Second phase of the Namibian Cheetah Survey

Camera traps surveys in the central Namib and Khomas Highlands using high resolution GPS telemetry data from free-ranging cheetahs

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Preface

The present document is a final report of the second phase of the Namibian Cheetah Survey submitted by the Cheetah Research Project of the Leibniz Institute for Zoo and Wildlife Research (IZW) of Berlin to the Namibian Chamber of Environment (NCE).

This current project was funded by the NCE Grants Fund and runs from the 13th of February 2020 until the 28th February 2022, by which time all work, outputs and deliverables have been completed.

This study was designed and planned by Joerg Melzheimer. The field work in the central Namib was carried out by Ruben Portas with the assistance of Sebastianus Amukoshi. The fieldwork in the Khomas Highlands was carried out by Rebekka Mueller and Ralf Roeder with the assistance of Konrad Amutenya and under the supervision of Joerg Melzheimer. The analyses were conducted by Ruben Portas and Joerg Melzheimer. This final report was written by Ruben Portas and edited by Bettina Wachter and Joerg Melzheimer.

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Acknowledgments

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We like to thank Kenneth Heinrich /Uiseb, deputy director of the Scientific Services of the MEFT for his unconditional support and for initiating this study. We would also like to thank Dr Chris Brown for his support for the second phase of this project. We further wish to thank the following farm owners, supporters and collaborators in the two study areas for their hospitality, knowledge sharing, help and unconditional interest during the last two years.

In the study area central Namib Desert: Our thanks go to the owners of the farm Abendruhe (Namib Naukluft Desert Lodge), farm Ababis, farm Solitaire, NamibRand Nature Reserve and farm Ruimte for their interest and continuous support. We also thank the Nauchas and Maltahöhe farmer's associations. Our thanks also go to the MEFT rangers and wardens of Ganab, Sesriem and Zais stations for their valuable help and information. Their information was important in helping us to start the project in this study site.

In the study area Khomas Highlands: We thank all the farmers of the Auas Oanob Conservancy for supporting our long-term IZW Cheetah Research Project. With their interest and contribution, we have carried out 20 years of research on cheetahs so far, answering crucial ecological and evolutionary questions which increased the knowledge of this species substantially. This survey was carried out in the farms Krumhuk, Heusis and Claratal.

We also thank the students from the Namibia University of Science and Technology (NUST), Sebastianus Amukoshi and Konrad Amutenya who helped in the field during their internships within our project.

A special acknowledgment also goes to all the current and former members of the IZW Cheetah Research Project for many years of hard work that have built up the knowledge to make this study possible. Special thanks go to Rebekka Mueller and Ralf Roeder who collected the data in the Khomas Highlands included in this report.

Executive Summary

The cheetah *Acinonyx jubatus* is the most threatened large felid species in Africa and is categorized as "vulnerable" by the International Union for Conservation of Nature (IUCN). The global cheetah population is estimated at approximately 7,100 individuals and confined to 9% of its historical distribution range. The largest remaining viable population of free-ranging cheetahs is located in southern Africa and estimated to be approximately 4,000 individuals, of which only 25% occur in protected areas.

Human wildlife conflict (HWC) due to perceived or real livestock and game predation, prey decline and habitat loss and fragmentation are the main threats to this population, whose future is currently uncertain. Previous population estimates for Namibia are vague and ranged from 2,000 to 8,000 animals. Reliable information on the abundance and density estimates of cheetahs in Namibia are scarce and the development of conservation strategies to conserve this valuable population is urgently needed.

The main objective of this study is to follow up from knowledge gaps identified during the first phase of the Namibian Cheetah Survey (Portas *et al.* 2017) and to estimate the cheetah abundance and density in two selected study areas within different ecological environments in Namibia, assess cheetah status and obtain more accurate information on the distribution of cheetah across the country.

During the second phase of this project which is presented in this report and lasted two years, we captured in our newly established study area in the central Namib 11 cheetahs (a single female, a female and her cub and eight males) and fitted four of them with GPS collars. In our long-term study area in the Khomas Highlands we captured five males and fitted three of the males with GPS collars. By checking the GPS telemetry data for locations that were repeatedly and regularly visited, we identified 172 cheetah marking locations in the central Namib and 74 in the Khomas Highlands. Confirmed marking locations in the central Namib were surveyed with camera traps during 68 days from the 14th of March to the 20th of May 2020 summing up to a total of 2,038 camera trapping nights. Confirmed marking locations in the Khomas Highlands were surveyed during 31 days from the 5th October until the 5th November 2020 resulting in a total of 840 camera trapping nights. Our study design using GPS data from

collared animals in combination with camera traps set at cheetah marking locations increases the camera trap success to obtain robust density estimates.

Cheetahs were found in both study areas with 0.2-0.4 cheetahs per 100km² density in central Namib and 0.1-0.3 cheetahs per 100km² in the Khomas Highlands. These two study areas have been surveyed systematically for the first time. Additional data on presence of cheetahs was collected in adjacent areas to the study sites during preliminary prospection, camera trapping and capture of cheetahs. During the project, data was collected on cheetah mortality. Six cheetahs died in central Namib: one was probably killed by spotted hyenas *Crocuta crocuta*, two died from unknown reasons and a coalition of three males died in the Namib Desert after feeding on a carcass of a mountain zebra *Equus zebra hartmannae* that tested anthrax positive. This is the first reported case of a wildlife species dying of anthrax in the Namib Desert. A report was published in the scientific journal *Frontiers of Veterinary Science* and is available open access. In the Khomas Highlands, one cheetah was shot on a farm and one died from unknown reasons.

Especially the ratio of territorial males to non-territorial (floater) males is a good indication for the status of the populations. In this case, both populations seem to be stable but are clearly at the lower end of viable populations.

Valuable data on distribution of other mammal and bird species were collected during the fieldwork and camera trap surveys. The data were uploaded to the Atlasing of Namibia project which records biodiversity and cultural heritage in Namibia and to the southern African Bird Atlas Project, respectively.

The results represent a snapshot in time of the cheetah population in both study areas. No previous information is available using the same methods as we used, and this report provides the first abundance and density estimates for those areas. Further surveys with the same methodology are needed to establish population trends.

We suggest to repeatedly monitor the population in all the study areas surveyed during both first (Kunene, Etosha National Park and Etosha Conservancy, southern Namib and east-central Namibia) and second phases of the Namibian Cheetah Survey. Additionally, we suggest surveying the Erongo (Omaruru – Uis) and Otjozondupa regions (Tsumeb-Otavi-Grootfontein) and the Namibian part of the Kavango-Zambezi Transfrontier Conservation Area (KaZa) to fill relevant information gaps in the distribution and density of cheetahs in Namibia. Further information in the northern Kunene would also be valuable to understand the population dynamics of cheetah south of the Kunene river and the potential connectivity with the Iona National Park in Angola, where work on the cheetah population is being currently carried out.

Introduction

The cheetah *Acinonyx jubatus* is the most threatened large felid species in Africa and is categorized as "vulnerable" by the International Union for Conservation of Nature (IUCN) (Durant *et al*. 2015). The global cheetah population is estimated at approximately 7,100 adult individuals and confined to 9% of its historical distribution range (Durant *et al.* 2017, Figure 1). The largest remaining viable population of free-ranging cheetahs is located in southern Africa and estimated to be approximately 4,000 individuals, of which only 25% occur in protected areas (Durant *et al.* 2017). Human wildlife conflict (HWC) due to livestock and game predation, prey decline and habitat loss and fragmentation are the main threats to this population (IUCN/SSC 2015) whose future is currently uncertain. Recent data published by experts (Durant *et al.* 2017) suggest that the species should be up-listed from the IUCN Red List category "vulnerable" to "endangered".

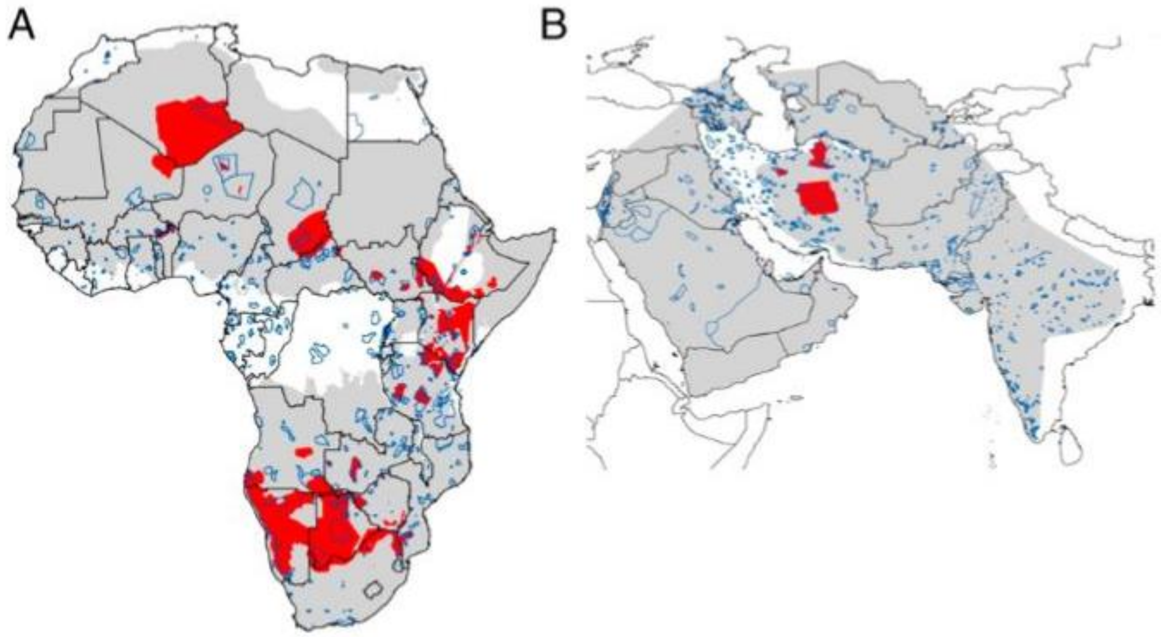

Figure 1: Currently known cheetah distribution (red) and historical range (grey) in (A) Africa

and (B) Asia. Boundaries of protected areas are marked in blue (extracted from Durant *et al.* 2017).

In the 1990's, Namibia was estimated to host an important part of the southern African population. Previous population estimates for Namibia are vague and ranged from 2,000 to 8,000 animals (Morsbach 1987, Hanssen & Stander 2004, Purchase *et al.* 2007, Myers 1975, Joubert & Mostert 1975). The latest estimation based on a collaboration of more than 50 scientists assessed a number of approximately 4,000 cheetahs for entire southern Africa (Durant *et al*. 2017). Reliable information on the abundance and density estimates of cheetahs in Namibia is scarce (Purchase *et al*. 2007) and the development of conservation strategies to conserve this valuable population is urgently needed.

The largest proportion of the Namibian cheetah population occurs on commercial farmlands, where the largest natural competitors (lion *Panthera leo* and spotted hyena) are extinct or at low densities. Water and prey is abundant throughout the year, but a large number of cheetahs are killed every year due to HWC. In Namibia, cheetahs are widely distributed and highest densities have been reported for the central parts of the country (Marker-Kraus *et al.* 1996, Marker *et al.* 2003).

Similar to other large carnivore species, cheetahs are notoriously difficult to survey due to their wide home ranges, elusive habits and secretive behaviour (Belbachir *et al*. 2015). Several studies have been conducted within Namibia in different habitats to determine the density of cheetahs. The methodology of these studies differs from each other and the resulting densities vary substantially (Table 1).

In 2003, a study on a national scale was carried out to obtain detailed information on cheetah distribution, abundance and density (Hanssen & Stander 2004). Sighting returns (n=701) from the public (including hunting guides, conservation authorities, tour operators and tourists) were merged with data from intensive field studies and extrapolated to obtain a national population estimate. The resulting abundance and density of cheetahs was calculated for three different areas with a combined population estimate of 4,456 (3,138- 5,775) cheetahs (Table 2 and Figure 2) (Hanssen & Stander 2004). The results suggested that the highest densities of the species occur outside protected areas.

Table 1: Summary of previous studies on cheetah density estimates in Namibia.

Studies	Joubert & Mostert 1975	Myers 1975	Morsbach 1987	Fischer 2012	Portas et al. 2017	Fabiano *et al.* 2020
Study period	1975	1975	1984-1986	2011-2012	2015-2017	2005-2014
Duration (years)	1	1	2.5	2	3	9
Study area (km²)	Namibia 825,625	Namibia 825,625	Unknown	20,000	ENP & EC: 6,766 SN: 7,207 KN: 6,925 ECN: 50,340	277-477
N° of radio collared cheetahs[1]	0	0	17	150	9	40
Density estimate (cheetahs/100 km²)	6,000 in Namibia[3]	1,500 in Namibia[2]	2.00 2,000 – 3,000 in Namibia	0.40-1.30	ENP & EC: 0.6 SN: 0.20 – 0.40 KN: 0.10 – 0.25 ECN: 1.06	1.94

[1]: the N° of radio collared cheetahs includes animals collared by the researchers already before the density studies began.
[2]: would result in 0.0018 cheetahs/100 km^2 if indeed the entire country was surveyed.
[3]: would result in 0.0073 cheetahs/100 km^2 if indeed the entire country was surveyed.
ENP & EC: Etosha National Park and Etosha Conservancy
SN: southern Namib
KN: Kunene
ECN: East-central Namibia

Table 2: Population estimates for three cheetah density categories and estimated area for these densities, extracted from Hanssen and Stander (2004).

