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Long-term changes in population size and the age-structure and sex-ratio of Waterbuck in a Sudanian savannah of Burkina Faso

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Abstract The waterbuck (*Kobus ellipsiprymnus*), though widespread throughout Africa, is suspected to be declining overall. Data on population numbers and structure are lacking for many parts of its range, especially in West Africa, where the subspecies *defassa* is found. The aim of the present study was to evaluate the abundance, distribution and attributes of waterbuck populations in the Nazinga Forest Reserve, southern Burkina Faso. We investigated waterbuck population trends in the park using transect data collected in 1985-2019. For the more detailed analyses of population structure and distribution of the animals we used census data gathered during 2019. Most animals were adults (46.6%), and the sex ratio was heavily skewed towards females (5:1). Most animals were concentrated along the larger rivers. There was no influence of poacher activity on waterbuck distribution. In the long term (1985-2019), the population dynamics of waterbuck can be roughly divided into two main periods: a phase of population increase from 1985 to 2005, and one of ongoing population collapse from 2007-2019 Although the declining population trend was obvious, coefficients of determination were low indicating that the years explained poorly the number of individuals and the number of sightings obtained. Waterbuck numbers in the Nazinga Forest Reserve are declining, but we found no single reason to explain this trend. It is likely that a combination of factors, including global warming (increased aridity) and illegal activities such as poaching, are responsible. Because there are probably multiple reasons for the observed waterbuck population decline in our study area, we suggest that a multifaceted approach should be adopted in order to enhance the conservation status of the local waterbuck populations.

Keywords *Kobus ellipsiprymnus defassa;* Bovidae; abundance; density; group size; sex ratio; age structure; ecology; West Africa

Introduction

The waterbuck (*Kobus ellipsiprymnus*) remains widespread across western, central, eastern and southern Africa, and occupies a range of habitats such as grassy savannah plains, and open woodland near permanent waterbodies (Nowak 1991). Waterbuck are also an important game species (e.g., Berry 1975; Cloete *et al*. 2007) but they are often poached. According to the IUCN Red List (IUCN 2020), the abundance of the species is suspected to be declining, but there is no evidence to confirm that the rate of decline meets the requirements for Near Threatened or Vulnerable status.

Although a number of studies on the ecology of the species has been published (e.g., Spinage 1968, 1969; Melton 1978, 1983; Tomlinson 1978; Kassa *et al*. 2008), reliable population estimates are scarce. This is especially true for waterbuck populations in the Sudanian savannahs of West Africa (subspecies *defassa;* Lorenzen *et al*. 2006), where the species is perceived to be declining (Chardonnet and Chardonnet 2004). Although some preliminary surveys have been undertaken on the population status of the species in Zakouma, Chad (Mackie 2004), Pendjari, Benin (Rouamba and Hi 2004), Gashaka Gumti, Nigeria (Nicholas 2004), and in Gambia (Jallow *et al*. 2004), few quantitative studies are currently available (i.e. in Benin: Kassa *et al*. 2008; Djagoun *et al*. 2013), and little is known of the population dynamics of any West African waterbuck population.

In Burkina Faso, where the waterbuck is found primarily in protected areas in the South of the country, some estimates data for the species (alongside other ungulates) are available for the gallery forests of the Comoé-Léraba region (Hema *et al*. 2017a) and the Nazinga region (Hema *et al*. 2018). In this study, we report abundance, density, group size, sex and age structure of waterbuck populations in the Nazinga Forest Reserve (FC/RGN). More specifically, we answer to the following key questions:

(1) Is the population structure of Burkina Faso waterbuck consistent with that studied elsewhere in Africa in terms of sex-ratio and age structure?

(2) Are the yearly density estimates of Burkina Faso waterbuck comparable with those observed in East Africa or, as expected on the basis of the widespread threatened status of West African ungulates, are they lower than in other regions of the continent?

(3) Is there any long-term consistent yearly trend (increasing, decreasing, stable) of waterbuck population in Burkina Faso?

Our results will serve to highlight the conservation needs of the species in West Africa, in the light of the extreme challenges that ungulates are currently facing in the West African savannahs due to extensive habitat loss and poaching (e.g. see Bouché *et al*. 2016).

