Camera Trapping and Occupancy Model as a Tool for Monitoring the Carnivore's Guild in Wadi Wurayah Man and Biosphere Reserve

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A thesis submitted in partial fulfilment of the requirements of the University of the West of England, Bristol for the degree of Master of Philosophy.

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May 2022

Word count: 19,929

.....To the few who could buy me the time I needed

To my wife, Anniek,

My kids Noah and Luna

And

To my Parents

Author's Declaration

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Abstract

Understanding species habitat relationships and their relative importance to the carnivore guild is fundamental to determining optimal conservation strategies and guiding long-term management efforts in a man and biosphere reserve. In this study, I used occupancy models to estimate the impact of anthropogenic effects and other factors on the habitat use of carnivores. I used one year of camera trap monitoring data between April 2016 and March 2017 across a ∼160 km of the reserve core area to develop single-species, single-season occupancy models for the reserve's carnivores. I estimated the impact of anthropogenic, environmental, and biotic factors on the habitat use of the Red Fox (Vulpes vulpes), Blanford's Fox (Vulpes cana), and Caracal (Caracal caracal). Occupancy models indicated environmental and anthropogenic factors as the main driver of the Red Fox occupancy, while biotic variables had a more significant influence on Blanford's Fox and Caracal habitat use during summer. Understanding the main drivers behind habitat utilisation, including other underlying factors, such as prey availability, human/wildlife conflict, interspecific, intraguild competition, between these sympatric carnivores is essential for the reserve management. Variation in response to environmental and anthropogenic factors suggested spatial niche segregation between the Caracal and Red Fox and a high correlation between the occupancy of Blanford's Fox and freshwater habitats. In this study, I demonstrated the power of a single-species occupancy model providing a baseline of habitat factors affecting the carnivore guild based on the detection/non-detection records. This method enhanced our knowledge of the ecosystem function and priority habitats for carnivores' persistence in the reserve and mountain areas, where humans encroachment and activities have re-shaped the community assembly and niche selection in this rapidly developing region.

Acknowledgement

First, I want to thank my supervisors Dr. Mark Steer of the University of the West of England and Dr. Steve Ross, for keeping me motivated, believing in me, and their guidance in the past five years. I also would like to thank Christophe Tourenq and Steven Ross, the two most prominent and influential persons who had the primary role in laying the ground for me to aim higher and focus on the right path; they were both friends and mentors. They were always happy to share their practical life experience, and without them, I would never imagine being a conservationist.

Several institutions have played essential roles in shaping my current career profile. Starting with the Ameri court and the crown prince office supporting the establishment of Wadi Wurayah National Park and Man and Biosphere Reserve. Through his interest in wildlife protection, H.H Sheikh Mohammed bin Hamad Al Sharqi, the crown prince of Fujairah Emirate, provided financial resources and political support for the conservation efforts in Wadi Wurayah Man and Biosphere Reserve, particularly the camera traps monitoring program. Second, comes Fujairah Municipality, which brought together a group of dedicated people at different levels who believed in conservation and supported the establishment of the reserve. I will always appreciate the opportunities I was given by Fujairah Municipality and the trust I gained from working close to the H.E Eng. Mohamed Saif Al Afkham, the Director-General of the municipality, H.E Mrs. Aseelah Al Mualla, the Director-General of the Fujairah Environment Authority and Eng. Ali Qasem, Director of Fujairah Natural Resources Corporation. I was privileged to work with them and Fujairah Municipality for eleven years.

Other organizations and institutions were also instrumental in establishing Wadi Wurayah Protected Area and the camera trap monitoring program. Emirates Wildlife Society in association with World Wide Funds EWS-WWF Headed by H.E. Razan Khalifa Al Mubarak. Together with HSBC Bank Middle East Ltd they had a vital role in supporting the protected area during establishment. EWS-WWF role was essential, and I gained much experience working with their team on the administrative level and in the field. Mainly working with Christophe Tourenq, Lisa Perry and Moaz Sawaf, who have the credit for initiating the camera trap program in 2009 and Olivier Combreau and Jacky Judas, who refined the program in search of the Arabian Tahr between 2013 to 2015. Many have contributed to the maintenance of the camera traps from EWS-WWF team; Marina Antonopoulou, Ajita Nayar, Oliver Kerr, Shirine Habash and Alexander Clok, not to forget the support of the head of EWS-WWF at that period Ida Tillisch.

