indirect impact of the security crisis on fishing activity on Lake Fitri

Harvest sustainability models based on the pre-crisis historical population of fishermen showed a high risk of overexploitation only for Sacred Ibis (Figure 3a). We found that the former population size of fishermen would have generated a significantly different distribution of SHI than the current situation, with a lower risk of overexploitation for White-faced Whistling Duck ($\chi^2 = 5{,}734{,}045$, $p < 0.001$), Sacred Ibis ($\chi^2 = 133{,}383$, $p < 0.001$) and Spur-winged Goose ($\chi^2 = 275{,}091$, $p < 0.001$).

4 | DISCUSSION

The present work provides possibly the first quantitative insight into the sustainability of subsistence harvesting of waterbirds in Africa. Our results show a high risk of overexploitation for four of the eight studied taxa: Spur-winged Goose, Sacred Ibis, Black Crowned Crane and pelicans. Currently, exploitation does provisionally not appear unsustainable for three species: Garganey, Knob-billed Duck *Sarkidiornis melanotos* and Ruff, although this should be confirmed. For the remaining species White-faced Whistling Duck, sustainability remains uncertain depending on the harvest sampling period assessed. While quantitative studies on waterbird harvesting sustainability are recurrent in Europe (Madsen et al., 2015) and North America (Koneff et al., 2017), they remain extremely seldom or virtually unknown in Africa. As shown by, for example, Benítez-López et al. (2017), larger-bodied species seem to be more impacted by overhunting than smaller-bodied species, likely because they provide more bushmeat per capture event.

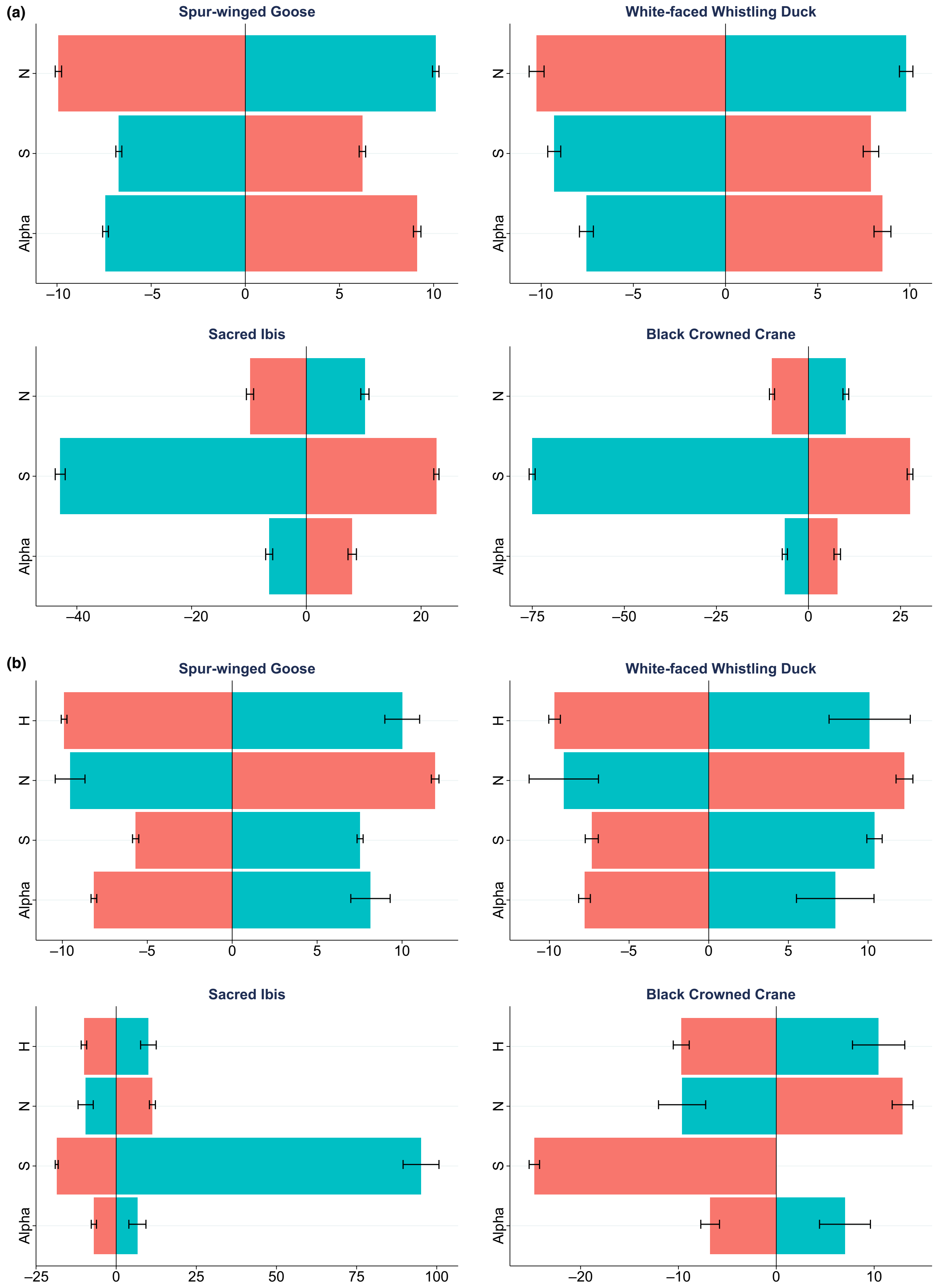
The systematic aerial surveys and DS methodology used are firsts in this major Sahelian wetland and probably in waterbird surveys in the Sahel, strengthening inference of the abundance estimations. These estimates for Fitri are more than five times higher than the most recent total count (2008) for Spur-winged Goose (Trolliet et al., 2008) and almost double the total count (in 2000) for White-faced Whistling Duck (Appendix J).