Methods

Study area

The field study was carried out in the FC/RGN, a protected area, 97436 ha surface, in south-central Burkina Faso (West Africa) (Figure 1). The vegetation of the study area is Sudanian-type woody savannah vegetation dominated by *Detarium microcarpum, Burkea africana, Afzelia africana, Isoberlinia doka, Pteleopsis suberosa, Acacia dudgeoni, Gardenia* spp.*, Vitellaria paradoxa, Terminalia* spp. and *Combretum* spp. The dominant perennial herbaceous plants are *Andropogon ascinodis* and *Schizachyrium sanguineum*. The woody species of the alluvial valleys are *Anogeissus leiocarpus, Daniellia oliveri* and *Mitragyna inermis*, associated with *Andropogon gayanus* and *Vetiveria nigritana* as perennial herbaceous dominant of this type of environment (Dekker 1985; Yameogo 1999). Along the water bodies, relatively closed, "wet" habitats made up of gallery forests can be seen; this formation is dominated by large woody species such as *Anogeissus leiocarpus, Khaya senegalensis, Diospiros mespiliformis* and *Piliostigma thonningii*, and for the herbaceous layer by grasses such as *Andropogon gayanus* and *Pennisetum angustum*. Annual rainfall in the region of FC/RGN is about 1,500 mm.

In the study area there still exist large populations of ungulates (*Tragelaphus scriptus, Sylvicapra grymmia, Alcelaphus buselaphus, Hippotragus equines, Phacochoerus africanus*; cf. Hema et al., 2018) and *Loxodonta africana* (Hema et al., 2016), with *Crocuta crocuta* being the largest predator (Hema et al., 2019). Illegal poaching is present, especially in the boundary strips of the park (Hema et al., 2017c).

Data collection

Large mammal censuses in FC/RGN have been undertaken in the park since 1981 along 30 equidistant 1.4 km transects (Figure 1), during the months of February to early April. In 2019, we performed all transects during 19-25 March. Data collection protocols were first set up in 1981 (as occasional and somewhat unstandardized surveys) and revised by O'Donoghue (1985) after which standardized line transects were to be walked each year to obtain comparable estimates of the local abundance of animals. Sexes of adults were distinguished based on the presence/absence of horns (present in males). We defined juveniles those individuals that were less than 8 months old, subadults those between 8 months and 1.5 years old for females and between 8 months and 2 years old for males. We used relative size and the appearance of the horns in males to determine the relative age of the observed animals.

All transects were oriented in a South-North direction throughout the entire park. The entrance and exit to each transect was signposted using a numbered metal disc fixed on a tree at eye level. During each annual census, the same 79 transects (691.811 km) in the seven FC/RGN zones were covered during the dry season. The methodology employed was always identical: after a training session, transects were walked by 12 teams of three people each; each team consisting of a team leader and two observers (i.e. a villager and a tracker). We applied unlimited bandwidth linear transects (Burnham et al., 1980, Buckland et al., 1993, 2001).

During each annual census, teams walked along the centre of a transect, equipped with binoculars, GPS, compasses, rangefinders, maps, and cards on which to note the species, number of individual animals observed, their sex and age, as well as radial distance, viewing angle, activity and signs of illegal human activities (bullets, tree cutting, humant racks, motor-bike tracks, tree-branch thinning and pastoralism tracks). Animal observations were georeferenced using a Garmin 64S GPS, and compasses were used to measure angle with range finders to determine radial distances. All surveys started at 6am, immediately after which visibility conditions allowed the surveyors to clearly see the animals, even at a distance.

Data analysis

In this study, we investigated waterbuck population trends in FC/RGN using transect data for the period 1985-2019. Data for 1985-2007 has already been published (Hema *et al*. 2018) and previous census results (1981-1985) were not used because a different field method was employed during this period (O'Donoghue, 1985). For the more detailed analyses of population structure (age and sex-ratio) and distribution of the animals in the park we used census data gathered in 2019 as the same type of data was not collected in the previous years.

QGIS 2.18.10 was used to map sighting records and for determining waterbuck concentration zones. QGIS was also employed to measure distances between the different waterbuck groups, and distances of waterbuck groups from the nearest waterbody, from paths/tracks and from signs of illegal human activity. We used the standardized Morisita dispersion index (Ip) (Zar 1999) to measure spatial dispersion. Ip ranges from -1.0 to +1.0. The random dispersion modes (Poisson distribution) give an Ip equal to zero, while uniform distribution modes have an Ip less than zero. Grouped distribution modes have an Ip greater than zero.

On the basis of the number of contacts and the number of waterbuck individuals, we calculated the proportion of sex and age classes in the population for 2019, as well as the density (measured as the Kilometric Index of Abundance, KIA, and as the Kilometric Index of Contacts, KIC) (Maillard *et al*. 2001). In KIC, we considered all independent sighting events; so, for instance, if we observed 5 individuals in a group and one solitary individual apart, the count was 6 for KIA but just 2 for KIC.

KIA = (number of individuals / numbers of kilometers covered).