Thanks to all the individual volunteers and organizations for joining us for camera trap maintenance despite the hot, humid weather and the rugged terrain. Thanks to the Arabian Wildlife Breeding Center in Sharjah, particularly Anniek Boshoven, Cornelie van der Feen, Fadi Yaghmour, Isabelle Theyse, John Pereira, Lisa Hebbelmann, Liselore Didion, Nele Koedooder and Nick Oldenburg. From Alain Zoo, Amir Islam, Jomy Johny, Judith Howlett, Lisa Banfield, Stephen Chege, Tatiana Aponte and particularly Hessa Alqahtani. From Mohamed bin Zayed Species Conservation Fund, Kirk Duthler and Nicolas Heard. Gary Feulner, the Dubai Natural History Group chairman, for volunteering in the field and his continuous support. From Dubai Municipality, I want to thank my head of department, Aisha Almurr Almuhery, for her kindness and support over the past few years.

The UAE military forces role was highly appreciated providing a helicopter to reach the inaccessible and remote areas in the reserve. Tour du Valat biological station through Satellite-based Wetland Observation Service"SWOS", this Project was instrumental in providing the vegetation cover maps I used in my study; in particular, I want to thank Jean Jilbert, Christian Perennou, Anis Guelmami and Kathrin Weise. Gulf Rocks is one of the private companies that provided some camera traps for our field research. Individual volunteers were also instrumental and highly motivated, thanks to Sultan Al Kaabi from Qidfa and Khalifa Al Abdouly of Wadi Al Abadilah for joining the field and the valuable information they provided about the local environment and traditions, I was privileged to work with them both. I also want to thank Dan Wright and his wife Nirjala for their participation in the camera trap maintenance and volunteering in many field activities.

I want to express my gratitude to Jim Sanderson and the Small Wild Cat Conservation Foundation "SWCC". Jim used his personal time while visiting the UAE to provide training and guidance on using (Camera Sweet), a camera trap program; he also upgraded his software to fit our needs. I also want to thank Mark Porath, one of the few dedicated specialists I met during my study. Mark helped me develop several codes in R to organize the database; Mark support came “on time”.

A special thank goes to Wadi Wurayah Rangers team, a small group of highly trained and reliable individuals. They were all dedicated, disciplined and highly efficient. The Rangers team took over the full responsibility of maintaining camera traps in the field starting in 2015. I owe this small team a lot of unforgettable memories; together, we had plenty of stories to tell our kids, stories of success, pain and survival. I still miss these days when we used to carry 20 kilos of supplies and equipment on our backs and spend two or three days in the mountains maintaining camera traps. Since we were a small team, we had to take the risk, split and walk individually to cover a larger area in many situations. The best time was at night meeting at the campfire to rest and prepare for the next day. Thanks to Sami Ullah Majeed, Swamiti Kakembo, Tharindu Wickrama Achchillage and Omar Obeidat. You are the best team I have ever had!

Finally, I have to thank my small family, my wife Anniek Boshoven, who stood next to me even when she needed me the most. She was with me in the field, on standby while I was in the mountains or taking care of the kids while I was studying. I also want to thank my parents, Khalid and Fatiah, my two brothers Ayham and Ghaith and my parents in law Ron and Winny, for their unlimited support. My family will always be the foundation of all the success in life.

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Introduction

Each species has a set of requirements only provided by specific habitats (MacKenzie et al., 2017). Thus, identifying habitat variables that species' respond to allows us to understand how habitat is related to their fitness and survival over time (Crooks, 2002; Mangas et al., 2008). Developing habitat models for species based on occupancy can contribute to habitat management and species conservation (Mangas et al., 2008; Rich et al., 2016). Some carnivores thrive in natural habitats, where ecological integrity and processes are still intact, and thus they can be considered indicators of ecosystem health (Noss et al., 1996; Ritchie et al., 2012). In hot, semi-arid ecosystems, mountainous habitats are highly productive, are generally less disturbed and have a range of available habitats (e.g. freshwater ecosystem and associated habitats and scrublands). These habitat areas are vital for the survival of large and medium-sized carnivores and their prey yet are poorly researched in our arid region (Mallon, 2011; Mangas et al., 2008).