Density category	Area covered (km²)	Cheetahs/100 km²		Population estimate (n° of cheetahs)	
		Min.	Max.	Min.	Max.
Low density (beige)	356,636	0.05	0.1	178	357
Medium density (violet)	125,058	0.7	1.5	875	1,876
High density (orange)	104,203	2	3.4	2,084	3,543
Total	**585,897**			**3,138**	**5,775**

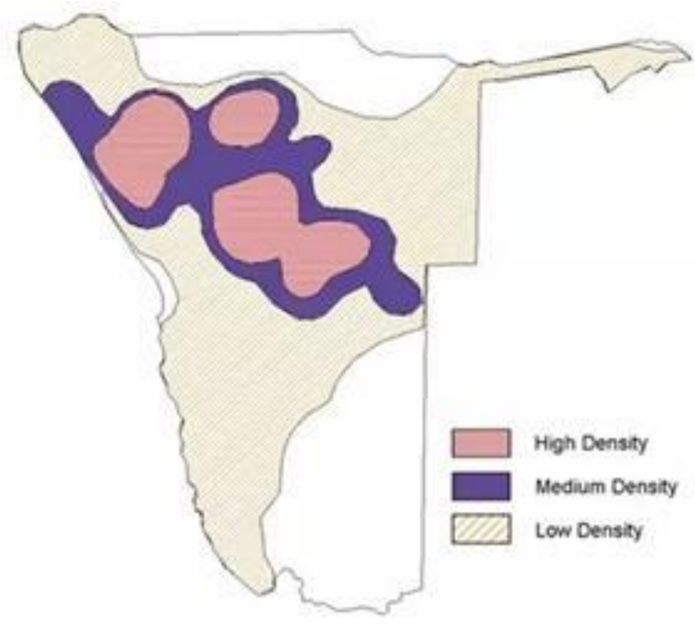

Figure 2: Cheetah density categories in Namibia extracted from Hanssen and Stander (2004).

Since 2004, only one attempt to update the national cheetah estimate has been made using information provided by questionnaires (Stein *et al.* 2012). The results have shown an increase of the population with a total of 7,648 to 13,520 animals which the authors have reported to be likely inaccurate and overestimated. Annual cheetah removals from freehold farms historically ranged between 650–890 individuals (Morsbach 1987). The Ministry of Environment, Forestry and Tourism of the Republic of Namibia (MEFT) has collected information on cheetah removals from the late 1970s to the mid-1990s and reported an annual average number of 553 killed cheetahs from the late 1970s to the mid-1980s (Nowell 1996). The number decreased from the years 1986 to 1995, when an annual average number of 297 killed cheetahs was reported (Nowell 1996). More recently, the MEFT recorded that the total number of killed cheetahs from 1997 to 2004 was 1,679, which averages as 240 animals per year. Of these, 1,088 were killed as “problem animals”, whereas 591 were hunted as trophy animals. The actual number of cheetahs removed as “problem animals” is likely to be higher than the number reported to the MEFT (Marker-Kraus *et al.* 1996). Since 1992, Namibia has been granted by the Convention for International Trade for Endangered Species (CITES) a limited trade of 150 cheetahs annually (both live export and trophy hunting) (CITES 1992. Between 2003 and 2013, almost 1,200 free-ranging cheetah trophies were legally exported from Namibia (CITES trade database).

From September 2015 until October 2017, the Cheetah Research Project of the Leibniz Institute for Zoo and Wildlife Research (IZW) together with the MEFT carried out a country-wide survey to obtain data on distribution and density of cheetah across different biomes in Namibia (Table 1) (Portas *et al.* 2017).

Free-ranging cheetahs were captured in 1) the southern Namib Desert, 2) Etosha National Park and Etosha Conservancy and 3) the communal land in the Kunene to obtain first GPS telemetry data and providing home range estimates and location of cheetah territories and marking sites. Camera trap surveys were run in these study areas and in Khaudum National Park (KNP) to provide first camera trap density estimates for cheetah and leopard (Portas *et al.* 2017, Portas *et al.* 2022).

During the first cheetah survey, knowledge gaps were identified and further steps for cheetah conservation suggested (Portas *et al.* 2017, Melzheimer *et al.* 2022). The work presented in this report aims to cover the knowledge gaps in two additional study areas: the central Namib where farmers have reported a notarial increase of the cheetah population and the Khomas Highlands which is a key area for connectivity between the central- and north-east stronghold of the cheetah population and the western and more arid parts of the country. Additionally, this report summarizes the main field findings and synthetizes future research priorities and conservation goals for the species.

Scientific background

The characteristic cheetah spatial ecology

Since 2001, our team investigates, among other topics, the spatial ecology of cheetah males. For this, we use high-resolution movement data collected from GPS collars fitted to free-ranging cheetahs within the frame of our long-term study. Our two main findings regarding the cheetah spatial ecology are:

1) We described two spatial tactics of cheetah males in Namibia (Melzheimer *et al*. 2018), similar to findings in the Serengeti NP in Tanzania. These findings show that adult males either:

a) defend small territories (in Namibia: 379 ± 161 km^2 [mean ± standard deviation]) by spraying with urine or defecating with faeces on prominent landmarks such as trees, termite mounts or rock in approximately 94% of their visits (Figure 2).

or b) travel in large home ranges (1,595 ± 1,131 km^2) encompassing 2 to 4 territories which they do not defend but visit to sniff and obtain information from the marking locations defended by the territorial males (Figure 3).

Females have home ranges of intermediate size (650 ± 278 km^2), overlapping with male territories and floater home ranges.


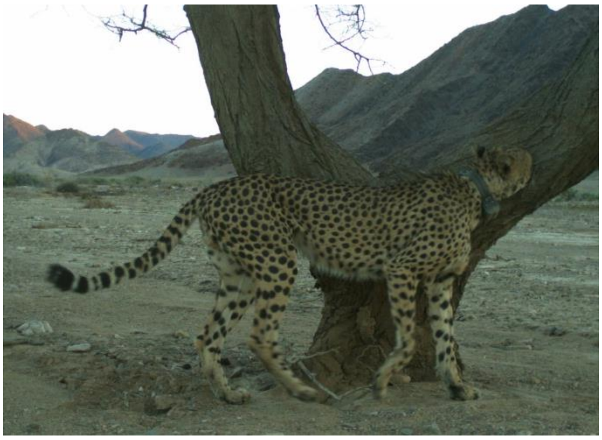

Figure 2: Territorial male scent marking a tree. Figure 3: Floater male sniffing a marking tree.

This spatial system with territorial males overlapping only a portion of the range of any one female and floater males covering large areas is unique in the mammalian system. We also identified several predictors linked to each spatial tactic of cheetah males. Territorial males exhibit marking behaviour, they have a high body mass index (BMI) and are aggressive when captured in traps. In contrast, floaters do only sniff at marking location, have a low BMI and are anxious in traps. These findings were published in the journal Ecosphere (Melzheimer *et al.* 2018) and are available open access.

2) We further identified "hotspots", i.e. areas of high cheetah activity, which are regularly distributed across the landscape with an average distance of 23 km between them. This means that the hotspots were not adjacent with each other but separated by a surrounding matrix of low cheetah activity (Figure 4). The hotspots represent clusters of marking sites such as conspicuous trees, rocks and termite mounts and are frequently marked with urine and faeces by territorial cheetah males (Figure 2). The marking sites are also visited by floaters and females and used by all cheetahs to receive and/or leave information (Figure 3). The locations of hotspots remain constant over time and are kept by successive territory holders, thus maintaining the overdispersed distribution in the landscape (Figure 5). We termed the hotspots "communication hubs" due to their function for the cheetah population. We defined the communication hubs spatially as the Kernel Density Estimation including 50% of the GPS locations of the territorial males (KDE 50). These findings were published in the journal Proceedings of the National Academy of Sciences (Melzheimer *et al*. 2020) and the article is available open access.

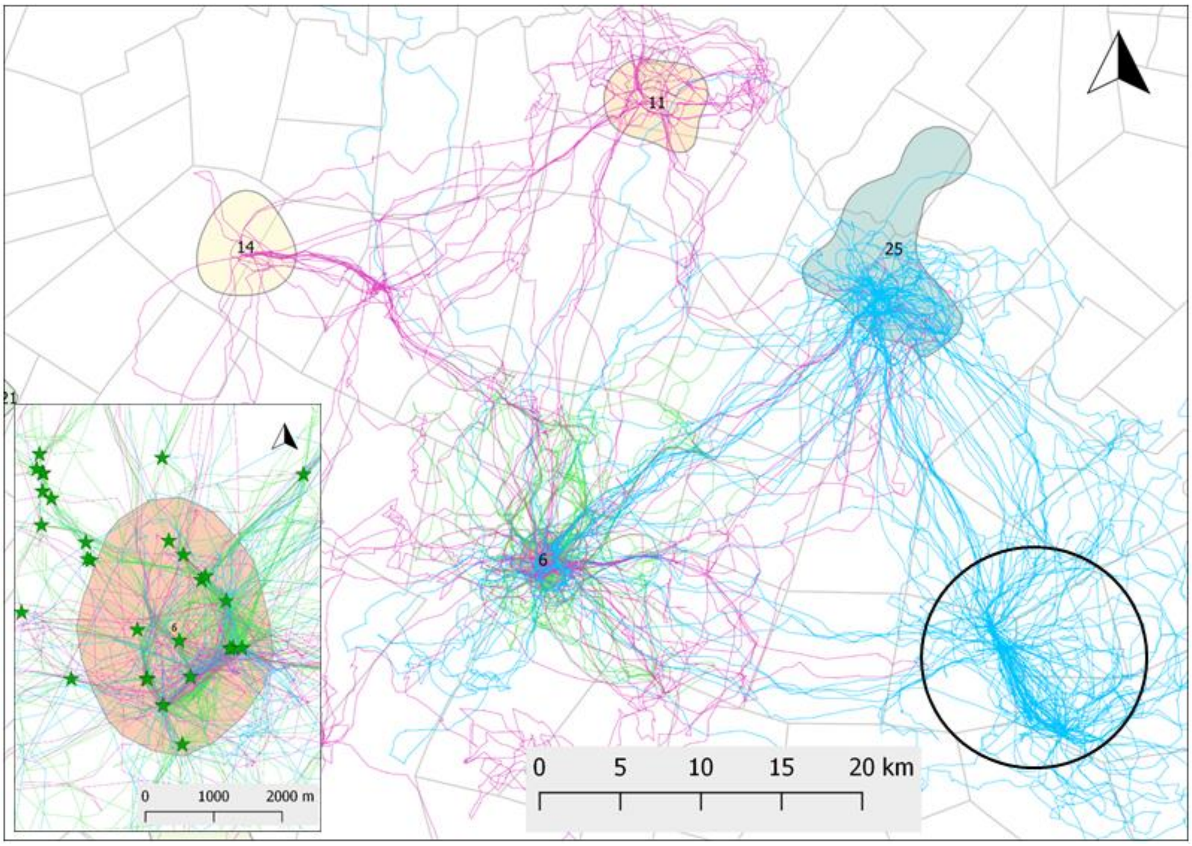

Figure 4: Movements of two cheetah floater males (pink and blue lines) and a cheetah territorial male (green lines) showing the locations of five communication hubs distributed within commercial farmland (grey polygons). Using the movement data of cheetahs, marking sites can be identified (green stars). Figure adapted from Melzheimer *et al*. (2020).

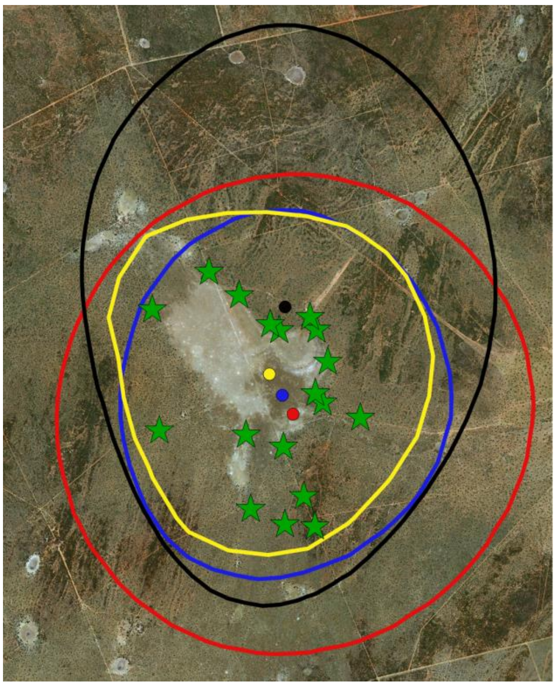

Figure 5: The circles represent the KDE 50 of four cheetah territory holders which represent the communication hub. The coloured dots show the corresponding centroid of each KDE 50. The green stars represented the marking sites defended by the territorial males. Figure adapted from Melzheimer *et al*. (2020).

Applied ecology: Using the gathered spatial knowledge to tackle human-wildlife conflict

Our findings have important implications for the conflict between farmers and cheetahs in Namibia. Identifying the locations of the communication hubs provides vital information to the farmers to adapt their herd management accordingly. When breeding herds are moved out of the high risk hotspots, cattle calf losses can be reduced substantially. In our study area in central Namibia, this adaptive management of cattle herds reduced the livestock losses by 86% (Figure 6). This suggests that efforts of conflict mitigation should include the spatial organization of cheetahs on a landscape level.