KIC = (number of observations / numbers of kilometers covered).

In these formulas, the number of kilometers covered represents the sum of the total distance of the transects.

We calculated the total number of encountered individuals among transects from 1985-2019, but with some years in which these numbers were not available due to the lack of field surveys. We estimated waterbuck density with the Distance Sampling method (Buckland *et al*. 1993, Thomas *et al*. 2002), using the DISTANCE software, version 7.2. This method makes it possible to estimate the population density by calculating the probabilities of detection of animals as a function of their distance to the transect. The general formula for estimating the density of waterbuck groups is as follows (Burnham *et al*. 1980):

$$\hat{D} = \frac{n\hat{f}(0)}{2L}$$

where $\hat{D}$ is the density estimator; n is the sample size (number of observations) of observations; L the total length of the transects; $\hat{f}(0)$ the estimator of the effective half-width of the band is the detection probability function estimated by the software through robust mathematical models related to the probability density function.

The following estimators, that are considered as the most robust (Buckland *et al*. 1993), were analysed: the cosine and polynomial-tuned uniform function, the cosine and Hermite polynomial-adjusted semi normal function, and the cosine and simple polynomial-adjusted chance rate function. The choice of the model was made according to the following criteria:

(i) the value of the effective strip width was close to the calculated mean perpendicular distance and the value obtained with the threshold method;

(ii) the expected group size (calculated by DISTANCE software) was closest to the mean group size (calculated on Excel);

(iii) the Akaike's Information Criterion (AIC) value was the lowest one, and the visual observation of the curve of the detection function was good;

(iv) χ^2 value was not significant.

Two types of densities were estimated: the density of groups (DS) estimates the number of contacts with animal groups per unit area (in our case per km^2); the density of individuals (D) estimates the number of single animals per unit area (also per km^2).

To evaluate age structure of the waterbuck population we distinguished three age classes: adults, sub-adults, and juveniles.

We used observed-versus-expected χ^2 test to check whether adult sex-ratio was even or not, and Pearson's χ^2 to test for differences in the frequency of waterbuck sightings among zones of the protected area. Correlations between (Box-Cox transformed) number of observed individuals and (i) (Box-Cox transformed) distances to illegal activities, (ii) (Box-Cox transformed) distances to the nearest path/track used by people, and (iii) (Box-Cox transformed) distances to the nearest water point, were carried out by

Pearson's correlation coefficient. Correlation between estimated yearly KIA and the (arcsine) percentage of females in the sample size was performed using a Pearson's product moment correlation coefficient.

Box-Cox transformation (Box and Cox 1964) was used to normalize variables whose data were not Gaussian (i.e. number of waterbuck individuals, distance separating the waterbuck groups to the illegal activities and to the nearest water points). The statistical software SPSS Statistics 21 and Past 3.0 were used to perform all analyses.

Results

Population structure by sex and by age (year 2019)

A total of 25 visual contacts of waterbucks were recorded during our 2019 census, with a total number of 103 observed individuals. Of the 25 visual contacts, in 13 cases the animals were fleeing or on alert, while in the rest of cases they were either resting or walking or grazing. Adults represented 46.6% of the observed population (n = 103), sub-adults were 6.8%, juveniles were 17.5% and undetermined individuals were 29.1%. Sex ratio was heavily skewed towards females (5:1; observed-versus-expected χ^2= 24, df = 1, P < 0.0001). The size of the great majority of the groups ranged 2-6 (Figure S1).

DISTANCE-generated estimates of population parameters (year 2019)

The probability of detecting waterbucks according to the Hazard rate/Cosine model (Figure S2) showed that there was a small number of observations between 0m and 30m compared to observations made between 31m and 49m. The summarized results on the estimates of parameters of the waterbuck population by the Hazard rate/Cosine model are given in Table 1. The population estimate showed wide confidence limits (Table 1) and there was large variation in the sizes of the various groups observed (up to 18 individuals; Figure S1). The fit between the observations and the visibility curve was also not good (Figure S2).The calculated population size in FC/RGN for 2019 was 502 animals (see Table 1 for the confidence intervals of the estimate).

Density and spatial patterns of occurrence (year 2019)

Waterbuck sightings in FC/RGN were concentrated along the principal rivers: 96% of the species' sightings were within 1.8km of the water, mainly around the artificial perennial waterbodies built along some streams for elephants (Figure 2). Most observations occurred in the core conservation area (density of individuals was 0.39 per km^2), but very few were in the hunting area (density = 0.05 individuals per km^2). These two sectors differed significantly in terms of waterbuck density: Pearson's $\chi^2=31$, df = 1, $P < 0.001$. We obtained a KIC = 0.036 and a KIA = 0.149. The dispersion analysis also revealed that waterbuck groups were spatially aggregated (Morisita Ip = 0.568; $\chi^2 = 902.3$, df = 78, $P < 0.0001$).