As they correct for detection bias, DS abundance estimates are generally larger than corresponding total counts based on non-corrected conventional surveys (Buckland et al., 2001). Therefore, it is difficult to conclude whether the increasing abundance trends in all but one (Garganey) of our eight study species (Appendix J) are due to detectability bias correction or to a genuine increase in abundance in the study area. These positive trends should thus be interpreted with caution, but suggest that these species may not be in decline at this wintering site, which is also supported by our maximum observed annual sample being the same order of magnitude as most of the previous total counts for most species (Appendix J).

Among the basic assumptions of DS methodology, perfect detection of objects at zero distance is central (Buckland et al., 2001). To ensure maximum detection in the closest distance band, aerial observers were all experienced professional ornithologists with previous practice in waterbird aerial surveys and Sahelian wildlife. These ornithologists were all required to primarily focus on detecting all target species in the closest distance band, thus ensuring that the assumption of maximum detection at zero distance was met. However, the fact that ‘observer identity’ was found to be one of the most influential drivers of species-specific detection in our data suggests that there is still room for improvement in our data collection protocol. This observation bias could be caused, for example by individual observer fatigue, or occasional very large number of species that may lead to an underestimation in abundance estimates. We recommend that mark–recapture distance sampling be carried out in the future to control for this possible ‘observer’ bias (Burt et al., 2014), although this was not possible in our study for logistical and economic reasons.

Nonetheless, our updated abundance estimates highlight the importance of Lake Fitri for some of our study species. According to Wetlands International (2021) and Ramsar 1% threshold, this wetland hosts 25% of the West African population of White-faced Whistling Duck, 36% of Egyptian Goose *Alopochen aegyptiaca*, 33% of Spur-winged Goose and up to 148% of Knob-billed Duck. Such figures make Lake Fitri one of the five most important known Sahelian wetlands (Zwarts et al., 2012) and highlight the need for increased sampling efforts in the International Waterbird Census in Africa.

FIGURE 4 Sensitivity of the PEG (mean potential excess growth, above: a) and SHI (sustainable harvest index, below: b) to a negative (red) and positive (blue) 10% variation in the four demographic parameters for four species: Spur-winged Goose, White-faced Whistling Duck, Sacred Ibis and Black Crowned Crane (s: survival rate; α: age of first reproduction; N: abundance; H: harvest size; harvest sampling used for this sensitivity analysis: H1 + C1 vs. H1 + H2 + H3).