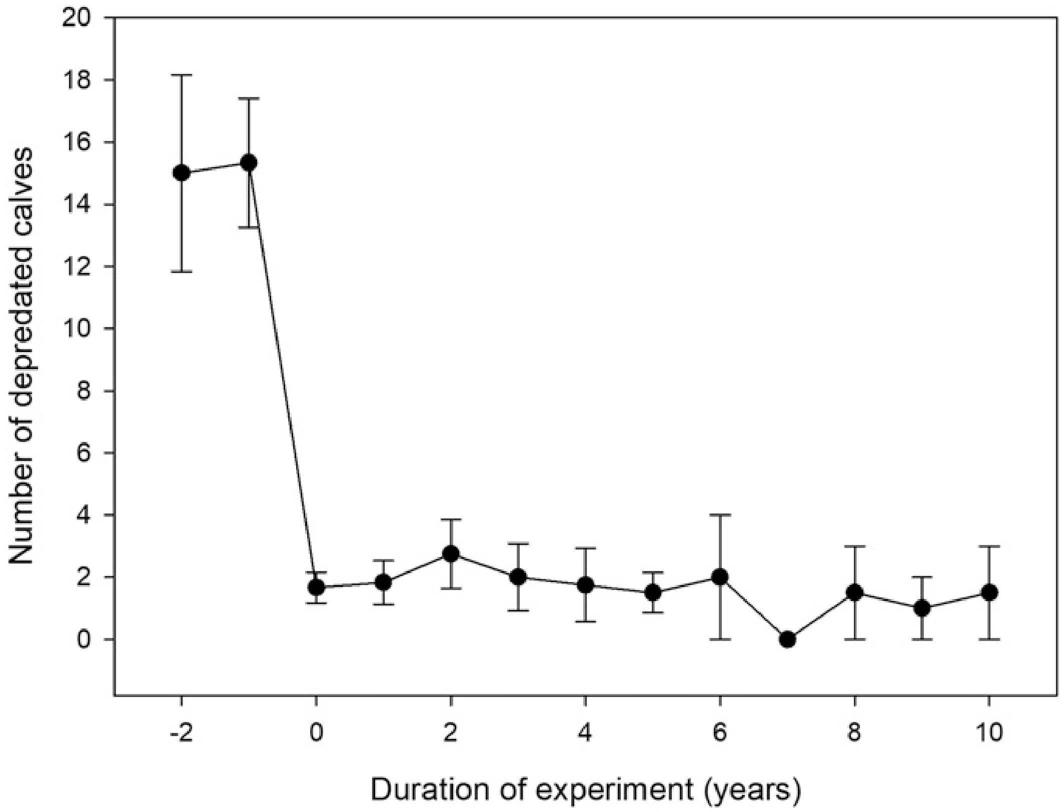

Figure 6: Number of losses before, during and after the experiment of four farms where communication hubs were identified and herding management actions were taken accordingly to reduce livestock losses. Figure adapted from Melzheimer *et al.* (2020)

Developing a specific methodology to survey cheetahs: Use of GPS telemetry data to find marking sites and increase camera trap success

Cheetah males exhibit intrasexual behavioural differences after they dispersed from their natal home range and established in a new area (Caro 1994; Melzheimer *et al.* 2018). Such differences in the spatial ecology of adult males and the resulting inhomogeneous distribution of cheetahs in the landscape are likely to result in differential use of the area. This is because territorial males remain within their territory while floater males are moving in and out the territories. When carrying out camera trap surveys, such inhomogeneous spatial distribution of cheetah across the landscape creates heterogeneity in capture probability (Edwards *et al*. 2018).

Using movement data from GPS collared cheetahs is a prime tool to identify communication hubs (CH)[1] and key in finding and selecting the most active marking tree locations within the landscape (Fisher 2012, Edwards *et al*. 2018, Melzheimer *et al.* 2020). Knowing the existence and location of CHs and marking sites, as well as the unique spatial ecology of cheetahs is crucial to plan research such as camera trap studies (Fisher 2012, Portas *et al*. 2017, Edwards *et al.* 2018, Melzheimer *et al.* 2020). This is because the high visitation rate of cheetah males to marking sites located within the CHs ensures high capture and recaptures rates. Thus placing camera trap stations at marking sites, albeit biased towards males provides a high detection probability (Marnewick *et al.* 2006, Fisher 2012, Boast *et al*. 2015, Brassine and Parker 2015). This approach ensures a high camera trap success and provides robust density estimates (Fisher 2012, Edwards *et al.* 2018).

Previous studies estimated the cheetah abundance and/or density by placing camera traps randomly, in grids and/or in combination with using cheetah signs and marking sites within the study area (Boast *et al.* 2015, Marnewick *et al.* 2008, Fabiano *et al.* 2020). Other studies have set camera traps mainly at cheetah marking locations (Table 3) (Brassine and Parker 2015, Fischer 2012, Portas *et al*. 2017).

[1]Communication hubs and hotspots are in this proposal used interchangeably with the same meaning and reference to the location where the marking sites visited by cheetahs for intraspecific communication thus leading to a higher cheetah activity in the landscape.

Table 3: Comparison of the capture success between studies and camera trap placement.

Study	Camera trap placement	**Capture success** Cheetah captures/100 trapping nights
Marnewick et al. 2008	Roads, game trails and marking sites	10.00
Fischer 2012	Marking sites using GPS data	13.60
Brassine and Parker 2015	Marking sites	0.68
Brassine and Parker 2015	Roads and game trails	0.31
Boast *et al*. 2015	Roads, game trails and marking sites	1.98
Belbachir et al. 2015	Roads, game trails and marking sites	0.47 and 0.63
Portas et al. 2017 Etosha study site	Marking sites using GPS data	19.00
Portas et al. 2017 Kunene study site	Marking sites using GPS data	2.92
Portas et al. 2017 Southern Namib study site	Marking sites using GPS data	11.53
Portas *et al.* 2017 Central Namibia study site	Marking sites using GPS data	20.52
Verschueren et al. 2021	Marking sites	11.32

Population estimates across larger landscapes can be calculated on the basis of the density estimates obtained with camera traps at the CHs. Producing accurate abundance estimates at a territory level is therefore a crucial first step for subsequent analyses to determine accurate population estimates (Fisher 2012, Portas *et al.* 2017, Edwards *et al*. 2018).

Methodology

Study areas: Central Namib and Khomas Highlands

1. The Namib Desert forms an arid strip along the coast of Namibia with most of the area located in protected land. The Namib borders the Atlantic Ocean in the west and it encompasses communal and freehold farmland in the east. A series of ephemeral rivers that originate in the Namibian highlands cross the heterogeneous and vast Namib from east to west to reach the coast or the sand dunes sea. These linear oases act as wildlife pathways through a landscape filled with sandy and gravel plains, rocky outcrops, inselbergs and sand dunes and support a diverse number of wildlife species adapted to the harsh conditions of the Namib (Seely and Pallet 2008).

   The study area was located in the central Namib encompassing the gravel plains north of the Kuiseb river in the north of the Namib Naukluft National Park (NKNP) and neighbouring farmland all the way to the Tsauchab river and the dune belt, covering also protected area and farmland (Figures 7 and 8, Annexe A). The vegetation is a dwarf shrub transition to desert and is characterized by the presence of grasslands and shrub lands with sparse trees such as *Acacia erioloba*, *Acacia tortilis* and *Boscia species* typically growing along drainage lines (Giess 1971, Mendelson *et al.* 2002).

   Its arid climate is influenced by the coastal weather of the Atlantic sea whose fog contributes to preserve a rich array of biodiversity and softens its temperatures. The coastal fog, which occurs predominantly during the cold-dry and hot-dry seasons, reaches up to 60 km inland. The yearly rainfall has an erratic pattern, thus within a year, it may precipitate as little as few millimetres or up to 150 mm of water. The low precipitation together with the high evaporation makes the Namib one of the driest and harshest environments on earth. The minimum average temperature ranges from 4˚C to 10˚C, the maximum average temperature ranges from 26˚C to 34˚C and the average temperature throughout the year from 18˚C to 20˚C (Mendelson *et al*. 2002). Outside the NKNP, the main economic and human activities are tourism and extensive cattle farming, with some small livestock (sheep and goat) farming. Due to the collapse of the karakul market in the 1980ies (Bubenzer *et al*. 2007) and to the growing tourism industry, there is an increasing number of private nature reserves adjacent to the

NKNP and the numbers of small livestock have been dramatically reduced. This scenario brought more tolerance towards large carnivores and created a buffer around this NP.

Figure 7: Sandy plains with dwarf shrubs and grasses in the central Namib study area.

Figure 8: Characteristic rugged rocky landscape with gravel and sandy plains and dunes in the central Namib. The vegetation is mostly present in the drainage lines and in the sandy and gravel plains.

2. The Khomas Highlands are located south and south-west of the capital Windhoek, in central Namibia and consist of a plateau which has some of the highest elevations (2,000 m asl) and some of the highest peaks of Namibia (2,450 m asl). The annual precipitation ranges from 300 to 350 mm per year concentrated within a rainy season from November to May. Temperatures range from 35°C in summer to frost in winter (Mendelsohn *et al.* 2002). The highlands are formed by an undulating to steep hilly and mountainous landscape, generally with shallow, stony soils (Figures 9 and 10). This very rugged landscape gives origin to diverse habitats and a rich biodiversity. The vegetation of the study area is the highland savannah, dominated by *Acacia hereroensis* and a diverse variety of grass species. The woody vegetation also contains other Acacia species such as *Acacia mellifera* and *Acacia karroo* and other trees and bush species such as *Ziziphus mucronata*, *Combretum apiculatum*, *Tarchonanthus camphoratus* and *Catophractes alexandri* (Giess 1998, Strohbach 2017). More than 50 species of grasses can be found in the study area within diverse habitats such as rivers, camelthorn savannah, high mountains, rocky hills and bush-encroached lowlands. The Auas mountain range has been identified as botanically important as 217 plant species occur of which 23 are endemic to Namibia (Strohbach 2017). The Khomas Highlands hosts a rich and diverse fauna and large mammal species such as mountain zebra *Equus zebra hartmannae*, kudu *Tragelahus strepsiceros*, oryx *Oryx gazella*, warthog *Phachocoerus africanus*, springbock *Antidorcas marsupialis*, leopard, cheetah, brown hyena *Parahyaenna brunnea* and a number of smaller herbivores and carnivores. More than 150 bird species have been registered in the area. The main use in the area is cattle and game farming, horse breeding, hunting and tourism. A group of farms have formed the Auas Oanob Conservancy which covers more than 1,000 km^2 with the common goal of sharing sustainably resources among all the members and promote the conservation of natural resources and wildlife. The study area covered several of these farms (Annexe A).

Figure 9: Typical open landscape in the Khomas Highlands dominated by *Acacia hereorensis*, *Tarchonanthus camphoratus* and a mix of grass species.

Figure 10: Characteristic mountainous landscape of the Khomas Highlands.

Field methods

The data collection in the field followed the subsequent procedure:

1. Camera trap placements:

We approached local stakeholders to obtain information on cheetah presence within the designed study area (Figure 11). Their information was used to set up a number of camera traps to determine suitable locations to capture free-ranging cheetahs in box traps.

Figure 11: Talk given during a farmers-union meeting to introduce the Namibian Cheetah Survey.

2. Capture of free-ranging cheetahs:

We used electronic box traps equipped with a small computer, a pair of infra-red (IR) light beams and a trigger mechanism (Figures 12 and 13). The traps were monitored with an in-built GSM/GPRS modem which sent SMS when the trap closed and pictures when movement was detected. In areas without coverage, we used TT3 Globalstar Satellite Trap Transmitters (VECTRONIC Aerospace GmbH Berlin, Germany). This device sent emails every 30 min once the trap gates closed. The electronic box-traps were programmed to be active only during cheetah activity time by activating the IR light beams at selected times. These beams were set at the height of a cheetah. Thus, the box traps were only triggered by crepuscular animals with cheetah body height, which considerably reduced the capture of non-target animals. In addition, our box traps minimized the time the animal spent in the trap by providing immediate alarm once the animal has been trapped (Portas *et al*. 2019).

Figure 12: Setting up a box trap in the Namib Naukluft NP together with the warden and rangers of the MEFT Ganab station.

Figure 13: Electronic box traps targeting a coalition of territorial males. The traps were set on a farm in the Namib Desert. Notice the solar panel in the left and the directional antenna attached to a pole in the middle of the tree canopy.

3. Immobilisation and sampling:

Captured cheetahs were immobilized with a mixture of ketamine (3.0 mg/kg; Kyron Laboratories, South Africa) and medetomidine (0.06 mg/kg; Kyron Laboratories, South Africa), and reversed with atipamezole (Antisedan, 0.25 mg/kg; Zoetis, South Africa) as described in Portas *et al.* (2021). During the immobilization, blood and tissue samples for additional research questions were taken, vital signs were monitored and sampling sheets filled (Figure 14). The process from darting to the antidote lasted approximately 50 minutes. Then, the cheetah was placed on a padded rug to monitor its recovery (Figure 15) or placed inside a box trap if leopards or spotted hyenas were present in the area. Once the effects from the narcosis vanished and the drugs were metabolized, the box trap gate was opened and the cheetah released back to the wild.

Figure 14: Immobilisation of free-ranging cheetah on a farm located in the Namib Desert.

Figure 15: Cheetah immobilised in the Namib-Naukluft NP.