In the past few decades, the population decline and loss of apex predators and other large mammals in the UAE are associated with increasing anthropogenic pressures, including habitat degradation, landscape fragmentation, human-wildlife conflict, and prey loss (Foley et al., 2005; Tourenq & Launay, 2008). Several species of mammals have been extirpated from mountainous areas of the UAE due to excessive hunting and persecution, such as the Arabian Gazelle *Gazella arabica*, Arabian Leopard *Panthera pardus nimr*, Arabian wolf Canis lupus *arabs* and Striped Hyena *Hyaena hyaena* (Edmonds et al., 2013; Tourenq et al., 2009). Even in protected areas such as Wadi Wurayah Man and Biosphere "MAB" Reserve (hereafter 'the reserve'), we have witnessed local extirpations of the Arabian tahr *Arabitragus jayakari* (last recorded in 2013) and Gordon's Wild Cat *Felis lybica lybica* (last recorded in 2011). In 2013 the reserve was closed to public and in 2015, the park management reinforced the patrolling and low implementation. Poachers proofed to traverse the reserve borders were prosecuted all ("RFA Newsletter," 2017). Law enforcement by the local government had a deterrent effect and proved efficient in the short term.

The reduction in landscape connectivity and resource overlap between predators alter carnivore interactions, leading to increased competition and causing a shift in species and habitat relationships (Davis et al., 2021; Hemami et al., 2018). Carnivore habitat selection is not independent, and it might be affected by species behavioural traits and resource availability, such as free water accessibility and prey abundance, particularly in arid areas (Atwood et al., 2011; Bender et al., 2017). Habitat selection can additionally cause segregation between ambush and cursorial predators (Eisenberg, 1986).

Resource competition during times of scarcity may lead to aggression and despotism behaviour by the dominant carnivores towards the subordinate ones (Fedriani et al., 2000). Competition could lead to a seasonal fluctuation in habitat use and niche segregation between sympatric species to promote coexistence (Bender et al., 2017). In the reserve, Red Fox *Vulpes vulpes* was recently recorded holding the carrion of a Blanford's Fox *Vulpes cana* during the summer season, indicating probable aggression between the two species. The competition between the two fox species could alter Blanford 's Fox's spatial or temporal behaviour and restrict habitat availability, limiting species distribution over the long term (Haswell et al., 2018; Pamperin et al., 2006).

Habitat loss is expected to increase carnivore vulnerability and lead to local extinction under the accelerated impact of climate change and anthropogenic effects (Di Minin et al., 2016; Visconti et al., 2016). The apex predator in the reserve, the Caracal, is the most vulnerable due to its low birth rate, extensive home range (probably overlapping semi-urban areas) and persecution for attacking livestock (Everatt et al., 2019; Harrison & Bates, 1991; Purvis et al., 2000). Carnivores have a trophic cascade effect on other subordinate carnivores and prey; thus, knowing their habitat preferences will contribute towards preserving a functional ecosystem (Ripple et al., 2016). Carnivores, in general, are vulnerable to habitat change; however, the factors that influence habitat selection and promote coexistence in the reserve remain unknown (Rich et al., 2016).

Study Objectives

Camera traps are an efficient tool to monitor mammals. They are less invasive and a reliable mean to detect large and medium-sized carnivores, particularly elusive and nocturnal species (O'Connell et al., 2006; N. Pettorelli et al., 2010). Combined with an occupancy modelling framework, camera traps have proven suitable for monitoring rare species where individuals are not identifiable (O'Connell et al., 2011; Pollock et al., 2002). Habitat relationships can be evaluated statistically using occupancy models (MacKenzie et al., 2003). Thus, combining camera trapping with occupancy modelling can allow park management to understand these relationships and predict how species would react to changes in habitat and resources such as water scarcity, vegetation cover, prey availability, and other variables in an arid ecosystem (MacKenzie et al., 2017). Seasonal variation can be extreme in the desert environment, where the whole ecosystem is affected by the fluctuation in annual precipitation (Atwood et al., 2011; Tourenq et al., 2011). Resources can be minimal for prolonged periods, and thus we decided to study the occupancy and habitat relationships in two seasons, summer and winter (Bender et al., 2017; Koehler & Hornocker, 1991). In drought years, the lack of resources is more likely to exaggerate the impact of competitive interactions between sympatric species. Such information would support reserve management and species management at the regional scale. To study the habitat associations of the three sympatric carnivores, I hypothesised that anthropogenic, biotic and habitat variables would influence the habitat use of the last three sympatric carnivores in the reserve, Blanford's Fox *Vulpes cana*, Red Fox *Vulpes vulpes* and the Caracal *Caracal caracal*, to a different degree. To assess the impacts of different environmental variables on occupancy, I used *a priori* hypothetical approach and constructed a single-species, single season occupancy model for each species