(a)
Spur-winged Goose
White-faced Whistling Duck
Sacred Ibis
Black Crowned Crane
(b)
Spur-winged Goose
White-faced Whistling Duck
Sacred Ibis
Black Crowned Crane
N
S
Alpha
H

The case of the Black Crowned Crane, classified as 'Vulnerable' by the IUCN, is particularly worrying. The estimated population size at Lake Fitri of 1947 individuals (±699) in January–February 2018–21 (Appendix G) can obviously not support a seasonal catch estimated at 1979 individuals (±366) (Appendix H), well above the maximum sustainable harvest level ($\widehat{PEG}=24$ individuals [9–49]). This finding is all the more alarming as this species declined more than 50% between 1984 and 2015 (Wetlands International, 2021). The factors for this are multiple and may still apply in the current context of Lake Fitri: wetland drainage, harvesting of adult birds for food and trade, and indirect disturbances due to bush fires and fishing activities (Williams et al., 2003).

Conversely, no risk of local overexploitation was provisionally detected for Garganey. Its current estimated harvesting level seems to be well below the number of acceptable removals, with only 3900 individuals estimated to be harvested yearly (±665) compared with a $\widehat{PEG}$ of 41,971 individuals (Appendix I). Black-tailed Godwit ('Near Threatened') shows considerable uncertainty in its abundance and harvest estimates; we advocate for an increased monitoring effort of this species in the Sahel.

Harvest sustainability of the long-tailed Cormorant (*Microcarbo africanus*) was not assessed because this diving species population cannot be properly estimated from aircraft. However, it is the most heavily harvested species (Appendix H). There is thus an urgent need to improve its monitoring: for example by surveying nesting colonies or roosting sites.

The sensitivity analysis of harvest sustainability models shows that, for both Sacred Ibis and Black Crowned Crane, variation or uncertainty in most input parameters such as age at first reproduction, population or harvest size had a relatively marginal impact on sustainability model outputs compared with survival rate. To enhance models of harvest sustainability, we strongly recommend improving survival rate estimations for those little-studied species of both conservation and exploitation concern. We also recommend improving the accuracy of abundance and harvest estimations, particularly for Spur-winged Goose and White-faced Whistling Duck.

Uncertainty in the estimation of the number of fishermen would also require an increased survey effort in time and space in relation to the fishing period. Aerial surveys of the number of pirogues (as carried out in March) could potentially be a more reliable and convenient index of the fishing population at a given period, but would require further calibration.

By using the historical number of fishermen before the security crisis in 2012, we were able to simulate past harvesting levels and thus sustainability for three species. Whereas in the past harvesting of White-faced Whistling Duck and Sacred Ibis would not have been predicted to be unsustainable, this is unlikely to be the case today with the sudden increase in fishing activity. The current harvesting unsustainability of these two species could be associated with the large influx of people fleeing from the conflict area around Lake Chad. Although pre-crisis waterbird abundance used to simulate this came from our abundance estimates obtained between 2018 and 2021, we assume they had been approximately similar since 2012, when the largest human migration started. We argue that this increasing fishing activity may potentially have switched a sustainable bycatch regime to an unsustainable one for at least some waterbird species. In other words, the Lake Fitri ecosystem likely used to be able to accommodate traditional resource use in a sustainable way, at least for waterbirds, but the sudden human population influx is now making this unsustainable. In line with this, other natural resources of Lake Fitri, such as fish stocks or wood, may also be potentially suffering from unsustainable exploitation since the security crisis. Should the influx of fishermen into Lake Fitri persist, the concerted design and establishment of a protected core area to be excluded from exploitation might be a recommended option.

Local authorities and community representatives who met during the field surveys were all aware of this resource issue. They have called for further monitoring in order to design a legal, rational and controlled community-based system of natural resource use, including the subsistence harvest of the most common waterbird species. Rational planning of activities over some or all of the Fitri ecosystem could help to allow some waterbird populations to be sustainably exploited again.

This work contributes to fill a long-standing knowledge gap (UNEP/AEWA Secretariat, 2022b) by proposing a tested methodological framework and providing a long-awaited example of quantified harvest unsustainability for bird resources in major wetlands. It fits into the strategic planification of several multilateral environmental agreements like the Strategic Plan 2019–2027 of the African-Eurasian Waterbird Agreement (UNEP/AEWA Secretariat, 2018) and the 4th Strategic Plan 2016–2024 of the Ramsar Convention (Secretariat of the Ramsar convention, 2022). In particular, this work could help implementing adaptive management of bushmeat resources (including birds) into Ramsar site management plans.