4. Fitting GPS collars and analysing the movements of cheetahs:

The cheetahs were fitted with GPS collars (e-obs GmbH, Grünwald, Germany) with a battery life of approximately two years and scheduled to take positions every 15 minutes. The collars weighed 330 g which represented 0.50 % to 0.70 % of the animal's weight. Data retrieval for these collars was done via aerial tracking flights as described in Wachter *et al.* (2006) which often allowed us direct observation of the study animals during the data download (Figure 16). The downloaded data were stored for long-term accessibility in the online platform Movebank (Kays *et al.* 2022). One animal was fitted with a GPS satellite collar (Tellus Satellite, Followit Wildlife, Lindesberg AB, Sweden) scheduled to record positions every 30 min between 15:00 and 7:00 and hourly positions between 7:00 and 15:00 Greenwich Meridian Time (GMT) for approximately four months. The collar weighed 270 g which represented 0.60 % of the animal's weight. Data retrieval was performed by Iridium satellite communication after every 11th position was taken. The collar was programmed to drop off from the animal´s neck after five months in order to not leave the animal with a collar once the battery was depleted and to avoid the need to recapture and immobilize the cheetah to remove the collar.

Figure 16: Coalition of male cheetah photographed during an aerial radio-tracking session.

5. Identification of marking sites:

GPS data from collared cheetahs was explored and clusters of GPS coordinates indicating locations that cheetahs regularly re-visit were identified using the free and open source software QGIS 3.10 A Coruña (QGIS.org, 2022). The identified GPS clusters were then visited in the field. Marking site locations were recorded into a database collating data such as the marking site type (e.g. tree, rock or termite mount) and number of cheetah scats found within the marking location.

6. Identification of camera trapping locations:

Using the number of scats found on each marking tree, we decide where to deploy the camera trap stations. We assumed there is a positive correlation between the number of scats and the level of cheetah activity on a marking tree. Thus, we chose the 10 trees with the highest numbers of scats per territory aiming to record a high cheetah visitation rate. We ensured that there was a wide spatial coverage of camera trap stations of each territory (Figure 17).

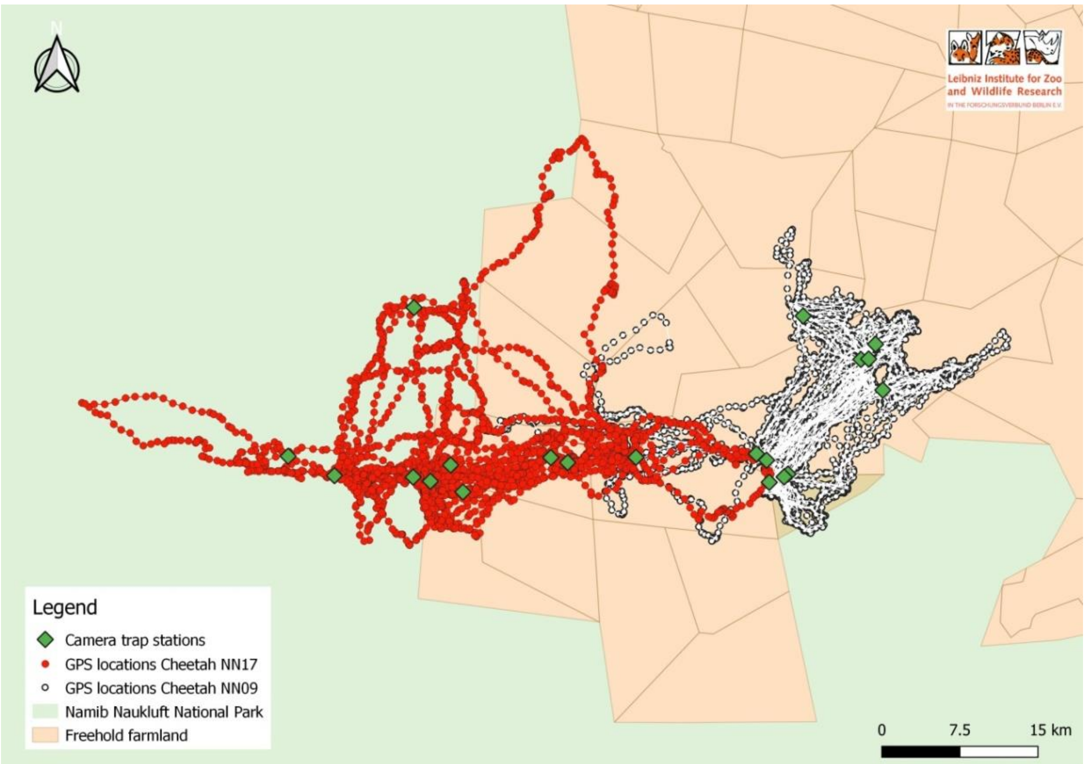

Figure 17: Camera trap survey in the Namib Desert. The green diamonds represent the camera trap stations surveying marking sites throughout two cheetah territories. One cheetah ranged

mainly on farmland (white dots), while the other cheetahs ranged on farmland and within the NKNP (red dots).

7. Camera trapping survey

Two camera traps monitored each of the 10 marking sites within a territory. The survey in the central Namib run for 68 days, whereas the survey in the Khomas Highlands run for 31 days. Three territories were surveyed in each of the two study areas and 60 Reconyx HC600 HyperFire H.O. Covert I.R. (Reconyx Inc, Holeman, Wisconsin, USA) camera traps were deployed per study area. The two camera traps per marking site were set opposite to each other with a lateral offset to avoid flash interference. Cameras were mounted in metal protective boxes at cheetah shoulder height (approximately 70 cm above the ground) and attached to metal H shaped poles that were set three to five meters away from the marking site (Figure 18). Bushes, grasses and other objects that could interfere between the cameras and the marking sites were removed. The cameras were programmed to high sensitivity, no interval between pictures (RapidFire) and three pictures per trigger. Local time was selected. Twelve rechargeable batteries and 8 GB memory SD cards were used and exchanged at least every three weeks.

Figure 18: Camera trap station consisting of two camera traps monitoring a marking tree in the Namib Desert.

Data analysis

Camera traps are well-established and efficient tools in conservation and ecological research (Rowcliffe and Carbone 2008, O'Connell *et al.* 2011, Rovero *et al.* 2013). Capture-recapture models using camera trap data to estimate species abundance and density have been successfully used with a large number of felid species (Karanth and Nichols 1998, Sollman *et al.* 2011, Edwards *et al*. 2018, Portas *et al*. 2022). Especially for rare and elusive animals, camera trap surveys might be the only way to estimate population density, but capture and recapture rates are often too low to allow for reliable estimates (Royle *et al*. 2014).

The data, i.e. picture files, were retrieved from our camera traps, stored in a hierarchical folder system and loaded into the software Camelot (Hendry and Mann 2018). Each cheetah was individually identified by its unique pelage patterns (Caro 1994). Basic information such as the species, group size, sex, age class, spatial tactic of the cheetah unit (i.e. territorial or floater), ID given to each unit and behaviour was tagged into all the images collected and written into the metadata of every photograph.

Pictures of cheetah were classified into independent events with a minimum of 30 minutes between consecutive pictures of the same individual or coalition members (O'Brien *et al*. 2003). Cheetahs rest during the heat of the day and become active during the night with peaks at sunset and sunrise (Broekhuis *et al*. 2014). Due to this, a *sampling day* was set to start at 12:00 and to end at 11:59 on the following day to avoid the 'midnight problem' in which an individual visiting the camera trap station either side of midnight would be classed as being present on two consecutive sampling occasions (Jordan *et al.* 2011). Therefore, several visits of the same cheetah unit within the same night were included within the same sampling day.

Once all the images were tagged and processed, several output files were exported as csv files. Output files included for example the camera trapping effort summary, species statistics, summary reports, trap station statistics, occupancy matrix files for the software PRESENCE, input files for CamtrapR (Niedballa *et al*. 2016) and a raw data export file. The latter included details on each uploaded picture of each single wildlife species photographed at each camera trap station during the entire survey. Additionally to the metadata which was manually tagged by the user, Camelot exports other information such as the date, the time the camera trap station was active and the survey location. The event file detailing each cheetah visit to the marking site was then transformed into a binary file describing the captures and recaptures of every cheetah photographed during the camera trap survey. Additional data such as the information related to the camera trap station (marking site code, camera ID geographical coordinates, date of start and end of the survey and length of the survey) is also automatically extracted in a separate Comma Separated Value (CSV) file.

Statistical analyses to obtain abundance estimates

The event file was transformed into a binary file containing the captures of each cheetah unit throughout the survey and during each one of the trapping occasions. A “0” was used when the cheetah unit was not detected by the camera traps and a “1” was used when the cheetah unit was detected (Figure 19). A *trapping occasion* was defined as four successive sampling days following Fisher (2012). The binary file data was copied into a Notepad++ and saved as an “INP” format to be imported for capture-recapture analysis into the program MARK (White 2008).

```
101011101101 1;
010000100010 1;
```

Figure 19: Example of a binary file in which the numbers “1” mean that a cheetah was detected by our camera traps and the numbers “0” means that it was not detected. The last number before the semicolon indicates that the history capture refers to a single individual. The upper row represents a typical capture history of a territorial male which is often detected by our camera traps within the communication hub (CH), while the lower row represents a typical capture history of a floater which is only detected when he entered the surveyed CH after arriving from a neighbouring CH.

The difference in capture probability between territorial males and floaters is problematic for abundance models, as most models assume equal capture probabilities for all individuals. To overcome this issue, we used finite mixture models (Pledger 2000) run in program MARK to estimate male cheetah abundance within territories, following Edwards *et al.* (2018). We chose mixture models because they give an accurate and highly precise estimate and do not require knowledge about the spatial tactic of each individual. This is very useful when working in new areas where the spatial tactics of individuals are not yet known. Furthermore, it can produce an estimate of pi (π) which indicates the probability of any individual in the population being a floater.

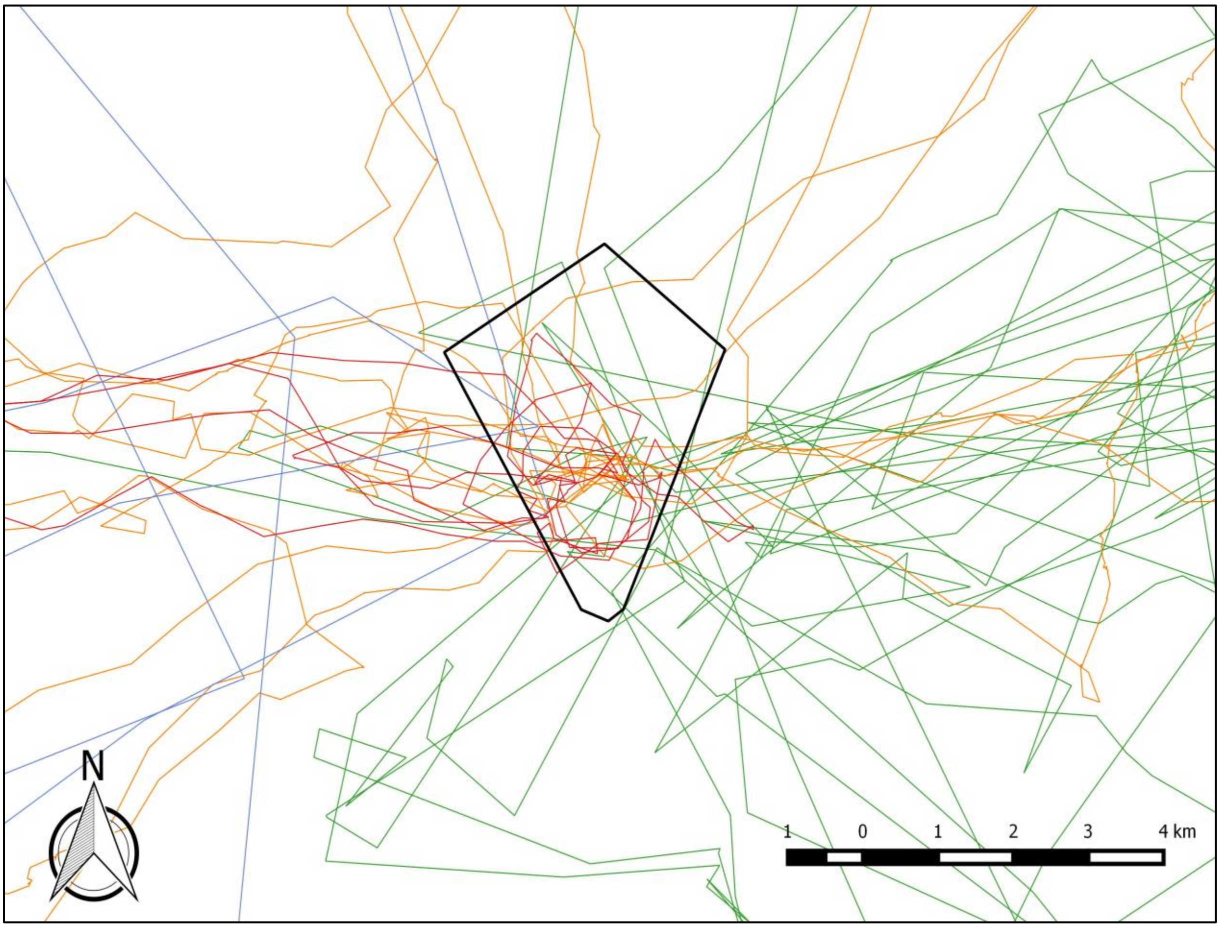

Figure 20: Movement data of four GPS collared floater males visiting a communication hub (CH) (black polygon). Figure adapted from Edwards *et al*. (2018). Floaters males have a lower visitation rate to the marking sites located within the CHs than territorial males (see Figure 4).

