Global Ecology and Conservation 24 (2020) e01389

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: http://www.elsevier.com/locate/gecco

Original Research Article

Habitat requirements of the Mhorr gazelle: What does this species need to survive in the wild?

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ARTICLE INFO

Article history:
Received 16 October 2020
Received in revised form 26 November 2020
Accepted 26 November 2020

Keywords:
Mhorr gazelle
Nanger dama mhorr
Reintroduction
Dama gazelle
Home range
Morocco

ABSTRACT

The mhorr gazelle (*Nanger dama mhorr*) is the westernmost-distributed mama gazelle subspecies and it has been considered extinct in the wild since 1968. Much of the survival of this subspecies depends on its *ex situ* captive population and future reintroduction projects. However, this subspecies disappeared before it could be well studied; and most of the knowledge regarding the mhorr's ecological requirements in its native range comes from early observations in the 40s and 50s and are general description of their native habitats. In 2015 a group of mhorr gazelle was released in the Safia Nature Reserve (Morocco) as the first step to establish a long-sustainable wild mhorr gazelle population. This project offered an opportunity to determine the habitat requirements of the mhorr in terms of surface area (size), landscape and the vegetation's characteristics. The results come from seven (2.5) collared adult mhorr gazelles. Once released into the wild, the gazelles explored extensive areas in all directions around the point of release but they established their territories - understood as the home range - just to the north of the point of release, far from any human presence (borders or roads) and in flat areas where the acacia tree cover was abundant; the core areas were settled also in the most flat and vegetated areas inside the home range. All the gazelles except one female occupy the same region with a very high overlap in their home range (between 28.4 and 75.8%). Regarding the extent of the home range (average 119.9 ± 27.5 km^2) and core areas (average 20 ± 4.2 km^2) depends on time of sampling and highlight the differences between the space needed by the mhorr gazelles to satisfy their needs in the wild and the space provided for the species in previous reintroduction projects in fenced-off areas.

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https://doi.org/10.1016/j.gecco.2020.e01389

1. Introduction

The dama gazelle (*Nanger dama*) is one of the five most threatened antelope species in the world, -along the addax (*Addax nasomaculatus*), the saiga (*Saiga tatarica*), the hirola (*Beatragus hunter*) and the Ader's duiker (*Cephalophus adersi*) (IUCN/SSC, 2009)- being classified as "Critically endangered" (IUCN/SSC, 2020) and listed in Appendix I of CITES and CMS. The mhorr gazelle (hereinafter mhorr) (*Nanger dama mhorr*) is the westernmost-distributed *Nanger dama* subspecies and it has been considered extinct in the wild since 1968 due to overhunting (Valverde, 1955; Cano 1991). To prevent the complete extinction of this subspecies, different conservation actions were initiated in 1971 (Abáigar 2018a). Among these conservation actions is the establishment of populations in fenced-off areas, as a prior phase to their full release into the wild. Until now most reintroduction projects carried out with mhorr in fenced-off areas in North Africa have had variable success. For example, whereas initially established populations completely disappeared, such as in the Bou-Hedma National Park (Tunisia) or Sous-Massa National Park (Morocco) (Abáigar, 2018 b; Jebali et al., 2019), encouraging developments have been observed in the Safia Reserve (southern Morocco), where the initial mhorr population has increased in seven years (Abáigar 2018b). The survival of a reintroduced species is related to its ability to occupy appropriate habitats for it to live and reproduce (Seddon 1999; Seddon et al., 2007). Thus, among the possible causes explaining the irregular success of reintroduction projects is that some of these have been conducted outside the species' native range and/or in habitat unsuitable for their survival RZSS and IUCN Antelope Specialist group, 2014; Senn et al., 2014). Animals released in areas where their ecological, physiological and behavioural needs cannot be fully met.

Most of the knowledge regarding the mhorr's ecological requirements in its native range comes from early observations in the 40s and 50s (Morales-Agacino, 1949; Valverde 1957). Expeditions by these naturalists to the Atlantic Sahara in the mid-20th century provided merely general knowledge of the mhorr's biological and ecological features; unfortunately, this unique subspecies disappeared before it could be studied in depth. The mhorr were distributed along the Atlantic Sahara, south of the Oued Drâa in Morocco, to northern Senegal, in a band approximately 200–300 km wide (Cano 1991). Based on original observations by Valverde (1957), we know that this subspecies occupies sandy plains and *oueds* (dry riverbed channels) where acacia trees are abundant. However, we do not know if the mhorr settled here permanently or only used it temporarily and information about the size of their territories and habitat requirements is lacking. Such information may help to ensure the success of future establishments of populations, either in protected areas or in the wild. The experience gained during previous reintroduction projects, such as those conducted in the Safia Nature Reserve (SNR), southern Morocco (Abáigar et al., 2019), would help to discover basic and fundamental aspects of the mhorr's habitat requirements that can be used to support future attempts with the same or other subspecies.