Regarding illegal activities, a total of 146 signs could be counted along the transects during our 2019 surveys (Table S1). These activities were observed throughout FC/RGN but were statistically concentrated (dispersion index of Morisita: Ip = 0.521) in its eastern side where waterbucks were not observed (Figure S3). The distance from the nearest sign of poacher activity did not influence the number of observed individuals ($r = 0.04$, $n = 25$, $P = 0.842$), and the same was true for the distance from the nearest water-body ($r = - 0.21$, $n = 25$, $P = 0.324$) as well as for the distance from the nearest path/track ($r = 0.191$, $n = 25$, $P = 0.360$).

Yearly population trends: 1985-2019

During the period 1985-2019, the population dynamics of the studied waterbuck population can be roughly divided into two main periods (Figure 3): 1) a population increase between 1985 and 2005 (Spearman's rank correlation coefficient: $r_s = 0.692$, $P < 0.05$), and 2) an ongoing population collapse from 2007-2019 ($r_s = - 0.715$, $P < 0.01$). There was also an annual slightly, non-significant, negative trend ($r_s = - 0.520$, $P = 0.123$) in the number of individual waterbucks observed during the period 2008 to 2019 (Figure 3). However, in this latter phase, the coefficients of determination (R^2) were low (respectively, 0.1366 (number of individuals) and 0.1803 (contact numbers)), thus indicating that the years explained poorly the number of individuals and the number of contacts obtained. In general, both the number of contacts and the number of individuals showed a sharp decline from 2010 to 2014 followed by a slight increase from 2014 to 2016.

The interannual observed sex-ratio was not affected by the density estimates: indeed, there was no correlation between estimated yearly KIA and the (arcsine) percentage of females in the sample size (r = 0.086, P = 0.893).

Discussion

Population structure by sex and by age

In FC/RGN, waterbuck groups are typically mixed families of adult females and juveniles, with females being largely dominant over males (5 to 1). Such a skewed sex-ratio was very different from that reported in the literature: for instance, in Uganda the male: female sex-ratio was 1: 1.6 (Spinage 1970), and in Ethiopia 1: 1.72 (Tsegaye *et al*. 2015). However, within a national park in Tanzania the sex ratio was 3: 1 in favour of females and 2: 1 outside the same national park in favour of females (Caro 1999). Thus, it seems that the adult sex-ratio is very variable in the species, with poor predictability on the basis of habitat characteristics, exposure to exploitation or resources available, but almost invariably with a higher number of adult females compared to the adult males. In ungulates, males are killed disproportionately to their abundance compared to adult females with local predation directly affecting patterns of sex ratio variation among adults (Berger and Gomper 1999). Since differences in survival of sexes may arise as a direct consequence of greater age-specific mortality among males, with selection operating differently on males and females (Berger and Gomper 1999), we suggest that the same should be possibly the case at our study area with predation-risks (especially by hyaenas and crocodiles) being much higher in males than in females. There are no available data on whether waterbuck males are indeed more preyed upon compared to females in FC/RGN. It is also possible, however, that the strong sex ratio deviation could be due to a higher incidence of illegal hunting on males or to behavioural differences between females and adult males causing less detectability in the latter. Although there are insufficient data to test any of these hypotheses, it is clear that the long-term changes in age structure and sex-ratio of the studied waterbuck populations played a minor role in the decline of numbers. Given this, the effects of hunting and changes in the animals' behavior should be more adequately assessed with ad-hoc studies.

Data on age structure of waterbuck populations in different parts of Africa are still limited. However, our data were comparable to other populations: in Ethiopia, for instance, adults accounted for 55.65%, subadults for 23.5% and juveniles for 21.06% (Tsegaye *et al*. 2015). However, if we exclude indeterminates (29%) from our study, the proportions of age classes are: adults 65%, sub-adults 10%, juveniles 25%, scarcely comparable to that of Ethiopia (Tsegaye *et al*. 2015). The ratio of adults/ juveniles averaged 2.66 in FC/RGN, which was very similar to that observed in (= 2.52) South Africa's Kruger National Park (Owen-Smith and Mason 2005). Thus, neither the sex ratio nor the age structure is comparable to that from other studies, and, in general, transect surveys can be suboptimal in determining the actual sex-ratios and age structure of savannah ungulates (Hema et al., 2020). In ungulate populations, age structure is an important determinant of adult survival as the mean survival is associated with age of adults (Festa-Bianchet *et al*. 2003). More studies are needed to understand annual variations in age structure and their implications for survival.