Four scenarios were run with the finite mixture model:

M_{h}: the capture probability varies due to individual heterogeneity

M_{b}: the capture probability varies by behavioural response to capture, e.g. trap happiness or trap aversion

M_{h2}: the capture probability varies due to individual heterogeneity of territory holders and floaters

M_{bh2}: the capture probability varies for two parameters, i.e. behavioural response to capture and individual heterogeneity of territory holders and floaters

MARK computes several goodness-of-fit and between-model test statistics and then selects the most appropriate of the different models for the dataset loaded. The output from MARK is a temporary Notepad file with the abundance estimate, the confidence intervals and the standard error showing the model that best fits the data at the top (Figure 21).

Estimates of Derived Parameters
Population Estimates of {Mbh2}

Grp.	Sess.	N-hat	Standard Error	95% Confidence Interval Lower	Upper
1	1	4.0000000	0.3250388E-016	4.0000000	4.0000000

Real Function Parameters of {Mbh2}

Parameter	Estimate	Standard Error	95% Confidence Interval Lower	Upper
1:pi	0.5000000	0.2499999	0.1234671	0.8765329
2:p	0.0901213	0.0685314	0.0188867	0.3375845
3:p	0.0901213	0.0685314	0.0188867	0.3375845
4:p	0.0901213	0.0685314	0.0188867	0.3375845
5:p	0.0901213	0.0685314	0.0188867	0.3375845
6:p	0.0901213	0.0685314	0.0188867	0.3375845
7:p	0.0901213	0.0685314	0.0188867	0.3375845
8:p	0.0901213	0.0685314	0.0188867	0.3375845

Figure 21: Results obtained after running MARK with our data set. Above, "*Estimates of derivated parameters*" reports the results of the best model fit (Mbh2) where the abundance estimate for the communication hub is 4 individuals with a very low standard error (<0.001) and 95% confidence intervals (CI) of 4 for both the upper and lower CI. Below, the "*Real function parameters"* of the current model Mbh2 provides the estimate of pi (π), which is parameter 1 at the top. π is the probability of any one individual in the population being a

floater, in this example it is 0.50 (SE=0.25, 95% CI 0.12-0.88). Therefore, in a population of 4 cheetah units, one would expect 4*0.50 = 2 cheetah units to be floaters. The other estimate provided is p = probability of first capture.

From abundance to density estimates

A consequence of the characteristic cheetah spatial ecology is that the use of spatially explicit capture-recapture (SECR) models may not appropriate to accurately estimate the density of the cheetah male population (Broekhuis and Gopalaswamy 2016). This is because SECR models presume individuals have roughly circular home ranges and that the probability of detection is a monotonically declining function of the distance from the home range centre (Royle *et al.* 2014). This is not the case for floater males who are most likely to be detected within territories rather than at their home range centre (Melzheimer *et al*. 2020).

To calculate the cheetah density in each of the study areas we made the following assumptions:

- The analyses were limited to male units because cheetah females are even more elusive than males and roam over vast areas and they only rarely visit marking locations (Caro 1994, Melzheimer *et al.* 2018). The population estimate was based on an assumed sex ratio of 1:1. This ratio was verified for east-central Namibia where 98 cubs from 30 cheetah litters were sampled, of which 47 were females and 51 were males (IZW, unpublished data).

- Cheetah CHs were the sampling unit in our study design. We assumed an average equal size of 41 km^2 of the CHs within Namibia and that they were regularly distributed across the landscape (Melzheimer *et al.* 2020). We further assumed that the communication hubs had an average distance of 23 km between them such that they were not contiguous with each other but separated by a surrounding matrix (Melzheimer *et al*. 2020).

Densities are calculated by the number of territories monitored (n), average distance between territories (d), abundance of cheetah males (A), number of territorial males (x) and number of floter males (y).

$$\frac{\left(\frac{A}{1+\frac{\sum_{i=1}^{n} yi}{\sum_{i=1}^{n} xi}}\right)+\left[A\,x\left(\frac{\sum_{i=1}^{n} yi}{\sum_{i=1}^{n} xi}\right)\right]+\left[\left(\left(\frac{\sum_{i=1}^{n} xi}{n}\right)+\left(\frac{\sum_{i=1}^{n} yi}{n}\right)\right)x2\right]\times n}{n\times d^{2}}$$

Results

In the newly established study area in the central Namib, we captured 11 cheetahs (a single female, a female and her cub and eight male cheetahs) and fitted four of them with GPS collars. The GPS collars gathered a total of 16,720 GPS locations (Annexe B). These locations allowed us to identify 172 cheetah marking locations (Annexe C). We surveyed this study site from the 14th of March to the 20th of May 2020 summing up to a total of 2,038 camera trapping nights. A total of 10,927 cheetah pictures were collected from the 103 cheetah events resulting in a capture success of 5.05 cheetah events/100 trapping nights (Table 4). Two female cheetahs and 11 male cheetahs were recorded during the camera trap survey. The males consisted of a coalition of two and another coalition of three males and six solitary males.

During our study in the central Namib, six of our study animals died. One was probably killed by spotted hyenas and his two brothers were still alive during the survey. A coalition of two cheetah males died from unknown reasons. I assume either natural death or killed by other cheetahs or larger competitors. These two cheetahs were old with age estimated above 8 years old. A coalition of three males died in the NKNP after feeding on a carcass of a mountain zebra that tested anthrax positive (Portas *et al.* 2021).

In the Khomas Highlands, we captured five males of which three fitted with GPS collars gathering a total of 36,787 GPS locations (Annexe B). The GPS telemetry data allowed us to identify a total of 74 marking sites (Annexe C). This study site was surveyed from the 5th October 2020 until the 5th November gathering a total of 840 camera trapping nights. A total of 4,486 cheetah pictures were collected from the 24 cheetah events resulting in a capture success of 2.85 cheetah events/100 trapping nights (Table 4). One female cheetah and six male cheetahs were recorded during the camera trap survey of which three males were part of a coalition and the other three males were solitary cheetahs.

During our study in the Khomas Highlands, two of our study animals died. One cheetah died shot on a farm while the other died for unknown reasons probably an injury.

Table 4: Summary of the camera trap data obtained in the central Namib and the Khomas highlands study area respectively.

Study area	Number of pictures collected	Number of cheetah pictures	% cheetah pictures	Cheetah events	Capture success Cheetah captures/ 100 trapping nights
Central Namib	21,465	10,927	50.90%	103	5.05
Khomas Highlands	162,557	4,486	2.76%	24	2.85
Total	184,022	15,413	8,38%	127	4,41

Cheetah abundance estimates

Central Namib

In the central Namib, five territorial units were photographed 54 times while three floater units were photographed three times (Table 5). In the Ababis CH, two cheetah units (a territorial solitary male and a coalition of three males) were captured 14 and 12 times, respectively, by our camera traps while two floater units (one of them previously known by us (NN05) see Table B1 in Annexe B) were photographed only once each. The real function parameters correctly identified a 50% of chance of the cheetahs being a floater. The camera traps surveying the Gemsbokwater CH photographed a coalition of two cheetahs (NN14 and NN15) which were previously known by us (Table B1 in Annexe B). The survey in the Tsondab CH revealed the presence of 3 cheetah units of which two showed marking behaviour, thus were classified as territorial males, with 8 and 4 captures each. The third male was photographed only once and did not mark, thus was likely a floater. The real parameter function identified a 25% of possibility that one of the three cheetahs was a floater, therefore providing a quite accurate result.

Table 5: Abundance estimates in the central Namib with standard error, 95% confidence interval (CI) and the best model fit.

Communication hub	Abundance of cheetah units	Standard Error	95% CI	Model best fit
Ababis	4.00	<0.001	4-4	Mbh2
Tsondab	3.00	<0.001	3-3	M0
Gembsbokwater	1.00	<0.001	1-1	Mh2

Khomas Highlands

In the Khomas Highlands, three territorial units and one floater unit were captured nine times by our camera traps (Table 6). One territorial unit and one floater were detected at each one of the Claratal and Krumhuk CH while in the third CH, Heusis, no cheetah was photographed during the survey.

Table 6: Abundance estimates in the Khomas Highlands with standard error, 95% confidence interval (CI) and the best model fit.

Communication hub	Abundance of cheetah units	Standard Error	95% CI	Model best fit
Claratal	2	<0.001	2-2	M0
Krumhuk	2	<0.001	2-2	Mb
Heusis	No cheetah was detected			

Density estimates

The resulting density estimates are presented in Table 7.

Table 7: Combined counts of collared territorial and floaters units and units captured with camera traps for all study areas and density estimates per territory.

Study area	Territorial units	Floater units	Ratio	Proportion of floater units	Density (cheetahs/100km²)
Central Namib	5	3	1 : 0.6	0.375	0.2-0.4
Khomas Highland	3	1	1 : 0.3	0.25	0.1-0.3
Total	8	4	1 : 0.5	0.33	

Other data collected

All wildlife pictures were uploaded in to the Environmental Information System (EIS) of Namibia for atlasing purposes http://www.the-eis.com. A total of 38,223 sightings were collected from the central Namib survey. Parallel to the project, data on bird presence was collected to contribute to the southern African Bird Atlas Project. More than 900 observations from 98 bird species from the central Namib and 170 species and more than 800 observations from the Khomas Highlands were logged and submitted to the atlas.

During the initial phase of this project, we additionally prospected two other areas: the Tsauchab valley and the NamibRand Nature Reserve, where we identified 7 and 12 marking sites, respectively (Annexes D). These marking sites were monitored during several months and we confirmed temporal presence of cheetah males and females living on the sandy and gravel plains surrounding the dune belt.

Additionally, we reported and collected data on off-road driving and poaching activities in the surroundings of our study site located in the Ganab area, in the north of the Namib Naukluft. While searching for marking sites, we found wires hanging from a tree where oryx were slaughtered and meat was dried. We also found off-road tracks and four of our camera traps were stolen whilst one of them photographed a Toyota Hilux bakkie in the same area, unfortunately not its number plate.

During the GPS data collection from the collared cheetahs, we investigated the death of the Tsondab cheetah coalition formed by three adult cheetah males (Figure 21). Samples were collected from the three dead cheetah bodies and their movements based on GPS locations where tracked. A GPS cluster led us to a dead mountain zebra on which the cheetahs have spent time less than 24 hours before their death and most likely have fed from the zebra. We also collected samples (i.e. nasal and bucal swabs) from the zebra of which all samples from the cheetahs and the zebra were tested for anthrax (*Bacillus anthracis*). The cheetah samples were tested negative while the zebra samples were tested positive for anthrax. We published the findings in the journal *Frontiers of Veterinary Science* (Portas *et al.* 2021) where we provided a review on the susceptibility of cheetahs to anthrax and cited previous reported cases. We further discussed the negative laboratory results of the cheetahs in the light of new insights of their immune system and its potential to mount a response against this bacteria. This is the first anthrax case in a wildlife species reported in a scientific journal for this area.

Figure 21: Carcasses of the three cheetahs found dead in the Namib Desert. Due to GPS locations coinciding with the location of a dead mountain zebra which was tested positive for anthrax we attributed their death to an anthrax infection. Note the GPS collar in the top right picture.

Knowledge transfer and capacity building

During this project, we employed two students from the Namibia University of Science and Technology (NUST).

Sebastianus Amukoshi assisted with fieldwork in the central Namib. He helped in checking and monitoring cheetah marking sites and assisted to run a pilot study on the diet of the three male cheetah coalitions in the central Namib (Figures 22 and 23). Sebastianus further assisted us with organisation and classification of camera trapping data and processed the impressive amount of 800,000 camera trap pictures from more than 50 mammal species. These pictures were used to train an image classification tool using deep learning artificial intelligence that we are currently developing. All this knowledge gathered in the Namib and the camera trapping skills brought him to NamibRand where he will start a camera trap survey.

Figures 22 and 23: Sebastianus Amukoshi recording data of a mountain zebra foal, the remains of a cheetah kill, and assisting during a cheetah immobilization.

Konrad Hamanyami Hamutenya assisted our team in our long-term central study area with several tasks such as data management (e.g. processing all the camera trap data to be uploaded to the EIS website, Figure 24), fieldwork (e.g. capture and camera trapping of free-ranging cheetahs) and management and maintenance of our research station.

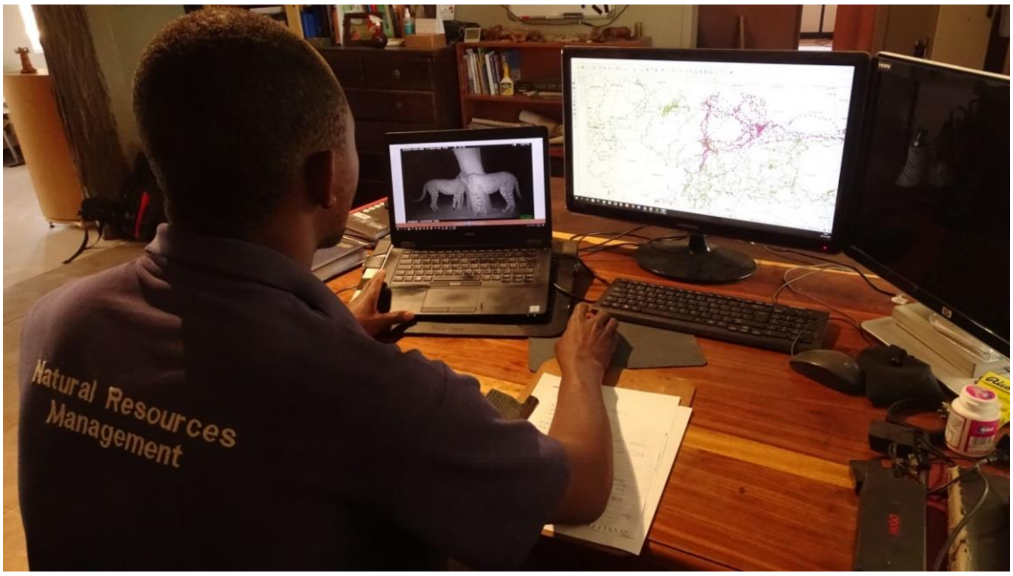

Figure 24: Konrad Hamanyami Hamutenya analysing GPS data and camera trap pictures to attribute spatial tactics to photographed cheetahs using their movement data.