Study Area

Wadi Wurayah Man and Biosphere Reserve is located in Fujairah Emirate (25.396 N, 56.269 E), the United Arab Emirates "UAE". The reserve covers a total of 277 km^2 (Fig. 1), which is divided into a core zone (120 km^2), buffer zone (99 km^2) and transition zone (58 km^2). Wadi Wurayah catchment basin covering the whole core zone was declared a Ramsar wetland of global importance in 2010 (site no. 1932), as its unique hydrogeology maintains a permeant freshwater ecosystem (Fig. 3) with water released into wadi beds as springs, streams creating seasonal and permanent water pools in wadis downstream (Fig. 4) (Tourenq et al., 2011).

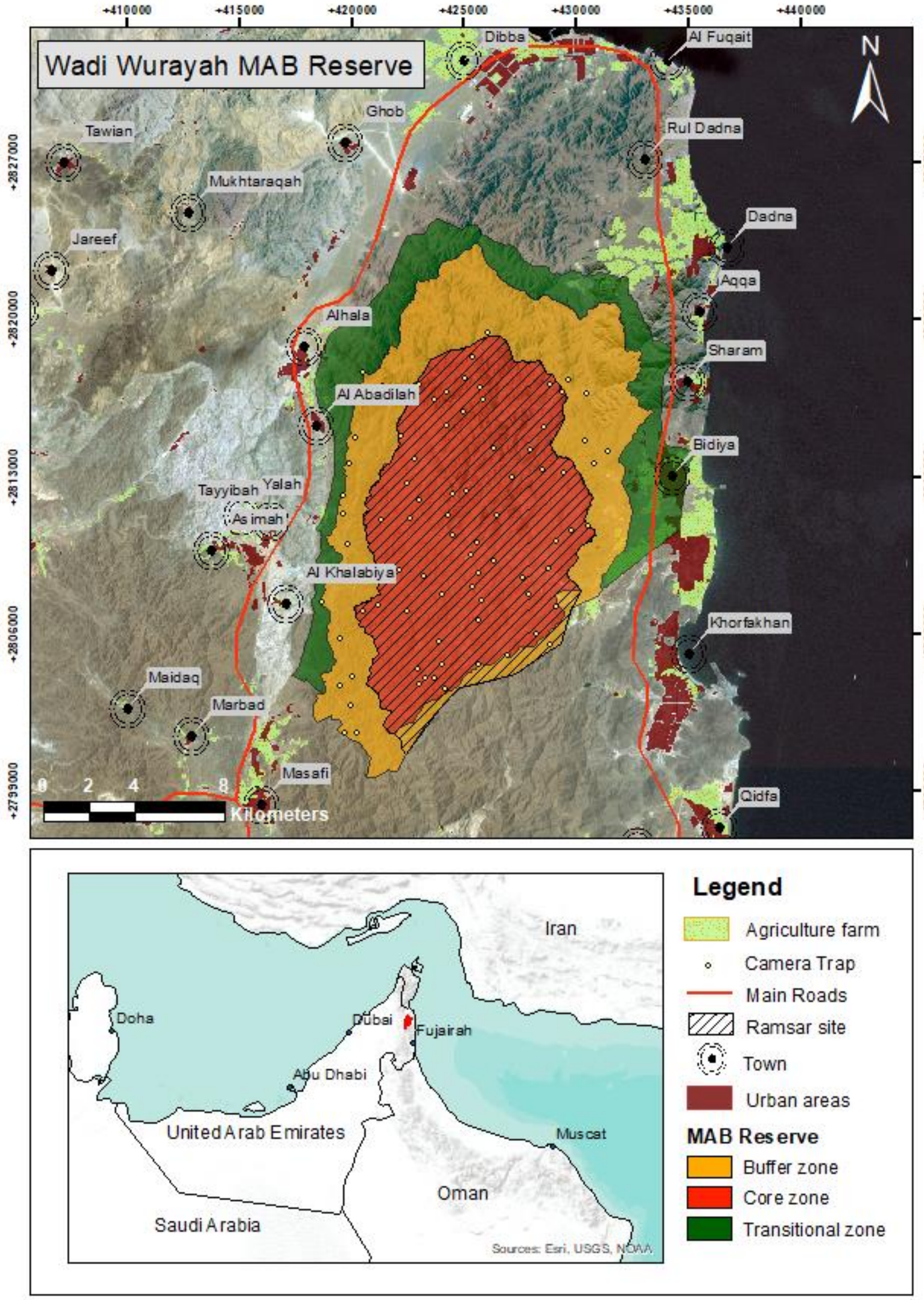

Figure 1. Map of Wadi Wurayah Man and Biosphere Reserve administrative zones and Ramsar site borders showing all camera trap locations used between the years 2009 to 2018

The UAE is a semi-arid area with a hyper-arid climate and extremely high temperatures reaching up to 50°C in Summer with a daily mean relative humidity range between 50 to 70% (Al-Hogaraty et al., 2013; Böer, 1997). Rainfall is low, erratic and patchy combined with flash floods occasionally (Fig. 2), with a mean annual rainfall average of 179 mm (range: 27.6 – 443.8); (Feulner, 2016; Nouh, 2006; Subyani, 2011).

Figure 2. Downstream flash flood during intense rainfall at a higher elevation

Elevation in the reserve ranges between 250 to 1000 m and is covered with sparse vegetation with a noticeable increase in vegetation cover in wadis, around water pools, and at higher elevations (Ghazanfar, 1991). Despite the relatively high number (≈200) of recorded plant species in the park, the high temperature, low rain, and poor soil contribute to low vegetation cover in the reserve (Feulner, 2016). Flora characterised by the association of several woody perennials can be found on the mountain slopes such as *Convolvulus virgatus*, *Lycium