Habitat models have become well-accepted tools to identify both, species distribution (habitat distribution models) and their habitat's requirements (Guisan and Zimmermann, 2000; Elith and Leathwick 2009; Guisan et al., 2017; Herrera-Sánchez et al., 2020). These models use animal locations obtained from GPS to estimate several indices related to size of inhabited areas based on, such as the home range (HR) and core areas (CA). Home range is generally defined as the area covered by an individual during its normal activities of food gathering, mating and caring for its offspring (Burt, 1943; Powell 2013). Core areas, on the other hand, are defined as small areas of intense use within the HR. Alternatively, the HR is an indirect measurement of the quality and quantity of the habitat available for the species, as well as the seasonal variation of resource availability, notably food and temperature (Morellet et al., 2013). In addition, landscape patterns (configuration and connectivity), social behaviour and predator avoidance determine animal movement and therefore could influence range size (Kie et al., 2002; Walter et al., 2009; Morellet et al., 2013). The most common procedures to estimate HR and CA are the Minimum Convex Polygon (MCP) and Kernel Density Estimation (KDE) applied to sets of points obtained from GPS collars (Owen-Smith and Cain 2007; Dvořák et al., 2014; Lei and Booth, 2018; Cohen et al., 2018). Due to its simplicity, MCP (Mohr 1947) has been widely used and is probably the only parameter comparable between studies. KDE is based on the individual's utilisation distribution and is also widely used as it enables a more precise definition and location of specific areas (i.e. core areas) within a territory (Seaman and Powell 1996). Once the area occupied by a population during its normal activities is known, this can be used to define the adequacy and habitat suitability of the species in terms of climatic conditions, food availability and landscape patterns (topography, connectivity). In this respect, freely available remote sensing datasets could provide crucial, spatially continuous information about terrain complexity as well as vegetation distribution and function that could be easily integrated within an analysis of the habitat's characteristics (Zlinszky et al., 2015).

The ultimate purpose of this study was to provide empirical data and key habitat features for future conservation and reintroduction projects, either with mhorr or with the other subspecies of dama gazelle, such as the addra gazelle (*Nanger dama ruficollis*). Both subspecies belong to one of the most endangered ungulate species in Africa and the results of this study are therefore of major relevance for the conservation of the entire species (RZSS and IUCN, 2014; Al Ain Zoo, 2019). To achieve this, we aim to determine the habitat requirements of the mhorr in terms of surface area (size), landscape and the vegetation's characteristics, so that this information can be used to select the most suitable areas to ensure future reintroduction projects are successful. As there is no clear pattern in climate seasonality with scarce precipitation and very long dry periods (years without any rainfall event), we do not expect any seasonal displacement for their territories. On the contrary, we expect the mhorr will select those areas with the highest density of vegetation and *Acacia* cover, and that they will select routes over the plain for their movements, avoiding slopes and rough terrain in the landscape. Base on previous observation and their social organization of the species (Valverde 1957), and a preliminary study that describe early displacements and social

relationships of mhorr gazelles followed their release in SNR (Abáigar et al., 2019), we also expect the gazelles occupy territories close to each other.

2. Materials and methods

2.1. Study area

This study was conducted in the Safia Nature Reserve (SNR), which is located in the south of the Dakhla-Oued Ed Dahab region, in the province of Aousserd (southern Morocco). The SNR covers 3075 km^2, bordering Mauritania to the south and the Atlantic Ocean to the west (Fig. 1). The climate is arid-Saharan with sporadic rainfall (less than 100 mm/year) mostly occurring in August–September (Valverde 1957). There is a longitudinal gradient of increasing temperature (from 19 to 27 °C in summer) and decreasing humidity (from 86% to 61%) from the Atlantic coast to the east (Maoulainine 2012). The landscape is characterised by a slightly elevated relief with stone plains, chains of dunes, *nebkhas* (small sand dunes that form around vegetation), *sebkhas* (depressions in the sand dunes) and *oueds* (dry riverbed channels). Vegetation is typically Saharan and mainly dominated by acacia trees (*Acacia raddiana).* See Abáigar et al. (2019) for additional information on vegetation composition in the study area and Fig. 1 for landscape. There are no permanent human settlements within the reserve and the only human activity is the seasonal livestock grazing of camels and goats. The dorcas gazelle (*Gazella dorcas*) is the only ungulate species still free-ranging in the area. In addition the African golden wolf *(Canis anthus)* and other small carnivores (Aulagnier et al., 2017) are notable mammal species in the study area.

2.2. Animals

In 2005, the Haut Commissariat aux Eaux et Forêts et à la Lutte Contre la Désertification (hereafter HCEFLCD) established a protected enclosure of 600 ha (hereafter the Safia enclosure) within the SNR. In 2008, a founder population of mhorr gazelle was established in the Safia enclosure as part of the HCEFLCD strategy to recover this species (Cuzin et al., 2007).

In May 2015, 24 (12.12) gazelles were released from the original group in the Safia 'enclosure. All of them were adults except for one young male (<6 m.o.). Of the 24 gazelles, ten adults (3.7) were equipped with GPS. During the first five days after release all the gazelles remained near the release site and only made small movements along the fence, sometimes returning to enclosure. Then, an unexpected surprise attack of a pack of 11 dogs left 7 (6.1) gazelles dead, two of them (1.1) were gazelles equipped with GPS collars. According to the information obtained after the attack, domestic dogs living in the military posts in the area occasionally form packs and attack nearby livestock (goats and sheep). Given this unexpected circumstance, we decided to return the rest of the gazelles to enclosure. This was possible for 11 (4.7) gazelles. The rest, 6 (2.4) in total, had dispersed into three groups: group A: 3 (1.2) with one collared female (gazelle F146) so that this group could be monitored; group B: 1 (0.1), collared female (gazelle FAB); and group C: 2 (1.1): the male without collar and the female equipped with a GPS never worked, so it was impossible to follow and monitor them throughout the study. Once the problem of dogs had been solved (capture) by the regional environmental authorities of Morocco, a second release was carried in July.