In addition to train students, we shared data, trained and involved farmers and rangers and wardens from the MEFT in our research. Further, our team maintained close contact and communication with stakeholders and gave talks at the following farmers meetings:

Portas R, Wachter B, Melzheimer J: The Namibian Cheetah Survey. Maltahohe Farmers Association, Annual general Meeting, 11th March 2020. Ababis, Namibia.

Portas R, Wachter B, Melzheimer J: The Namibian Cheetah Survey. Maltahohe Farmers Association, Annual general Meeting, 11th March 2020. , Namibia.

Mueller R, Roeder R, Portas R, Melzheimer J and Wachter B. Update on the cheetah research project and camera trap survey in the Auas Oanob Conservancy. Annual General Meeting, 17th November 2020. Farm Lichtenstein Sued, Namibia.

Portas R, Roeder R, Mueller R, Melzheimer J and Wachter B. Update on the cheetah and leopard research projects and camera trap survey in the Auas Oanob Conservancy. Annual General Meeting, 16th November 2020. Farm Claratal, Namibia.

Toegether with the Namibian Scientific Society, we also organized a public outing in the farm Claratal of the Auas Oanob Conservancy in the Khomas Highlands to raise awareness for carnivore conservation. This event was attended by 180 people, and two game drives with 60 people each were organized with stops at selected locations: a) a cheetah marking tree where information was given on cheetah spatial ecology, mating system and introduction to our research procedures and b) an electronic box trap set to capture free-ranging leopards where information was provided on data that our project gathered on leopards in central Namibia (diet, spatial ecology and spatial distribution). We also provided information to mitigate the existing human-leopard conflict in Namibia.

During the entire project, we maintained close contact with the rangers and wardens of Ganab and Zais MEFT stations. We trained them in cheetah research methods such as finding marking sites, setting up camera traps and box traps (Figure 25) and reported off-road driving as well as poaching activities detected in the Namib Naukluft National Park (see above).

Figure 25: Training session on trapping methods with the rangers and wardens of Ganab station. Here, we introduced them to one of our electronic remotely monitored box traps for the efficient capture of cheetahs while avoiding the capture of non-target species. With three of these traps, we captured 11 cheetahs in the central Namib.

Discussion and implications for cheetah conservation

Cheetah status and future perspectives in the central Namib and Khomas Highlands

Cheetahs were found with breeding and healthy populations in both study sites. In the central Namib, cheetah sightings seem to have increased in the last decades, similarly as reported for the southern Namib (Portas *et al*. 2017). Due to the collapse of the karakul market in the 1980ies (Bubenzer *et al*. 2007) and to the growing tourism industry, there is an increasing number of private nature reserves adjacent to the NKNP and the numbers of small livestock have been dramatically reduced. This scenario brought more tolerance towards large carnivores and land available to wildlife, thus creating a buffer zone around this National Park (Portas *et al.* unpublished data). The creation of the Greater Sossusvlei-Namib landscape in 2011 to enhance landscape and biodiversity conservation has firmly contributed to the benefits which the tourism increase brought into the Namib (http://www.landscapesnamibia.org/sossusvlei-namib/). During our entire study period in the central Namib and during the first phase of this project (Portas *et al.* 2017), reported sightings and camera trap data collected revealed a healthy cheetah population which has the potential to act as a population source thanks to low human wildlife conflict in the Namib. However, climate change is expected to increase the water stress and average surface temperatures, impacting soil moisture, water availability, vegetation composition and productivity, which in turn leads to an increase of desertification and habitat loss (Engelbrecht *et al*. 2015). The NKNP and surrounding private protected areas and farmland dedicated to tourism are also the least productive land in the Namib due to the west-east rainfall gradient of Namibia. Thus, the Namib may not remain a long-term stronghold for the species and their survival in the surrounding farming areas will be a key in preserving the species in the western most arid parts of the country.

In the Khomas Highlands, leopards are the most reported carnivore species and main source of human-wildlife conflict. Cheetahs are not common in rugged and mountainous landscapes but present at low densities in the highest flat lands of the Khomas plateau as reported in our study. The Khomas Highlands are crucial for connectivity between the farmlands of east-central Namibia, where the highest densities of the species are reported (Portas *et al*. 2017, Fabiano *et al*. 2020), and the western arid lands of Namibia. Main land uses in the study area are livestock production and hunting, thus the long-term presence of cheetah is inevitably linked to tackling human-cheetah conflict and increasing the tolerance towards the species.

Threats detected in the study areas

Cheetah removal due to real or perceived conflict with livestock and game farming activities, decline of natural prey and habitat loss and fragmentation are the main reported threats to the long-term survival of cheetahs (Durant et al. 2015, RWCP and IUCN/SSC 2015, Melzheimer et al. 2022). During this study, several of these threats were also detected. Cheetahs are not well perceived and tolerated in the small-livestock farms bordering the central Namib and several cheetahs were reported to be shot during our conversations with the local farmers.

In the Khomas Highlands, one of the collared cheetahs was shot on a farm. Out of 13 cheetah deaths reported over the last years for this study area, four were linked to human-wildlife conflict and two were uncertified, representing between 31% and 46% of the reported cheetah mortality (IZW unpublished data). In this study area, tolerance and perception towards the species varies greatly among farmers with a few farmers responsible for most cheetah losses, not always linked to livestock losses (Marker-Kraus *et al.* 1996). Thus, raising awareness and tackle human-wildlife conflict are actions locally needed to reduce the numbers of cheetahs removed by individual farmers.

In the central Namib, a cheetah was killed by a car between Sesriem and Sossuvlei. in the Khomas Highlands during our study, two cheetahs were hit by a car and died on the B1 between Rehoboth and Windhoek, one of which was collared. Additionally, between 2011 and 2022, seven cheetahs were reported to our team of being hit by cars along the B6, between Windhoek and Gobabis. This represents 15% of the reported total mortality in the Khomas Highlands since our team works in this study area. We are currently involved in a global study focussing on comparing road crossings of wildlife animals and road kill locations to determine which factors determine successful and unsuccessful road crossings and to identify the best places to implement road mitigation measures. Our GPS data compiled 2,830 road crossings of cheetahs and the ten above mentioned road kills. The increasing traffic and fragmentation (e.g. building of game fences) is a rising threat to the cheetah population as fragmentation has a high impact in flat landscapes when no safe crossings are provided to wildlife. A critical example is the road from Windhoek to Okahandja where the double lane was implemented along several farms with game fences without considering the free movement of wildlife to ensure population connectivity.

Another threat detected in both study sites is the illegal harvest of wildlife. In the NKNP and its adjacent farmland, poaching has been pointed out to be on the rise. During our survey, we detected off-road driving in remote areas, four of our camera traps were stolen and we found wires hanging from a tree and dry meat from oryx carcasses that were slaughtered. The Namib is a wide and unpopulated landscape and its remoteness challenges the efforts and good work of the MEFT and Namibian police forces which nevertheless has led to several arrests. In the Khomas Highlands, cattle theft and carcasses of game and cattle slaughtered are found and reported on a weekly basis. Poaching threatens the long-term conservation of wildlife and law reinforcement is required to ensure every arrest ends with an exemplary sentence that sends a clear message to those behind such illegal activities.

Trophy hunting alone may not be a direct threat to the Namibian cheetah population, however when combined with removals, particularly removals of adult females, it is questionable whether the population is large enough to remain viable (Berry et al. 1997, Crooks et al. 1998, Melzheimer et al. 2022). Cheetahs were trophy hunted in both study areas but most cheetah deaths reported were linked to human-cheetah conflict (see above). However, two trophy hunting permit were given to the same farm within the same year in the Namib where the removal of two cheetah males in such a low density area may have a severe local impact on the population. Trophy hunting permits for cheetah should be firstly attributed to farmers who experienced livestock losses, and combined with reported cheetah removal. Then, the permits should be spread in a wide geographical scale to reduce as much as possible local impacts on the cheetah population.

Recommendations and knowledge gaps

Our results represent a snapshot in time of the cheetah population in both study areas. No previous information is available using the same methods as we used, and this report provides the first abundance and density estimates for both areas. Further surveys with the same methodology are needed to establish population trends.

We suggest to repeatedly monitor the population in all the study areas surveyed during the first phase (Kunene, Etosha National Park and Etosha Conservancy, southern Namib and east-central Namibia) and the second phase of the Namibian Cheetah Survey (central Namib and Khomas Highlands).

Little data is available in the entire south-east of Namibia where no other study focused on large carnivores due to the extensive sheep farming. Information gathered by questionnaires sent to farmers by the Namibia Professional Hunting Association (NAPHA), suggests that cheetahs are sparsely present and reported in the south-east of the country. It is, however, unknown whether this area contains reproductive populations or reports rather refer to only transient cheetahs.

No data on cheetah density is currently available for the Erongo region (Omaruru – Uis) and for the north-east of Namibia, i.e. the Otjozondupa regions (Tsumeb-Otavi-Grootfontein) and the Namibian part of the Kavango-Zambezi Transfrontier Conservation Area (KaZa), to fill relevant information gaps in the distribution of cheetahs in Namibia. We suggest these are

priority areas to run camera trap surveys and estimate cheetah density. Further information in the northern Kunene would also be valuable to understand the population dynamics of cheetahs south of the Kunene river and the potential connectivity with the Iona National Park in Angola, where work on the cheetah population is currently being carried out (Monterroso et al. unpublished data).

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Annexes

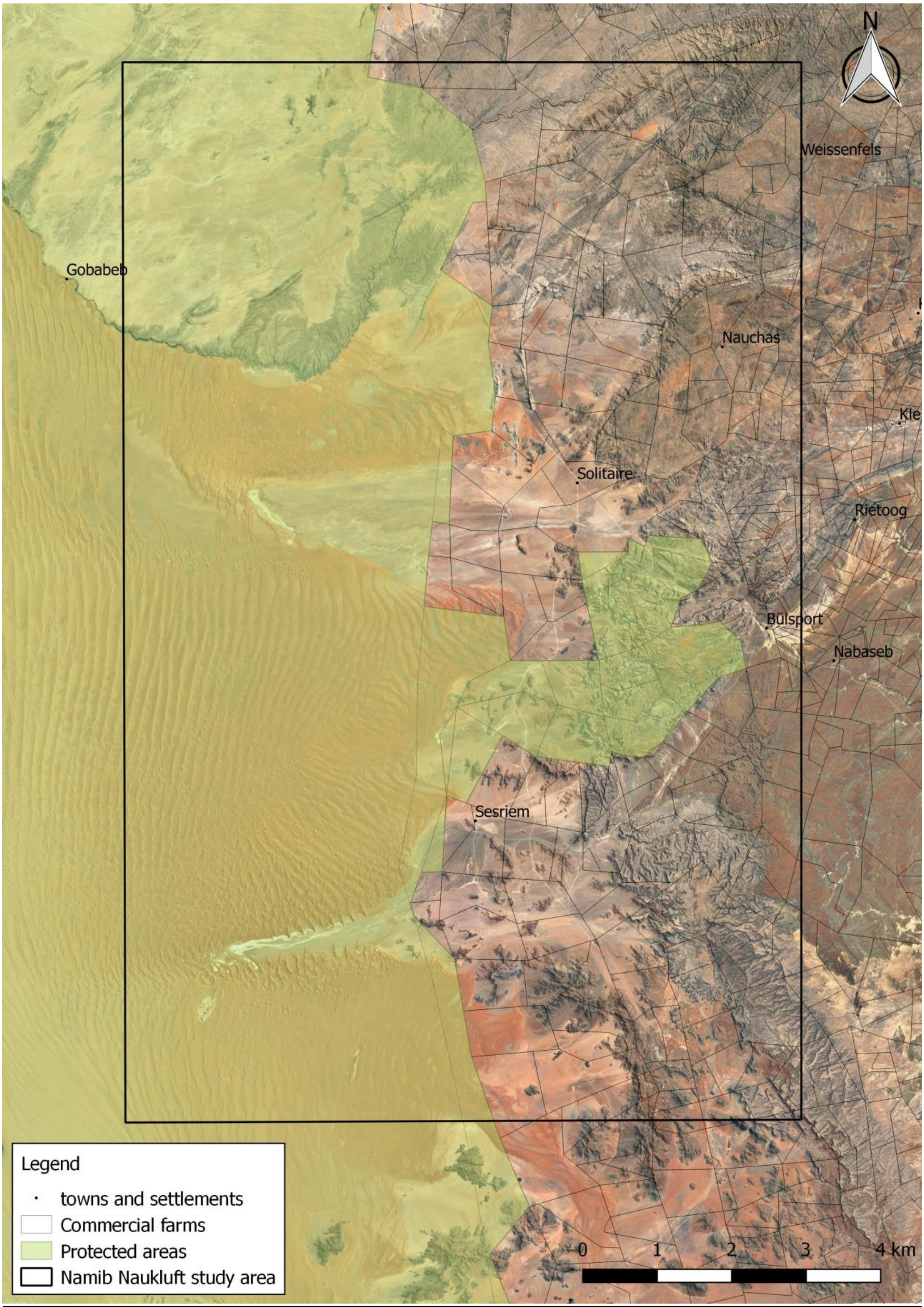
Annexe A: Maps of the study areas.