The Sahelian socio-economic context—for example the bushmeat crisis (Van Velden et al., 2018) and population growth (Shekar et al., 2016)—and the uncertainties in key demographic parameter estimates for our study species make it challenging to formulate clear, straightforward conservation recommendations for potentially overexploited species. Nevertheless, this study provides the first methodological framework for quantitative assessment of the sustainability of waterbird subsistence hunting and fishery bycatch in a vast wetland of international importance such as Lake Fitri. This study further suggests that certain species are negatively affected by these activities, which are cryptic but widespread practices in African rural communities. Mammals are the wildlife group most affected by armed conflicts (Gaynor et al., 2016) and in Sahel indeed, only large mammals were known to be threatened by armed conflicts (Brito et al., 2018). This work shows that a much larger array of wildlife species is indirectly threatened by the Lake Chad armed conflict through the displacements of civilians. Although largely suspected to impact nature through bushmeat exploitation (IUCN, 2021), movements of displaced civilians due to armed conflicts were seldom demonstrated to affect birdlife in an unsustainable way (Gaynor et al., 2016; IUCN, 2021). Armed conflicts being more concentrated in Africa relatively to other continents (IUCN, 2021), we strongly recommend scientific cooperation with local and international stakeholders to support integrated monitoring of natural resources of African wetlands including waterbird species, particularly those subject to subsistence hunting or with unfavourable conservation status. This is all the more important given the fast-changing context in the Sahel in terms of civilian movements (exacerbated by local security crises), food crises, wetland reclamation for agriculture or water, climate change, etc. These factors are increasing the pressure on wetland natural resources (Raimond et al., 2019) and need to be addressed in an inclusive way to avoid potential conflicts between users.

AUTHOR CONTRIBUTIONS

Jean-Yves Mondain-Monval, Pierre Defos du Rau, Abakar Saleh Wachoum, Maxime Rotoudjimbaye Betoloum, Bruno Portier, Audrey Mbagogo Koumbraït and Sébastien Le Bel conceived the ideas and methodology. Abakar Saleh Wachoum, Pierre Defos du Rau, Jean-Yves Mondain-Monval, Maxime Rotoudjimbaye Betoloum, Julien Birard, M'Baïti Narcisse Djimasngar, Yves Kayser, Ib Krag Petersen, Jaime Dias, Mahamat Adoum Wachoum, Nicolas Carenton, Marie Suet and Clémence Deschamps collected the data. Nicolas Carenton, Pierre Defos du Rau, Delphine Ducros, Jean-Yves Mondain-Monval, Marie Suet and Clémence Deschamps analysed the data. Nicolas Carenton, Pierre Defos du Rau and Jean-Yves Mondain-Monval 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 are available from the OFB Digital Repository https://ged.ofb.fr/share/s/XiFQtejFQy28DG6u0TDzoA/folder (Carenton et al., 2024).

ORCID

Pierre Defos du Rau https://orcid.org/0000-0002-8876-8529
Delphine Ducros https://orcid.org/0000-0002-3227-7085

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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 A. Habitat classification method.

Appendix B. A priori hypothesis, description, and method of extraction of detection covariates used in the DS models.

Appendix C. Estimates of dry season waterbird numbers in Lake Fitri.

Appendix D. Sampling of fishing camps—March 2021.

Appendix E. interview questions asked to residents of lake Fitri by Abakar Saleh Wachoum, Maxime Rotoudjimbaye Betoloum, Pierre Defos du Rau & Jean-Yves Mondain-Monval.

Appendix F. Mean age at first breeding (α), survival rate (s) and life history strategy for the studied waterbird species.

Appendix G. Distance sampling abundance estimates and associated coefficients of variation (CV) for 24 waterbird taxa in Lake Fitri in January–February 2018–2021 and March 2021.

Appendix H. Harvest estimates for the three harvest periods of 2020-2021 (H1, H2 & H3) for the nine waterbird species studied (plus two species groups).

Appendix I. Summary of harvest sustainability analyses for the eight waterbird species studied.

Appendix J. Estimated mid-winter abundance of eight waterbird species on Lake Fitri between 1984 and 2021 (total counts between 1984 and 2008; one Distance Sampling estimate produced from pooled yearly surveys from 2018 to 2021 and our maximum observed annual Distance Sampling sample).

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