A second unexpected and dramatic event happened the night of October 2 to 3 when a group of poachers broke into one of the main territories of the gazelles causing their flight and dispersion. According to the data provide by the collared gazelles, they dispersed into at least two groups. A group of unknown size and composition but with three collared-gazelles (two males, M510 and M520, and one female, F145) escaped to the east, towards the Adrar Sotouff Mountains. The second group, also with an unknown composition but one collared gazelle (F147) went to the southeast. The hunters pursued the two groups of gazelles and killed M510, F145 and F147; their GPS collars were never recovered. Fortunately, M520 survived and returned to its territory 12 days later. Two females, F146 and F500, did not suffer any harassment from the hunters because they were in a different area. So, data for this study came from seven collared adult mhorr gazelles (2.5). The monitoring period for each individual varied from 58 to 248 days (d) as follows: female FAB, 58 d (May to July 2015); female F147, 67 d (July to October 2015); female F145, 70 d (July to October 2015); male M510, 70 d (July to October 2015); male M520, 217 d (July 2015 to February 2016); female F500, 242 d (July to March 2016) and female F146, 248 d (May to January 2016). See Abáigar et al. (2019) for further details about release, monitoring period and social organization of the monitored gazelles.

2.3. Data collection

Collared Gazelles were equipped with three different models of GPS: three gazelles (id F145, F146, F147) were fitted with Lotek GPS 7000SA (Lotek Wireless Inc. Ontario, Canada) tracked via the Argos satellite platform. Another three gazelles (id F500, M510, M520), were fitted with Sirtrack G5C 375 A) recovered via the Iridium satellite platform and one gazelle was fitted with a GPS-GSM Ecotone-Guanaco logger (id FAB). All collars incorporated a timed drop-off for their programmed, automatic release and had VHF transmitters except for the Ecotone model. Sirtrack collars were originally scheduled for eight fixes day-1 (every 3 h). After two months, they were scheduled for four fixes day-1 (every 6 h) to save battery power. Lotek collars were scheduled for 16 fixes day-1 and the Ecotone collar provided 24 fixes day-1 (every hour). Directly using such irregular data in terms of times may result in biased utilisation distribution (UD) estimates because areas that have been sampled intensively receive too much weight (Calabrese et al., 2016). Moreover, these kinds of datasets are expected to be spatially and temporally auto-correlated. Both problems have been tackled by resampling data to a homogenous 6-h interval,

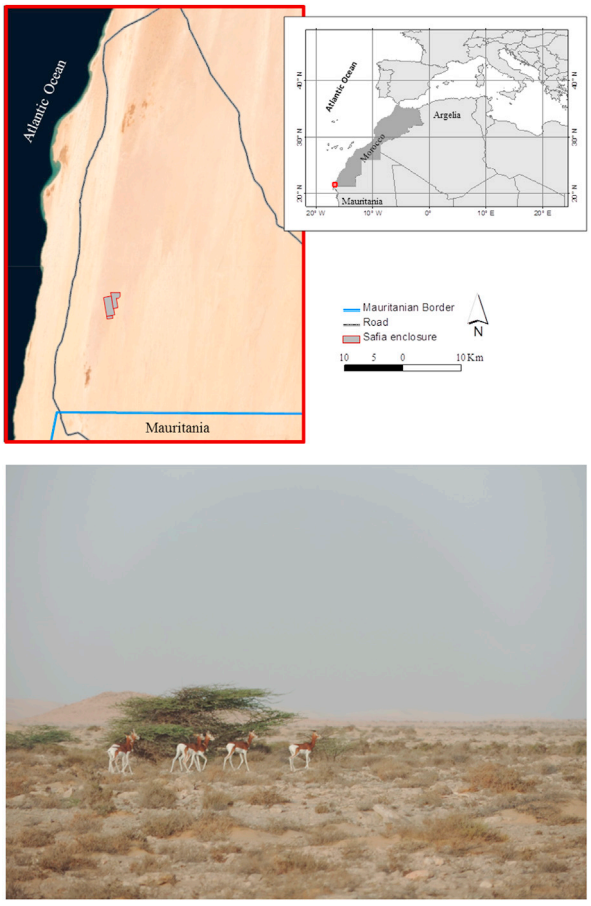

Fig. 1. Study area, landscape and mhorr gazelle' herd.

according to temporal resolution of the Iridium collars (6 h with four points per day at 01:00, 07:00, 13.00 and 19:00). To do this we identified the data records, on the Argos and Ecotone collars, that were closest to these 4 different time points within the day and assigned this data as a specific measurement corresponding to this time point (See Abáigar et al., 2019 for further details).

The mhorr gazelle is a browsing herbivore (Kaiser et al., 2009) and *Acacia* spp. trees one of the most frequently selected species (Valverde 1957). Consequently, Acacia *raddiana* trees were mapped from freely available, very high spatial resolution Bing images (Web-based mapping service provided by Microsoft). For this, we downloaded all the scenes within the area of 5 km around spatial extent of all points locations using the Satellite Aerial Image Retrieval code proposed by Chen (). All the scenes were assembled in a mosaic and the final mosaic was divided into two different sub-scenes. One of these was used to train a support Vector Machine classification using a dataset of 100 training points, corresponding to individual trees of *Acacia raddiana*. The second was used to validate the trained algorithm with an additional dataset of 100 validation points, obtaining a Kappa index of 0.91. This classification was used to estimate the coverage of *Acacia raddiana* within each grid cell of 200 m resolution, coinciding with the pixel size of the UD function. Moreover, we used the ALOS World 3D (AW3D30) digital elevation model of 30 m of spatial resolution (©JAXA) to estimate the Random Roughness index (RR) over the same extent. This is related to terrain complexity (abrupt changes in slope) and was calculated within a mobile window of 3 pixels, according to the equation proposed by Rodriguez-Caballero et al., (Rodríguez-Caballero et al., 2012), Eq. (1).

$$RR = \sqrt{\sum_{i=1}^{i=Nw} (Z_w - \mu_w)^2 \Big/ (1 - N_w)} \quad (1)$$

where Nw is the number of pixels in the window of size w, Zw is the height of each point and μw is the mean height in window of size w.