Annexe B: Tables containing the information related to the study animals.

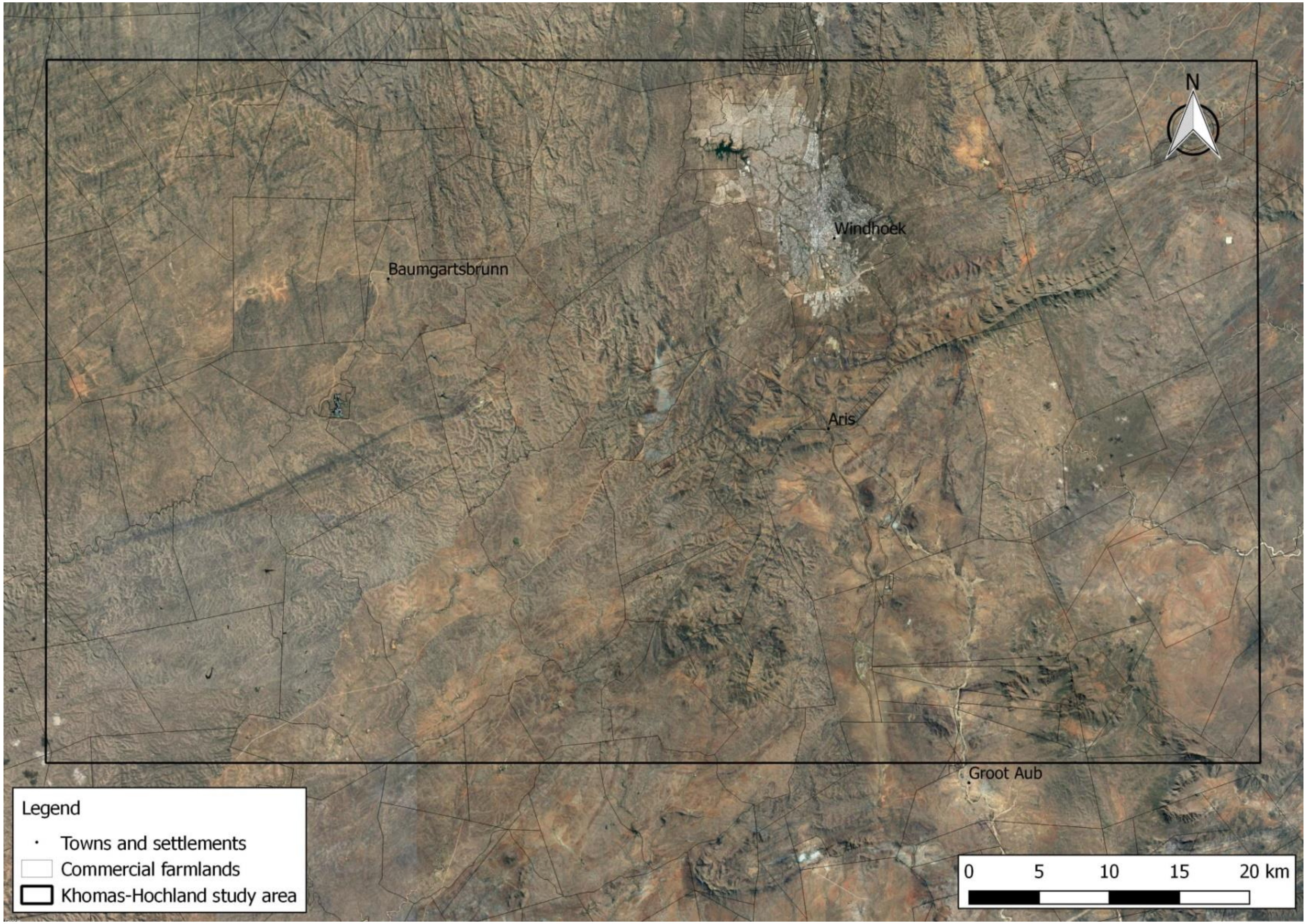
Annexe C: Maps showing the movements of the free-ranging cheetahs fitted with GPS collars and the marking sites that were surveyed by the camera traps in each of the study areas.

Annexe D: Maps of other areas prospected.

Annexe A: Maps of the study area



Map of the central Namib study area.


N
Windhoek
Baumgartsbrunn
Aris
Groot Aub
Legend
Towns and settlements
Commercial farmlands
Khomas-Hochland study area
0
5
10
15
20 km

Map of the Khomas Highlands study area.

Annexe B: Tables containing the information related to the study animals.

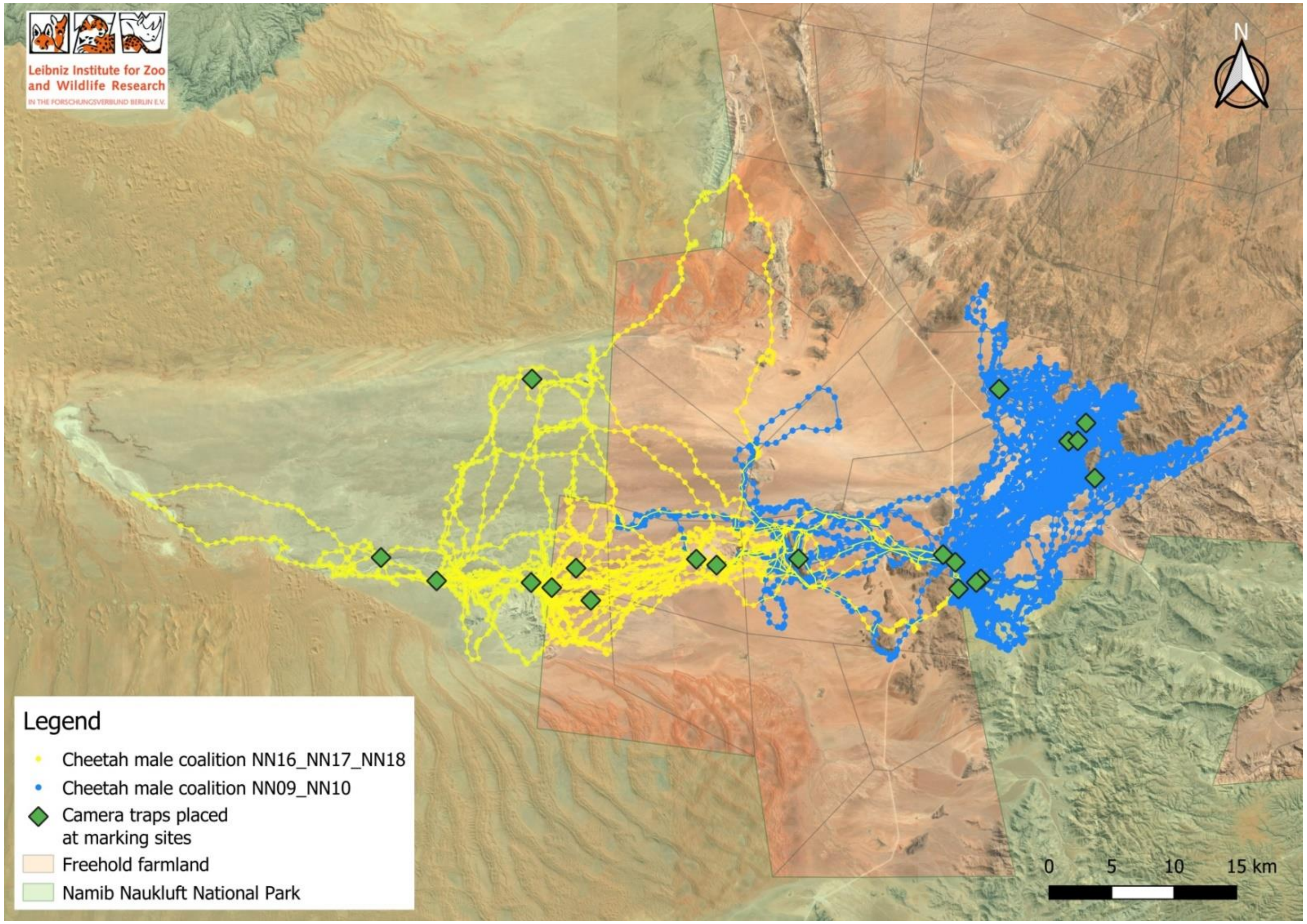
Table B1: Study animals in the central Namib

Cheetah ID	Coalition code	sex	Age estimated (years)	Spatial tactic	N° of GPS positions	Duration period (days)	Comments
NN05	1	male	4	Floater	83	4	Collar failed after few days. Cheetah captured with injury in the hind leg. Photographed twice by the camera traps fully recovered
NN06	1	male	4	Floater	n.a.	n.a.	Cheetah captured with injury in the hind leg. Photographed twice by the camera traps fully recovered
NN09	2	male	8	Territorial	9,548	320	Died on the 01.11.2019 around 6:30. Collar found in the field, Body never found.
NN10	2	male	8	Floater	n.a	n.a	When brother disappeared, it was also never seen again
NN11	n.a	female	4	n.a.	n.a	n.a	Mother with a cub (NN12)
NN12	n.a.	male	1	n.a.	n.a	n.a	Cub captured with its mother (NN11)
NN13	3	male	4	Territorial	2,432	76	Collar found on a rock, cheetah probably killed by spotted hyenas
NN14	3	male	4	Territorial	n.a.	n.a.	Animal alive during the survey
NN15	3	male	4	Territorial	n.a.	n.a.	Not captured, Animal alive during the survey
NN16	n.a.	female	3	n.a.	n.a.	n.a.	Female captured close to Sossusvlei
NN17	4	male	6	Territorial	4,657	130	Found dead of Anthrax
NN18	4	male	6	Territorial	n.a.	n.a.	Found dead of Anthrax
NN19	4	mle	6	Territorial	n.a.	n.a.	Not captured. Found dead of Anthrax

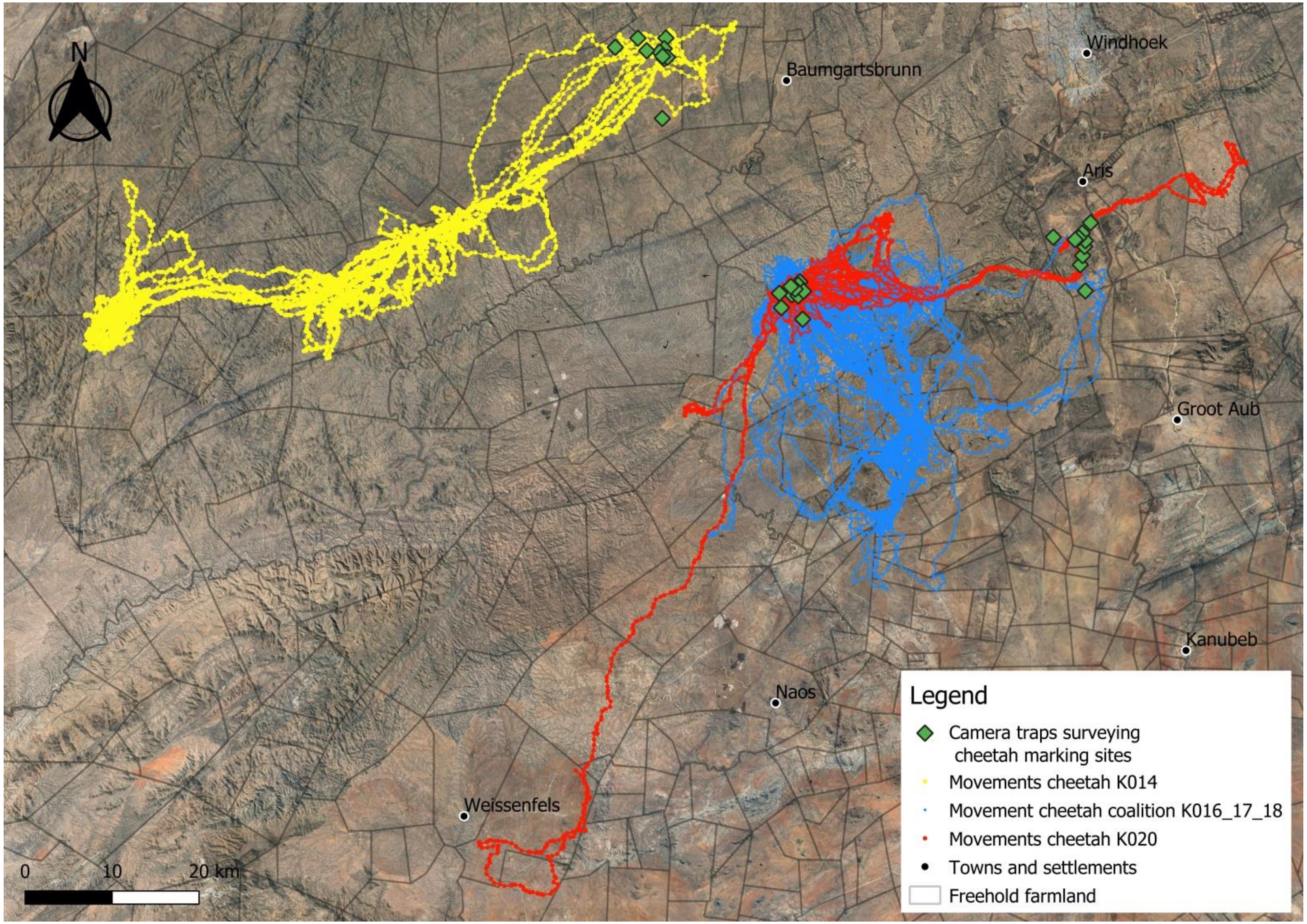
Table B2: Study animals in the Khomas Highlands.