Density and associated parameters

Our study revealed that (i) waterbuck density varied significantly among the different FC/RGN zones (ranging from 0.05 individuals per km^2 up to = 0.39 individuals per km^2), and that (ii) the various groups showed clumped spatial pattern of distribution. The various groups observed tended to be non-randomly distributed within the FC/RGN area but showed “spatial contagion” effect between each other. When we tried to identify the main factor explaining this “aggregated pattern”, we rejected any linear relationship with both anthropic negative factors (distance from paths/tracks and distance from sites with sign of illegal activities) as well as environmental positive factors (distance from waterbodies). However, our survey was undertaken during the dry season when water is clearly a limited resource, and since these ungulates are highly water-dependent species (e.g. Melton 1978), there was obviously a greater chance that they are grouped around the permanent water points (Hien *et al*. 2007). This would explain the strong aggregative distributions of their groups around permanent water points without any linear relationship with the distance from the waterbody itself.

We estimated an average density of 0.25 individuals × km^2 and a mean group density of 0.21 × km^2. Although the individual density observed at FC/RGN was much lower than the highest observed so far in Africa (at Lake Nakuru in Kenya, with over 10 individuals × km^2; Kutilek 1974), it was still higher than in most areas: indeed, the mean density is 0.05-0.15 × km^2 in areas where the species is reasonably common and 0.2-0.9 × km², more frequently 0.4-1.5 × km^2 in remote areas that are presumably in good habitat status (Furstenburg 2005). Thus, our data suggest that waterbuck population abundance is still high in FC/RGN despite the observed declining population trend. Waterbuck density at Lake Nakuru, as a comparison, was likely to have been artificially high to be stable, and we suggest that this extraordinary concentration of animals was perhaps unusual due to abnormally favourable ecological conditions (high food resource availability in an exceptional year, migrations, or something equivalent) that do not occur in the other above-mentioned areas. In fact, high densities of *K. ellipsiprymnus* populations have been observed during very favourable years. For example, in FC/RGN, in 2010 there was a density four-fold higher than in 2014 (Fig. 3), so annual variability should be mentioned as an important factor when making comparisons between populations, and an important factor to be considered in further studies of the demography of this species. Since the data were not analysed with the same statistical methodology in the various areas of Africa studied so far, the density estimates reported in the various studies may not be totally comparable. DISTANCE methodology also requires about 60 contacts to obtain unbiased density estimates (Buckland *et al.* 1993, 2001) whereas our study achieved an insufficient number of contacts (n = 25) for obtaining a robust estimate. Thus, the density values reported in this paper should be considered merely as preliminary. Similarly, previous estimates of waterbuck densities using DISTANCE methodology in West Africa were also biased by too small sample sizes: for instance, Brugière *et al.* (2005) in Guinea and also Cornelis (2002) in our same study area. Group density at FC/RGN was consistent with published studies (range 0.27-0.96 × km^2; see Brugière *et al.* 2005).

On the basis of the KIA estimates (that is least prone to statistical biases than DISTANCE but obviously more empirical), our data (KIA = 0.149) suggest a much higher abundance in the FC/RGN savannah than in the gallery forests of south-west Burkina Faso (Comoè-Léraba National Park: KIA = 0.022; Hema et al., 2017a). In the latter, available habitat is differently shaped as it basically exists along the banks of the river Comoé (Hema *et al.* 2017a).

Yearly population trends: 1985-2019

Our study revealed that in FC/RGN, Waterbucks had a phase of population growth between 1985 and 2005 and then a significant decrease between 2007-2019. However, for the declining phase, the determination coefficient and sample size (10 years) are low and the strength of the negative tendency cannot be totally reliable. We consider that the low value of the coefficient of determination is due to the low slope in the straight line after 2008, so that a relatively small population decline cannot be explained as having such large variations between years. In other words, a leap up from a new year can make the negative trend disappear. Hema et al. (2018) analysed the fluctuations in population size of waterbucks in FC/RGN during 1985-2008 and found that these fluctuations were stronger than for other sympatric ungulates. It should be taken into account that, concerning the period 2009-2019, the population estimates showed wide confidence limits because the number of contacts was relatively low and there was large variation in the sizes of the various groups observed, thus reducing the estimate performances of the DISTANCE method. The low number of contacts also produced the suboptimal fit between the observations and the visibility curve as estimated by DISTANCE.