2.4. Data management and analysis

The final point dataset at 6-h time intervals was used to estimate the HR and CA of each collared gazelle using Kernel Density Estimation (KDE) with two different approaches: i) a Gaussian kernel for fixes (Kf) of a constant radius (h) and ii) the Brownian bridge approach (KBB) (Horne et al., 2007) to include possible barriers in the territory. The radius of the smoothing parameter in the Kf is usually fixed via Least Squares Cross Validation (LSCV). However, in our case it did not fit any of the monitored gazelles. It was therefore iteratively fixed at 300 m (ranging from 50 m to 500 m), which was the minimum required for overlap without overestimating the territory of each individual. Fixing bandwidth "a priori" is acceptable given the specific biological questions in order to respond to the continuity in selecting territory (Wand and Jones 1995; Berger and Gese, 2007; Jacques et al., 2009; Kie et al., 2010). In addition, 300 m bandwidth is consistent with field observations. For the KBB method, the Sigma 2 value was fixed to 15 m, according to GPS accuracy, and the maximum likelihood function was used to estimate the optimum Sigma 1 value for each individual (Supplementary Table S.2). Once the utilisation distribution (UD) maps had been obtained, the HR and CA of each individual were calculated using both the Kf and the KBB methods. Generally, the HR consisted of the smallest area containing 95% of the activity and the CA likewise at 50% (White and Garrot 1990). Both results obtained with the Kf and KBB were combined in a committee average ensemble and only those areas identified as HR or CA by both methods were considered for further analysis (hereinafter referred to as HRe and CAe, respectively). Ensemble methods are commonly used in predictive models of space occupation and species distribution (Araújo and New 2007; Marmion et al., 2009; Herrera-Sánchez et al., 2020). We estimated the HRe and CAe for each individual during the entire study period, as well as for each month with more than 25 GPS records. The home range and core areas obtained during the whole study periods provide general information about the territory occupied by each gazelle, whereas monthly estimates allow us to analyse variations over time and the fidelity of each individual to the territory. In addition, the MCP containing 95% of the points was also estimated. This was carried out for comparison with other studies, as most previous literature is based on this. The maximum convex polygon containing 100% of the points was calculated as the maximum area explored by the gazelles. The maximum convex polygon and Kf were estimated using the adehabitat package for R (v1.8.20) (Calenge 2006), and the KBB method was estimated using the adehabitatLT for R (Calenge et al., 2009).

Based on the HRe and CAe estimates, we calculated the niche overlap between the different gazelles, for the total study period and for each month separately, as a measure of joint-space use and the degree of interaction among individuals (Kernohan et al., 2001; Millspaugh et al., 2004). We also assessed the degree of site fidelity, defined as the extent of HRe that each Mhorr gazelle used repeatedly over time, by calculating the intersection of kernel contours for consecutive months. Finally, we estimated the mean density of *Acacia raddiana* (m^2 of Acacia per Ha of territory) and mean RR within the CA and HR polygons of each gazelle as indicators of food availability and terrain complexity. T-test comparisons were used to test sex and period of sampling on HR and CA values. Regression analysis was used to study the correlation between HRe and CAe. Statistical analyses were performed with STATISTICA for Windows (Statsoft UK, Letchworth).

3. Results

3.1. Home range and core areas

As expected, the different HR and CA estimates for the mhorr gazelle depended on the procedure used (Table 1). The largest HR values were obtained with the MCP, whereas HR from Kf provided the lowest values. KBB provided intermediate values about three times those obtained with the Kf. In the case of the CA, KBB-based values were almost double those of Kf. Using Kf and KBB we built an ensemble that was retained as the best model to estimate the HR and CA for the mhorr in our study area. According to this, the gazelles studied occupy an area of about 120 km^2, ranging between 82 and 153.3 km^2, whereas the core areas ranged between 16.2 and 27.8 km^2 with mean values of 20 km^2.

When individuals were analysed separately, we found there were some differences between them in both HR and CA estimated based on the complete dataset (see Table 2 for data and Fig. 2 for locations). These differences were not explained by sex, as they were not statistically significant (*t*-test; $p > 0.05$). Sampling period, on the other hand, seems to be more important. As observed in Table 2, there were significant differences in HRe (*t*-test; t: 6.30, df: 5, $p = 0.0014$) and CAe (*t*-test, t: 3.74, df:5, $p = 0.013$) between gazelles with a short sampling period (two months) (average HRe = 91.2 km^2, average CAe = 17.1 km^2) and gazelles that were monitored for more than 6 months (average HRe = 139.7 km^2; average CAe = 23.8 km^2). HRe and CAe were correlated (regression test $F_{(1,29)}$:172.1, $P < 0.000$, R^2: 0.85).

Fig. 3 (also Table 3) shows the trend over time of HR and CA for the three mhorr gazelles with long periods of data records (more than 6 months): females F146 and F500, and male M520.Female F146 show a progressive increase, both in her home range and core areas, during the first three months after release that is finally established at values around 30–40 km^2/month for HR and 6–8 km^2/month for core areas. A different pattern was observed in female F500 who showed two peaks of occupancy during her monitoring in October–November and in January. Finally, male M520 reached a maximum one month after release (August). After that, the home range and core areas values progressively decreased during two months, reaching a minimum of HR: 45.6 km^2 and CA: 9.9 km^2 in October.

Individual analysis of monthly HR and CA for the three gazelles with longer monitoring periods showed that they moved around the overall territory delimited by the HR and CA calculated using the complete dataset, with poor fidelity to specific patches within the territory. Fig. 4 shows site fidelity for F146, M500 and M520, represented as the extent of home range areas

Table 1
Home range (HR) and core area (CA) values (km^2) for mhorr gazelle (*Nanger dama mhorr*) obtained following three procedures: Mean Convex Polygon (MC), Kernel for fixes (Kf) and Kernel Brownian Bridge (KBB), as well as the ensemble of Kf and KBB.