Cheetah ID	Coalition code	sex	Age estimated (years)	Spatial tactic	N° of GPS positions	Duration period (days)	Comments
K014	n.a.	male	6	Territorial	10,845	429	Died, probably due to an injury, unknown reason
K015	1	male	4	Territorial	n.a.	n.a.	Alive when report is submitted. Member of coalition K015_K016_K017
K016	1	male	4	Territorial	20,765	638	Alive when report is submitted. Member of coalition K015_K016_K017
K017	1	male	4	Territorial	n.a	n.a	Alive when report is submitted. Member of coalition K015_K016_K017
K020	n.a	male	5	Floater	5,177	181	Shot on a farm

Annexe C: Maps showing the movements of the free-ranging cheetahs fitted with GPS collars and the marking sites that were surveyed by the camera traps in each of the study areas.

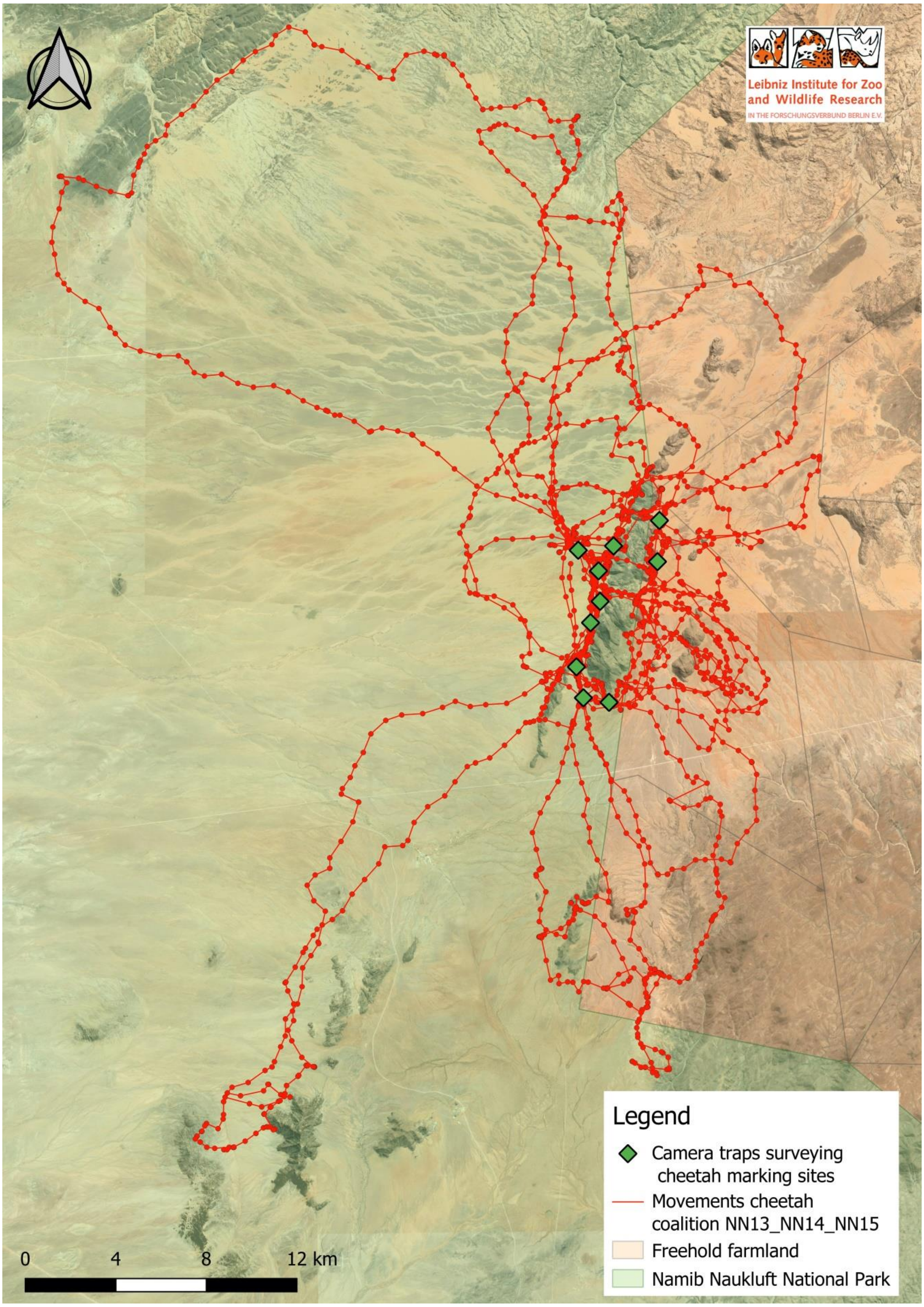


Map showing the movements of the two cheetah male coalitions collared in the southern section (Tsondab river) of central Namib study area and the clusters of marking trees that were surveyed by the camera traps indicating the location of the communication hubs.



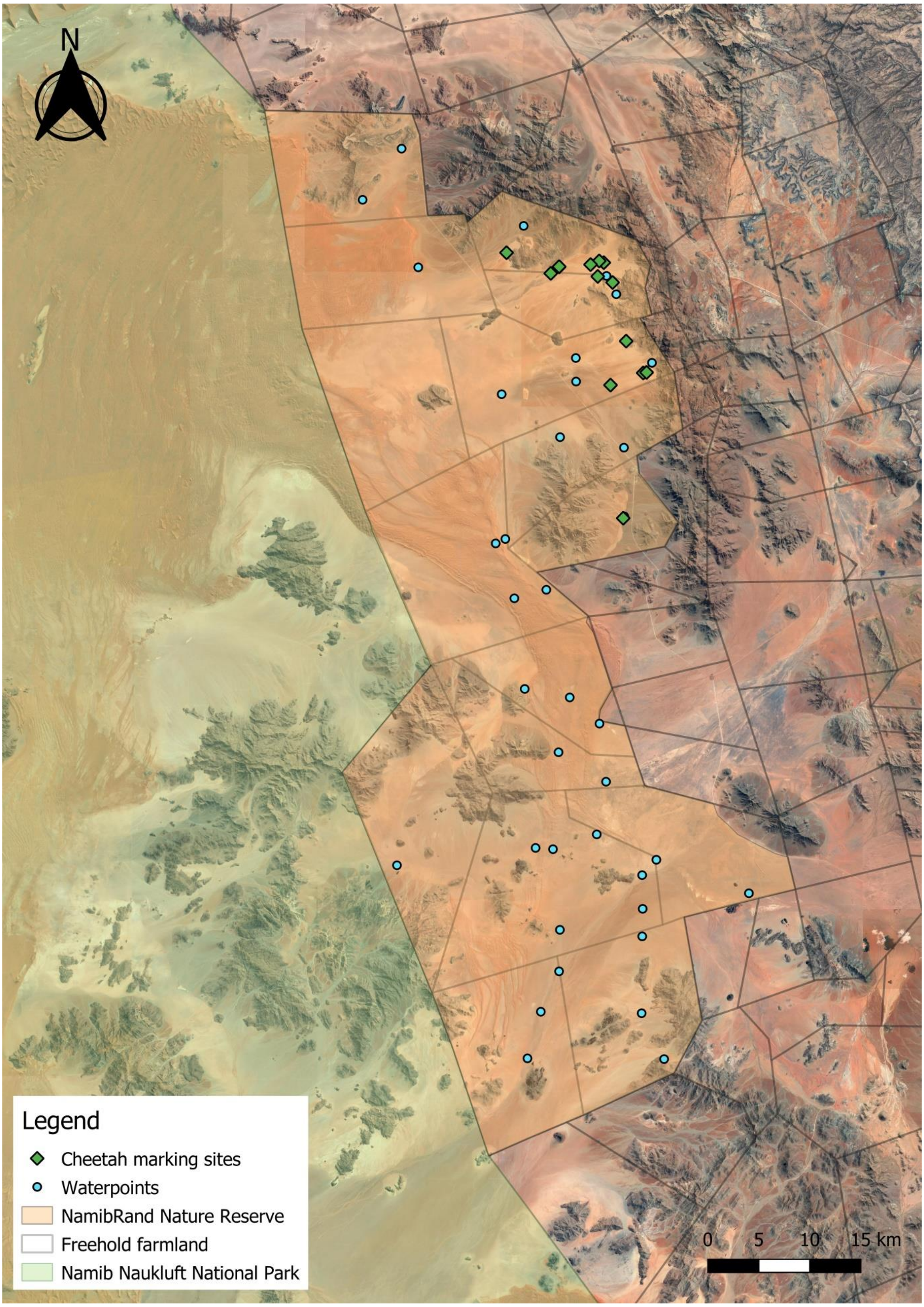
Map showing the

movements of the three cheetah males collared in the Khomas Highlands study area and the clusters of marking trees that were surveyed by the camera traps indicating the location of the communication hubs.

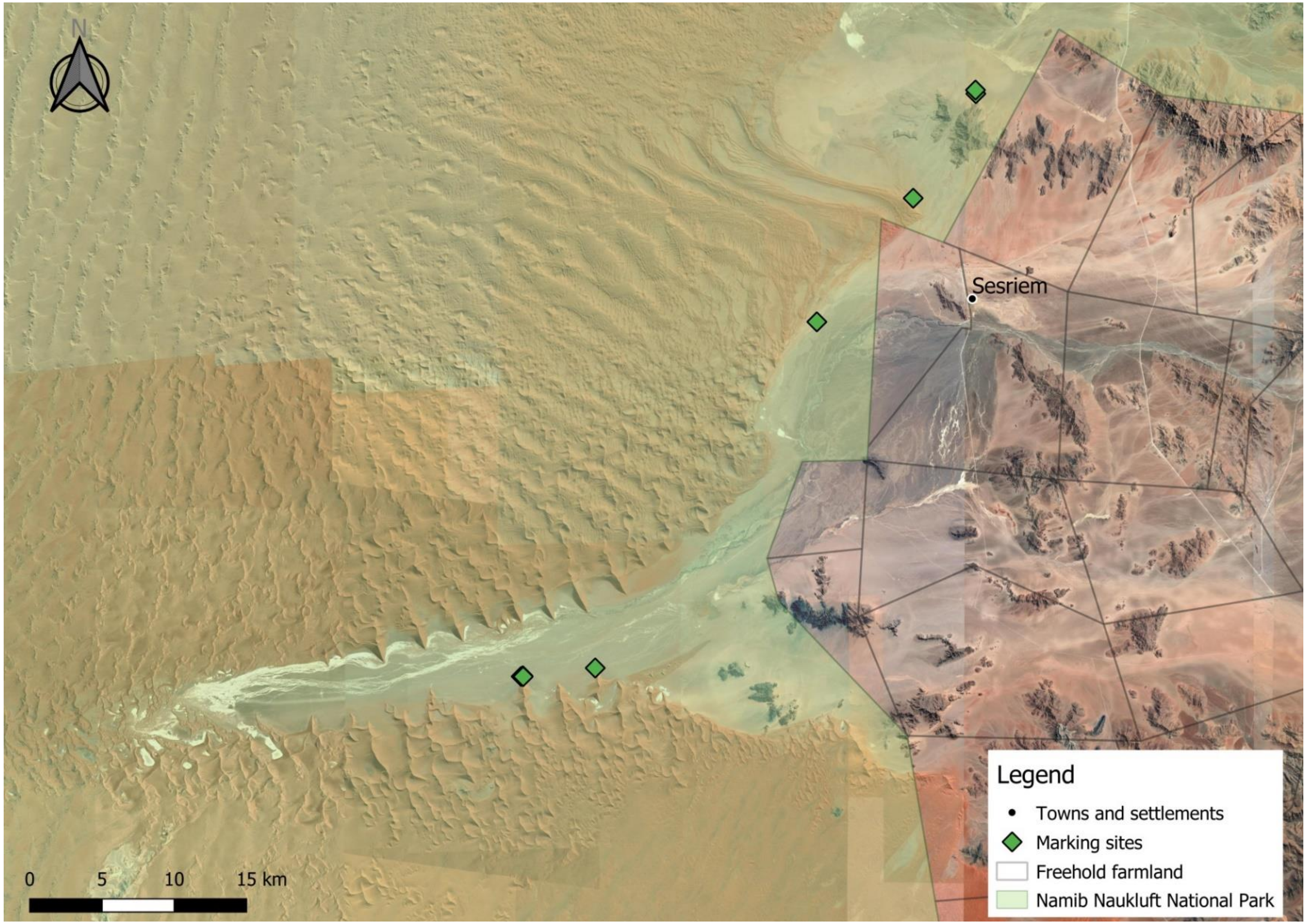


Map showing the movements of the cheetah male coalition collared in the northern section (Ganab plains) of the central Namib study area and the clusters of marking trees that were surveyed by the camera traps indicating the location of the communication hubs.

Annexe D: Maps of other areas prospected.



Map showing the marking sites detected in the NamibRand Nature Reserve.



Map showing the marking sites detected in the Sesriem-Sossusvlei complex within the Namib Naukluft National Park.

Thank you