shawii*, *Boerharvia elegans* with *Euphorbia larica* and *Tephrosia appolinea* at higher elevations. Tree species in the reserve include the widely distributed *Vachellia tortilis*, with *Moringa peregrina* found on mountain slopes and *Ficus cordata* and *Ziziphus spina-christi* found in wadis (Feulner, 2016; Jongbloed et al., 2003; Tourenq et al., 2009).

Honey gathering and goats herding are two cultural activities still in practice in Hajar mountains to these days. Goat and sheep breeding was part of the locals livelihood for centuries, while now, it is a supplementary source of income for the local community in the villages around the reserve (EWS-WWF, 2006; Van Neer et al., 2017; Zaibet et al., 2004). In 2016-2017, we mapped 52 permenant goat farms, 60% are located on the eastern side of the reserve. One farm was located in the core zone with around 200 free roaming goats while the majority are inside the buffer and transitional zones. In some cases, goat farm owners had a shepherd and usually used areas in the reserve buffer zone for grazing while most of the owner have let their goats to graze freely outside the mating seasons, knowing that goats will return eventually to the farm for fodder and water. Feral and domestic goats Capra aegagrus hircusi have become part of the ecosystem as many old farms inside the park core zone were abandoned in the middle of the 70’s, and many goats back then have turned to feral (locals call them “horob” which means the “fugitives” in Arabic) and some are occasionally killed by the Caracal inside the reserve.

Figure 3. Wadi Wurayah famous permanent waterfall and permanent pool (inside the circle) showing from a distance are considered one of the natural attractions in the country (© Sami Allah Majeed).

Figure 4. Permanent water pools can persist all summer season and are found in several locations downstream of Wadi Wurayh catchment basin.