	HR_MCP	HR_Kf	HR_KBB	CA_Kf	CA_KBB	HRe	CAe
average	315.5	114.5	278.1	22.4	43.3	**119.9**	**20.0**
sd	122.8	28.9	51.3	4.6	10.7	**27.5**	**4.2**
min	236.4	82.8	203.4	17.7	31.6	**82.0**	**16.2**
max	569.1	159.5	341.2	30.1	58.2	**153.3**	**27.8**

that each mhorr used repeatedly during different months. As observed female F146 showed the lowest fidelity to a specific area within the territory delimited by the HR estimated based on the complete dataset, with the largest decrease in home range areas used repeatedly during different months as the degree of monthly overlap increased. In fact, areas that overlap for more than 4 months account for less than 10% of the total home range of this gazelle (Fig. 4b). The range of monthly home range overlap between different months for female F500 and male M520 were greater than this observed in F146, and it decreased at a lower rate than in the previous case (F146). However, differences were minor and these two gazelles also showed poor fidelity to their territories.

3.2. Home range overlap

Overall, the HR of each mhorr showed a high proportion of overlap with its congeners (ranging from 28.4 to 75.8%) (Supporting Information, Fig S.1) except for female FAB who remained isolated from the herd and established a separate territory to the north of the area occupied by the other mhorr gazelles. Out of the different gazelles in the group, F145 and F147 had the largest proportion of overlap with the others. Core area overlap was lower than HR overlap in all cases and, as previously mentioned, whereas most individuals showed values between 10 and 50% (table S1), FAB had almost no overlap with any of the other gazelles. F500, who established her territory in the eastern part of the region, also had very low values when compared with the rest of the group.

Fig. 5 shows a detailed analysis over time of HR and CA overlap between individuals. In June and July, the only two monitored females (F146 and FAB) were separated and did not share any territory. In August, the four females and the two males in the herd shared a larger part of their HR but covered different CAs except for the two males who shared around 50% of their core areas. In September there was a significant increase in the home range and core areas shared between gazelles, especially between M510 and F145 (sharing more than 80% of their HR and CA) and between M510 and M520 (sharing more than 87% of their HR). From October to the end of the monitoring period, the group had only three gazelles: two females (F146, F500) and one male (M520). According to the HR overlap, the three gazelles remained together, sharing an important part of their HR and CA. Based on CA overlap, we assume breeding pairs were established in November between F146 and M520 (sharing more than 75% of F146's CA), and between F500 and M520 in December and January, sharing more than 75% of F500's CA.

3.3. Selection of habitat features: acacia density and roughness

All gazelles established their territories in areas with a higher density of *Acacia raddiana.* As can be seen in Fig. 6a, acacia density was always higher in the home range and core areas established by the gazelles than in the maximum area (MCP at 100%) explored by them. Moreover, when vegetation density within the core areas and home ranges were compared, we found that this was always higher in the core areas, except for female F146. Remarkable inter-individual differences were found for female FAB and the rest of the group. This female remained alone after release, explored larger areas far from the point of release and never found an optimal area to establish a stable territory. Terrain complexity also seems to be an

Table 2
Average and individual values of home range and core areas (km^2) of mhorr gazelle (*Nanger dama mhor*). HRe and CAe: home range and core areas based on ensemble method."F" for female, "M" for male.

ID	HRe (km^2)	CAe (km^2)	Sampling (months)
F145	87,.0	16.8	2
F146	124.9	21.9	8
F147	82.0	16.2	2
F500	153.3	21.8	8
FAB	94.8	16.8	2
M510	100.8	18.7	2
M520	136.5	27.9	7
average	***111.9***	***20.0***	
sd	***27.5***	***4.2***	
min	***82.0***	***16.2***	
max	***153.3***	***27.9***	

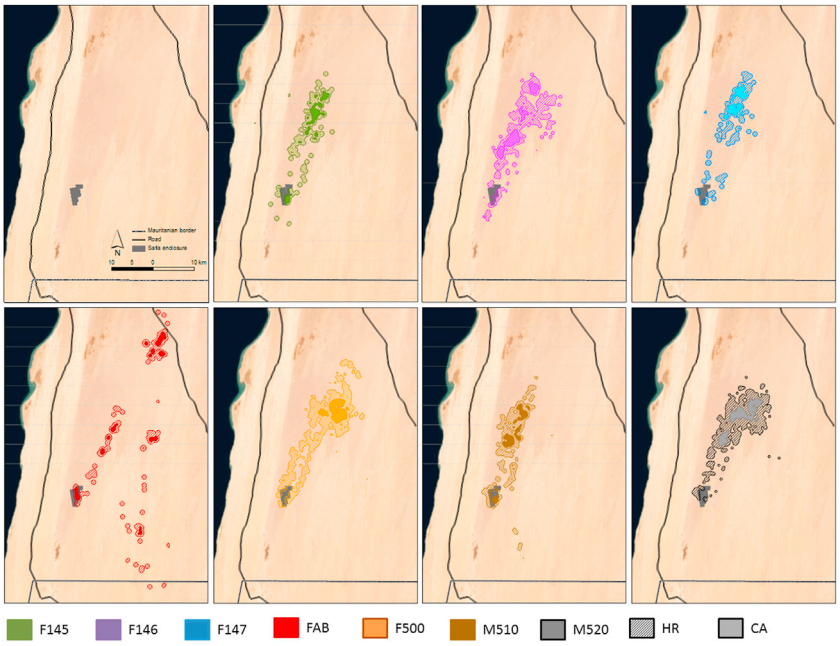

Fig. 2. Individual home range (line) and core areas (solid color) of mhorr gazelles (*Nanger dama mhorr*) according to the ensemble method for Kernel fix and Kernel Brownian Bridge. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

important factor determining home range and core area establishment for these gazelles. All gazelles avoid areas with complex topography, such as dune chains, and established their home range and core area in areas with a low roughness index (Fig. 6b). Thus, whereas there are inter-individual differences in the values of roughness within the maximum explored area (MCP at 100%), values for roughness of the core area and home range were almost equal, except in the case of female FAB which established its core area in the smoothest area of its HR (see Fig. 6b).