Why then did the population trend become constantly negative after 2005 and with a clear collapse after 2007? Previous studies uncovered a significantly positive correlation between rainfall and population size of *Kobus ellipsiprymnus* (Ogutu *et al*. 2008; Bouché *et al*. 2016), and at FC/RGN it was demonstrated that the probability of high population sizes of this species increased with an increase of precipitation in August (Hema *et al*. 2018). Therefore, it can be hypothesized that the increasing aridity due to global warming that is affecting the Sahel region may be an important cause of the decreasing trend of the waterbuck population at the study area. Other reasons, for instance the changes in the management schemes adopted by the authorities (responsible for considerable population fluctuations in the warthog *Phacochoerus africanus*; see Hema *et al*. 2017b), are least likely to be involved in this declining trend. These management strategies implemented by the FC/RGN managers involved the strengthening of the FC/RGN surveillance teams, the development of reservoirs and salt water basins, and the permanent monitoring of the fire system. Indeed, waterbuck population fluctuations did not mirror the changes in management type observed in warthogs (Hema *et al*. 2017b). Illegal exploitation by poachers may also be an additional reason for the declining trend of the local waterbuck population (Hema *et al*. 2017c). Indeed, other two ungulate species are declining at FC/RGN (*Ourebia ourebi* and *Sylvicapra grimmia*), and their decline has been attributed to overhunting because these species were highly valued in the illegal bushmeat trade (Hema *et al*. 2017c). In addition, in another protected area of southern Burkina Faso (Comoé-Léraba), Hema *et al*. (2017a) uncovered a negative correlation between hunting intensity and KIA estimates for waterbucks as well as for *Kobus kob, Ourebia ourebi* and *Cephalophus rufilatus*. Nonetheless, there was no direct evidence that poaching was a main reason for the continued decline of the species in our study area. Overall, it is likely that a combination of factors may explain the negative population trends of waterbucks in FC/RGN. Factors, including global warming (by increasing aridity) in combination with illegal activities such as poaching, may be responsible. We suggest that a multifaceted approach should be adopted in order to enhance the conservation status of the local waterbuck populations.

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Data availability statement. The authors declare that their data will be provided in case of request by interested readers

Conflict of interest. The authors declare no conflicts of interest

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Table 1. Synthesis of the density and population size estimates obtained by DISTANCE methodology on the bushbucks at the study area in southern Burkina Faso.

Parameter	Estimate
DISTANCE model	Hazard rate/Cosine
f (0)	0.0118
Var [f (0)]	0.02
Width of the W band (m)	85.011
density (D) of waterbucks per km^2	0.515
Variance of (D)	1.164
95% upper confidence limit	1.359
95% lower confidence limit	0.195
% Coefficient of Variation	51.60
Estimate of waterbuck population size	502
95% upper confidence limit	1325
95% lower confidence limit	190
χ^2	5.184
P	0.269
df	4
Number of individuals per group (range)	1-18
Density of groups per km^2	0.212
Mean number of individuals per group	4.12

Figure 1. Map of the study area, showing the seven zones in which, the protected area was divided.