The reserve topography is characterised by highly rugged mountains, wide terraces down streams (Fig. 5) and meandering wadis. The mountain associated freshwater ecosystem supporting variety of wetlands habitat in the reserve making it one of the main hotspots for biodiversity in the UAE. Besides its recognition as a wetland of global importance and Man and Biosphere Reserve, it has been recognised as an Important Birds Area since 2017 (*BirdLife Data Zone*, 2021). Mammals recorded in the reserve include Bovidae, Arabian Tahr (*Arabitragus jayakari),),* though recently extirpated; Canidae (Blanford's fox, *V. cana*), the Red Fox (*V. vulpes*) and Felidae, Caracal (*Caracal Caracal*). The reserve has one species of Erinaceidae, Brandt's Hedgehog *Paraechinus hypomelas* and three small mammals of the Muridae family, the Arabian Spiny Mouse *Acomys dimidiatus*, Wagner's Gerbil *Gerbillus dasyurus* and one invasive species recorded from one locality Black Rat *Rattus rattus*. In addition to the recently discovered species, the Indian Crested Porcupine *Hystrix indica* of Hystricidae family was recorded for the first time in UAE in 2015 (Chreiki et al., 2018). Domestic and feral animals recorded in the park include domestic goats *Capra aegagrus hirta,* Feral Donkey *Equus asinus*, and more recently, domestic cats and dogs have been recorded increasingly frequently inside the core zone.

Figure 5. Aerial view with a typical landscape of the reserve showing the extremely rugged mountain, wadis and expansive terraces of quaternary alluvial deposits

Carnivore monitoring program

Developing a long-term biodiversity monitoring program is one of the main guiding principles for the reserve development (EWS-WWF & Fujairah Municipality, 2013). The reserve had six conservation targets upon establishment: (a) freshwater ecosystems, (b) terrestrial vegetation or habitats, (c) the Arabian leopard, (d) mid-size carnivores, (e) endangered ungulates, and (f) birds, small mammals, and reptiles. These targets were selected to ensure the contribution of the reserve to species and habitat conservation at the local and national levels.

A camera trap monitoring program was established to support the reserves objectives in advancing conservation, based on a scientific foundation (EWS-WWF & Fujairah Municipality, 2013). Supporting the carnivore guild is one of the main objectives of this monitoring program. The guild includes the last three carnivores persist in the reserve, Blanford's Fox (*Vulpes cana*), Red Fox (*Vulpes vulpes*) and the Caracal (*Caracal Caracal*) (Fig. 6).

The three species are sympatric over the mountain area in the UAE with diet overlap. Blanford's Fox and Red Fox weigh less than 6 kg in our region, whereas the Caracal has a global range of 8-20 kg (Eli Geffen & MacDonald, 1992; Lenain et al., 2004; Moqanaki et al., 2016). Caracal is a generalist feeder with a diet based mainly on meat (C. Stuart & Stuart, 2007), whereas Red Fox and Blanford's Fox are omnivorous (Cunningham & Howarth, 2002; Lenain et al., 2004). Caracal and Red Fox are more resilient than Blanford's Fox due to their generalistic habitat utilisation, whereas Blanford's Fox is more specialized (Cavallini & Lovari, 1991; Ilemin & Gurkan, 2010).