4. Discussion

The results of this study define and quantify the ecological variables that characterise native habitats of the mhorr gazelle into their former distribution area (Valverde 1957). This is an important step forward in the conservation of this subspecies of dama gazelle, which disappeared before it could be well studied. Thus previous information was not enough to define and accurately delimit suitable sites for future reintroduction into the wild, which is crucial for successful conservation actions to ensure their long-term survival (Al Ain Zoo et al., 2019).

To the best of our knowledge, there is no comparable data to our results regarding the size of the HR (average 112 km^2) and CA (average 20 km^2) for the mhorr, not even for any other subspecies of dama gazelle in the wild. So the data provided here are the first for *Nanger dama* living into the wild. The only information of a similar nature that can be used for comparison are data about the home range and core areas for five addra gazelle (*Nanger dama ruficollis*) (three adults and two subadults) living in a large fenced pasture (89.9 km^2) in West Texas (Mungal, 2018); the author, using Kf method, refers to different smaller HR and CA sizes for adult and subadult gazelles: 17.8 km^2 (HR) and 4.4 km^2 (CA) *vs* 31.5 km^2 (HR) and 3.8 km^2 (CA) respectively. Our study shows there are no statistically significant differences regarding the size of HR and CA due to the sex of the gazelles but there are regarding the length of time monitored. This result confirms a previously described sample-size effect on home range analysis using Kernel density estimation (Worton 1989; Seaman and Powell 1996). The three gazelles with a longer period of monitoring progressively extended their home range and core areas by exploring new territories to the northeast of their point of release.

The results of HR and CA overlap between different gazelles (Table S1), as well as direct observations and detailed analysis of the social behaviour of these gazelles (Abáigar et al., 2019), corroborate previous findings by Valverde (1957), who already described the mhorr as a gregarious and social specie. This author observed groups of different sizes (two to fifteen) and composition, including mixed herds with Dorcas gazelle, but never isolated females. In that respect, something strange must have happened with the female FAB who remained isolated and far from the group. Consequently, she explored areas further from the point of release and selected poorer sites in terms of *Acacia* tree cover to settle. Two months after release, this female returned to the point of release in a very poor physical condition and died. We postulate that stress due to isolation and to the poorly selected habitat as the main factors causing the death of this female. Values of increasing sociability within the group and the establishment of breeding couples were observed from October as increased values of overlap in HR and CA (see Fig. 5

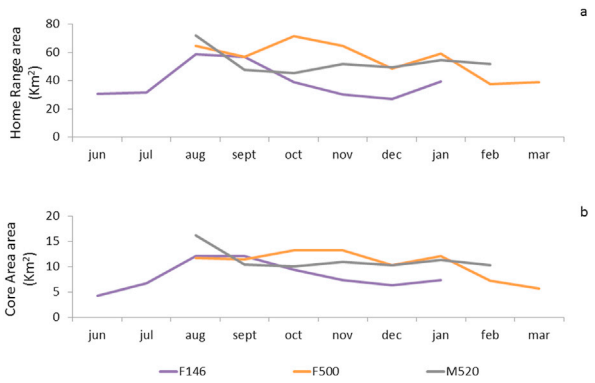

Fig. 3. Monthly values of home range (a) and core areas (b) for the three mhorr gazelles (*Nanger dama mhorr*) with data record periods longer than 6 months: females F146 and F500 and male M520.

Table 3
Monthly average values of home range and core areas (km^2) of individual mhorr gazelle (*Nanger dama mhorr*) based on ensemble method.

	HRe	SD	CAe	SD	n
	average		average		
F145	44.3	9,7	7.9	2.5	2
F146	39.3	12.2	8.2	2.8	8
F147	53.6	1.8	9.6	2.1	2
FAB	49.2	41.8	8.6	2.8	2
F500	55.2	12.3	10.6	2.8	8
M510	56.3	33.6	11.1	4.4	2
M520	53.3	8.8	11.3	2.2	7

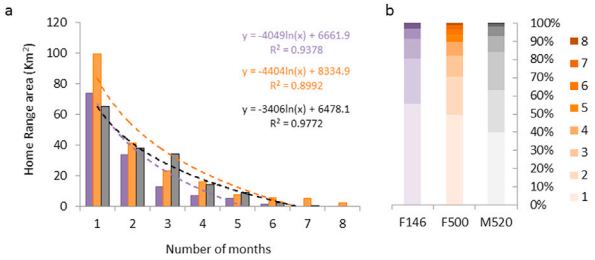

Fig. 4. Site fidelity represented as the extent of home range areas (km^2) that each mhorr gazelle (*Nanger dama mhorr*) used repeatedly for 1–8 months (a). In b, the proportion of each individual home range along the time. Data for the three mhorr gazelles with longer periods (>6 months) of sampling: females F146 and F500, and male M520.

and Table S1). Although we only have one direct observation on sexual behaviour in the group studied (mating in September), we suspect that gazelles of different sex that share more than 70% of their CAs are a couple or breeding group. This suspicion is also supported by the sudden change in the proportion of CAshared, from just 5% to almost 90%, as happened, for example, with couple F147-M510 from August to September, couple F146-M520 from October to November and couple F500-M520 from November to December. Based on these findings, we can confirm the end of summer and autumn (September to November) as the main breeding season for the mhorr gazelle living in the southern Atlantic Sahara region, coinciding with the rainy season (Valverde 1957; Cano 1991).