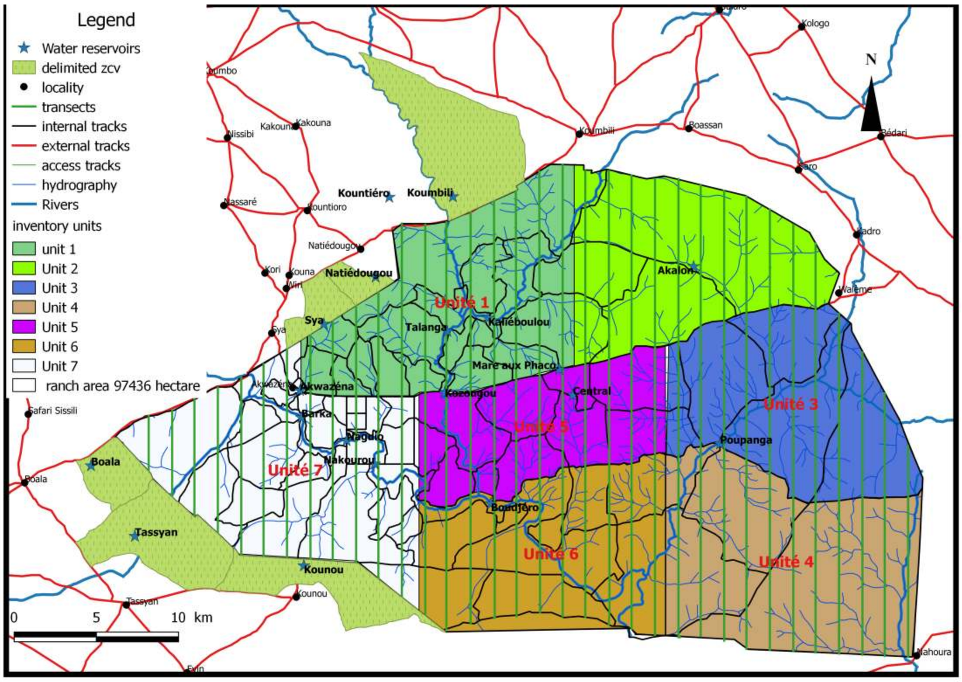


Figure 2. Distribution of the waterbuck sightings in the study area, during the year 2019.

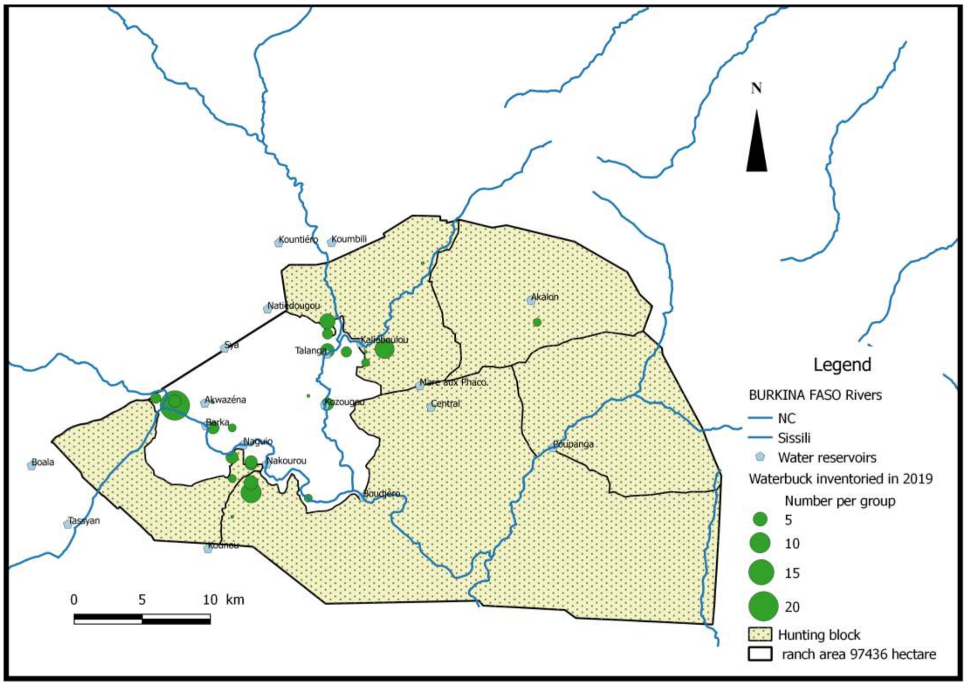
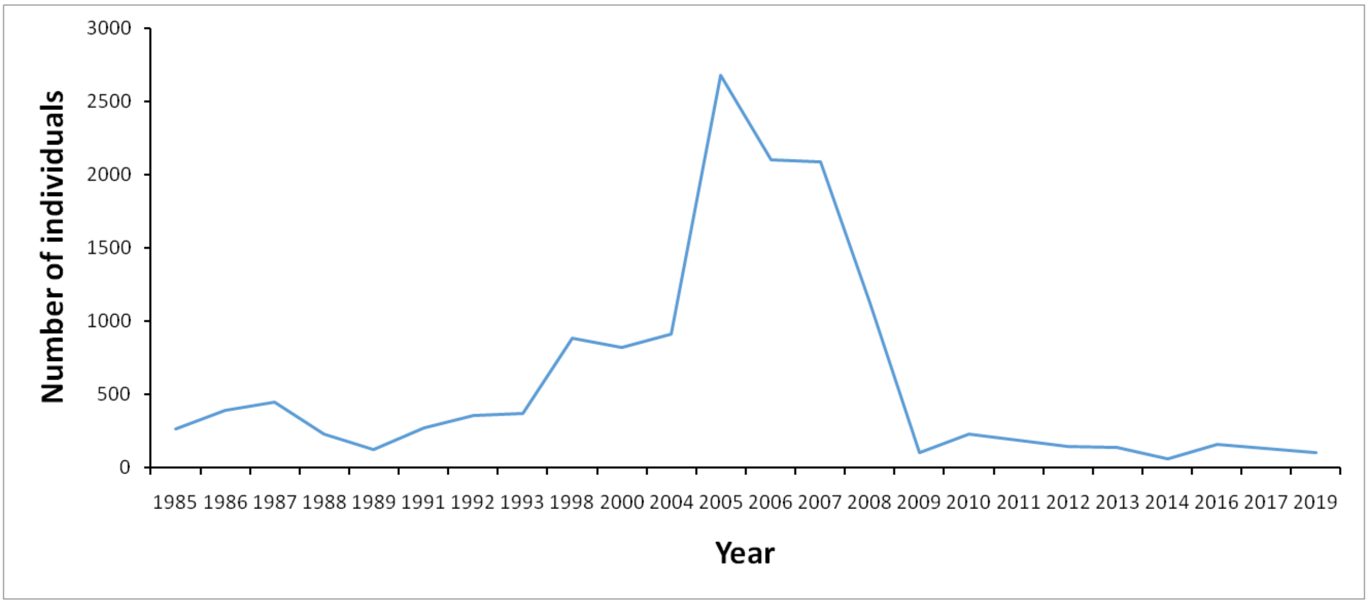