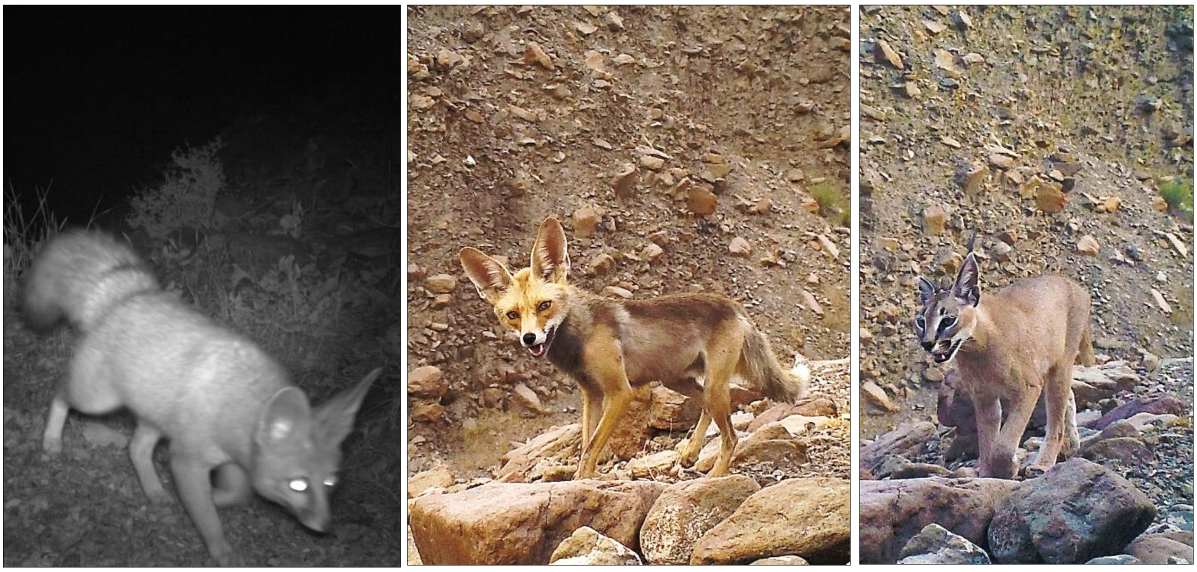

Figure 6. (Left to right) Blanford's Fox *Vulpes cana,* Red Fox *Vulpes vulpes* and the Caracal *Caracal caracal*

The reserve is a typical representative of the Hajar Mountain ecosystem, with a unique habitat and highly adapted species of fauna and flora enabling the carnivore guild to survive, the status of the three targeted species was considered "Good" in 2013, according to the reserve management plan. However, this assessment was based on assumptions rather than on rigorous scientific data. The conservation status of the three species varies between the global, regional, and the United Arab Emirates "UAE" National Red List published recently in

2019. The global conservation status of the three species is Least Concern (LC) (Hoffmann et al., 2021; Avgan et al., 2016; Hoffman et al., 2015). On the national level, Blanford's Fox conservation status was Vulnerable (VU) according to the regional Red List assessment of 2011 due to population decline (Mallon & Budd, 2011), and it maintained this status (VU) in the last national assessment in 2019. While, the Caracal is considered a Critically Endangered (CR) species within the UAE national Red List assessment of 2019 due to the increased threats (Mallon et al., 2019). Red Fox is relatively common in the UAE and considered Least Concern at the National level (Mallon et al., 2019).

Family	**Species**	**Common name**	**Global red list***	**Regional Red list 2011**	**UAE National Red list 2019**
Canidae	*Vulpes cana*	Blanford's Fox	LC and stable (IUCN 2015)	Vu (Declining)	VU
Canidae	*Vulpes vulpes*	Red Fox	LC and stable (IUCN 2021)	LC (Increasing)	LC
Felidae	*Caracal caracal*	Caracal	LC and unknown (IUCN 2016)	LC (Fluctuating)	CR

Table 1. The global and national conservation status of the carnivores species (*Significance of the IUCN Red List criteria: LC: least concern, VU: vulnerable, CR: critically endangered)

The carnivore's home range varies between regions due to prey availability and dispersion (MacDonald, 1983). The minimum distance between the camera of 500 m corresponds in theory to both species of foxes, Blanford's Fox with a home range of 0.55-2.75 km^2 (Geffen et al., 1992b) and 6.75 to 27.3 km^2 for the Red fox in Saudi open desert (Macdonald et al., 1999), but not with the Caracal having a bigger home range that could vary between 7.39-26.9km^2 in South Africa (Avenant & Nel, 1998) to 1116 km^2 in Saudi Arabia (Lenain et al., 2004; Van Heezik & Seddon, 1998). This issue is not of great concern within the scope of this research for two reasons: species do not use their whole home range all the time; in our case, we selected six months as one season, targeted species with bigger home range such as the Caracal might utilise only part of their home range within this period (Mackenzie, 2005; Petrunenko et al., 2016). The second reason is related to our research objectives, giving more emphasis on carnivore habitat use and affecting variables (Mackenzie, 2005) rather than estimating occupancy (Mackenzie & Royle, 2005).