The selection of sites to settle was not random and reveals some behavioural and ecological traits characterising the mhorr gazelle. In all cases gazelles avoided human disturbances, such as the Moroccan wall close to the Mauritanian border to the south and roads to the west and north. Moreover, they chose areas with the highest *Acacia* tree densities and avoided complex terrain resulting from the presence of the dune chain to the east and upper half to the west.

The mhorr has a wary character and a tendency to suffer from stress associated with any change in their management. Although they are well adapted to living in captivity and their *ex situ* conservation has been successful (Cano 1991; Barbosa and Espeso 2005; Abáigar 2018a), changes associated with their exhibition in zoos close to visitors or with the exhibition of mixed species result in a decrease in food intake and fertility (C. Enseñat, M.A. Quevedo pers. comm.). When release in fenced-off areas the first change, from the very beginning, is a progressive and proportional increase in the safe distance maintained

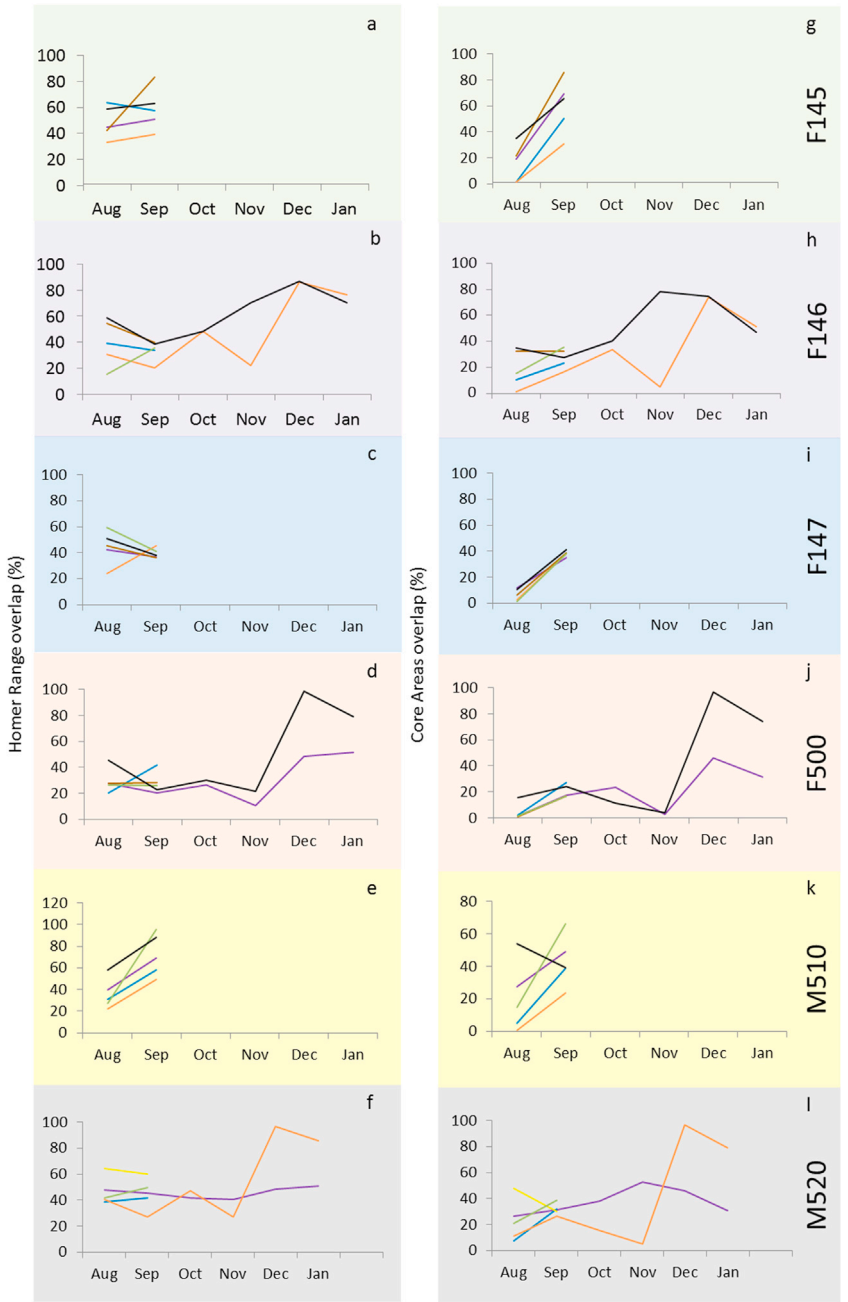

Fig. 5. Percentage of interindividual monthly home range (a to f) and core area (b to i) overlap of mhorr gazelles (*Nanger dama mhorr*).

from the observer, as reported in the reintroductions in the Guembeul Reserve and Katane enclosure (Senegal) (T. Abáigar pers. obs.) and in Bou-Hedma National Park (Tunisia) (Abáigar et al., 1997). So, when released into the wild, the mhorr selected areas far from human presence and disturbance. Consequently, the survival of the last remaining wild Sahel-Saharan antelope populations is related to their settlement in areas far from human presence as, in many cases, this means poaching and competition from livestock (Rabeil et al., 2013; Stabach et al., 2017; Herrera-Sánchez et al., 2020).

Our results have also corroborated previous observations and speculations from the mid-20th century (Morales-Agacino, 1949; Valverde 1957; Cano 1991) that describe that *Acacia* trees are keystone species (Mills et al., 1993) when the mhorr need to establish new territories and areas of intense activity.