Figure 3. Yearly trend (period 1085-2018) in the number of individuals of waterbucks at the study area in southern Burkina



ONLINE SUPPLEMENTAL MATERIALS

Table S1. Synthesis of the dataset collected on the tracks of illegal activities within the study area during 2019.

	number of cases
Poaching	42
Pastoralism	34
charcoal	18
tree cutting	22
human tracks	14
motor bike tracks	11
tree-branch thinning	5
Total	146

Figure S1. Frequency distribution of the various waterbuck groups in relation to the number of individuals in each group.

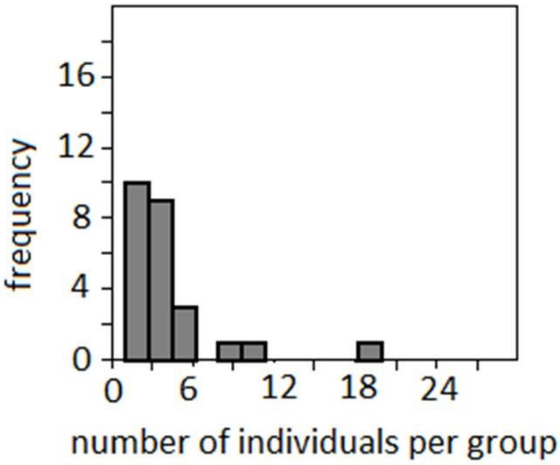


Figure S2. Profile of the visibility curve for the waterbuck observations at the study area, during the year 2019

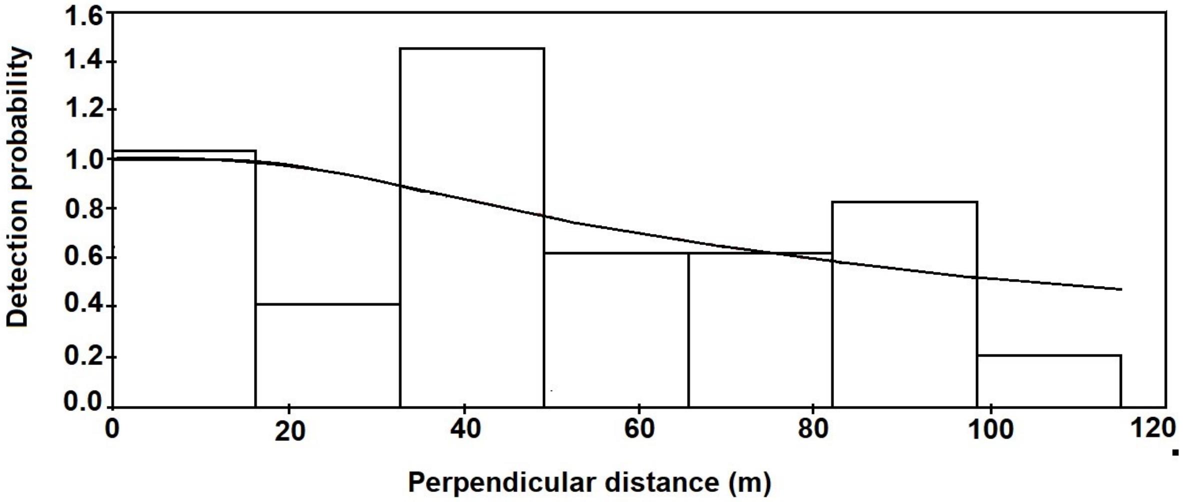


Figure S3. Spatial distribution of the tracks of illegal activity within the study area in the year 2019, in relation to the group size of waterbucks.