Although the study area does not have any great topographical variation, based on our results it seems that mhorr's prefer flat, less rough terrain where they can move around more easily while also ensuring greater visibility (in case of predators) at

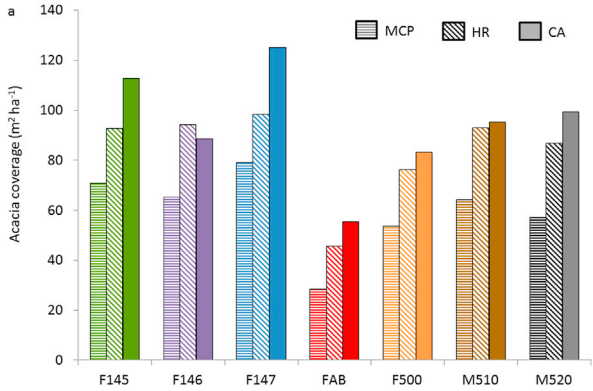

Fig. 6. *Acacia raddiana* cover (m^2/ha) (a) and Roughness (m) values (b) in the home range (HR) and core area (CA) of mhorr gazelle (*Nanger dama mhorr*) estimated following the ensemble method, as well as the home range measured by Mean Convex Polygon (MCP).

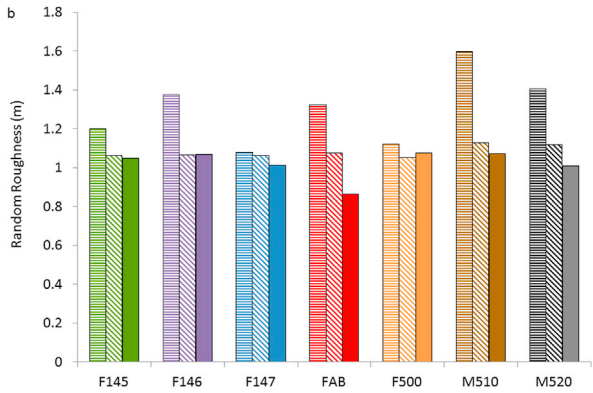

Fig. 6. (*continued*).

the same time as maintaining contact between group members. However, in the case of a particular need or threat, the mhorr are able to pass through areas with greater relief (dunes in our case) and flee long distances to the mountainous areas in the Adrar Sottouf (160 km from their territories), as happened after poachers entered the established territory of the gazelles (Abáigar et al., 2019). Similar behaviour has been observed in the dama gazelle (*Nanger dama dama*) in the Termit massif (Niger) when it is threatened (Rabeil et al., 2013).

The results of this study are valuable and encouraging in terms of future conservation actions in the wild, not only for the mhorr gazelle but for the entire dama gazelle species. Firstly, we have confirmed the main biological and ecological traits of the subspecies that, until now, have only been briefly defined. Secondly, the study provides empirical data in terms of habitat requirements and territories for future conservation actions and reintroduction projects. Although space is a trade-off in terms of food availability (including its seasonal variability) and the density of the reintroduced population, the results of this study establish guidelines, in term of advisable area, for future reintroductions of the mhorr gazelle. As can be seen in Table 2, the space needed by mhorr gazelles to meet their needs in the wild seems to be larger than the space provided for this subspecies in previous reintroduction projects in fenced-off areas. These projects fixed areas that ranged from a few hundred hectares in the reintroduction of R'Mila Royal Reserve in Morocco (330 ha) to several thousand in the Bou-Hedma National Park, Tunisia (2000 ha) (Abáigar 2018b). Finally, all these results are promising as this subspecies of dama gazelle has been preserved in captivity for generations since its disappearance (Cano 1991; Valverde 2004; Barbosa and Espeso 2005). Such captivity imposes not only human presence but also a loss of genetic variability, as is the case of the mhorr gazelle (Ruiz-López et al., 2012), which could impair the ability of the species to adapt to freedom again. However, it seems that monitored mhorr gazelles have maintained what appears to be an innate ability to select, within a wide and varied territory, the most favourable sites to settle and survive; n all probability, the acclimation period they had in semi-free conditions in the Safia enclosure (600 ha of a fenced-off area with similar habitat conditions to the wild) (Abáigar et al., 2019) contributed to their successful settlement in the wild. These results are in line with some findings on the reintroduction of the scimitar-horned oryx (Oryx dammah) in Chad (Mertes et al., 2019) where size of home range and distance of the territories to the point of release are determine by size and time in acclimatized enclosure as well as period of release (wet *vs* dry season).

5. Conclusion

The project of reintroduction of mhorr gazelle in Morocco offered a unique opportunity to verify and determine the habitat requirements of this species in terms of surface area (size), landscape and the vegetation's characteristics, Although the results came for a limited number of individuals and time of sampling, the results of this study corroborate the importance of flat terrain with high acacia tree covers as main factors for the establishment of mhorr gazelle in their native range along the Atlantic Sahara. The study also provides, for the first time, data size on home range and core area into the wild. Although the size of home range is a trade-off between in terms of food availability (including its seasonal variability) and the density of individuals for any species, current results highlight the differences between the space needed by the mhorr gazelles to satisfy their needs in the wild and the space provided for the species in previous reintroduction projects in fenced-off areas.

Declaration of competing interest

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

Acknowledgements

Authors thanks To the Haut-Commissariat des Eaux et Forêts et à la Lutte Contre la Desertification, their staff at Dakhla and Bir Ganduz, as well as guards of the Safia enclosures (Hossein Jisso, Bilid Ajid, Ali Shmiss, Abdelouadoud Zafir). To volunteers from the Nature Initiative Ass. for their field work and assistance and to the Spanish Ministry of Ecological Transition. This project has been funded by UNESCO/Man and Biosphere Program (France) (nº 4500261532), HCEFLCD and the National Spanish Research Council (Spain) (CSIC OTT2005X0269). E.R.C was supported by the HIPATIA-Almeria University (Spain) postdoctoral fellowship founded by the University of Almeria.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2020.e01389.

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