Research Methodology

Camera Trap Data

The reserve management deployed camera traps at 115 locations between 2013 to 2018 (Fig. 7). The reserve area was divided into a 2x2 km grid, and inside each cell, two cameras were deployed (Fig. 10). Each cell was 4 km^2, which corresponds to the average home range of the Arabian Tahr *Arabitragus jayakari*, an endangered ungulate species that was a focal species when the surveys were initiated (Ross et al., 2017; Ross et al., 2019). Due to the ruggedness of the terrain, cameras were deployed opportunistically. Whenever possible, cameras were installed in different habitats with a minimum of 500 metres apart to promote the independence of observations (Gálvez et al., 2016). We distributed camera traps in wadis (wadis and gorges) and mountain slopes (bottom, middle and top, including the alluvial terraces and mountain ridges) to represent habitat variety and promote camera independence through habitat separation.

Figure 7. (Left) Camera trap installed in a wadi (Right) Side view of a camera installed in the field

We placed cameras along fauna trails on mountain slopes or in wadis (preferably at wadi convergence points) and near-permanent water pools whenever possible to increase detection probability (Curveira-Santos et al., 2019; O'Connell et al., 2011). We installed all cameras on rocks at 0.5 m above the ground; in exceptional cases, we fixed the cameras at 1.5-2 m high to avoid flash floods in narrow wadis. Camera traps were oriented towards animal trails, and the distance was maintained between 2-5 metres from the targeted point to allow for a wider field of view and a larger detection zone (TEAM Network et al., 2011). We cleared the vegetation in front of cameras to reduce the number of false triggers due to vegetation movement by the wind and to maximise the camera detection within its field of view (Gillespie et al., 2015; TEAM Network et al., 2011).

We used two camera trap models, Bushnell 119776C (Bushnell Outdoor Products, Cody, Kansas, USA) and Reconyx HyperFire PC800 (Reconyx, Holman, WI, USA). Both are equipped with passive infra-red sensors and infrared flash in the dark. Both cameras have a similar trigger speed of 0.2sec; the only difference was the sensor range and detection zone. Reconyx camera trap can cover up to 324 m^2 while its infrared sensor range can reach up to 30.5m, compared to Bushnell (164.3 m^2 and 18m); we found these differences minor as the targeted point did not exceed 10m at all times. Both camera models were adjusted to take three photoburst at every trigger with 5 seconds between each trigger. In most cases, sensitivity was adjusted to high since the area has a very low vegetation cover. No bait was used at camera stations.

Prior to sorting, photos were bulk relabelled using Renamer (Kozlov, 2009; Schmitt, 2013). A small proportion of files were recorded with the wrong date and time; these were either manually relabelled or automatically using the software namexif (DigicamSoft, 2021), benefiting from the software ability to re-adjust the date and time of the taken picture if required.

Photos were then manually sorted according to species and the number of individuals in each photo prior to the complete record of species sightings (detection history), organised per site, and extracted using the software package (CameraSweet) available for free on Small Wild Cat Conservation website (Sanderson & Harris, 2013). The software also provided metrics of effort and the number of independent sampling events per month and year.

Determination of Environmental Factors

The variable selection process consisted of our knowledge and the existing literature on the main ecological requirements of the targeted species (Franklin, 2010). I extracted 29 variables that may affect the occupancy and the detection probability of Blanford's Fox, Red Fox, and the Caracal. Variables were divided into anthropogenic, biotic, and habitat; and into five subcategories (Table A.1). To extract the spatial variables, I constructed a geographical database using ArcGIS 10.2.2 (ESRI, 2014).

Mammalian carnivores are sensitive to habitat fragmentation, human disturbance and correspond differently to land-use intensity (Long et al., 2011; Ramesh & Downs, 2015; Vitekere et al., 2020; Wang et al., 2015). To assess the impact of anthropogenic infrastructures such as urban areas, goat farms, agriculture farms and roads (Fig. 8); I calculated the euclidean distance between the different types of development and camera trap locations using the spatial analysis tool in ArcGIS 10.2.2 (ESRI, 2014) and Landsat satellite image with 5x5m resolution from 2014 (Benson et al., 2016).

Biotic interactions, such as competition and predator-prey dynamics, can influence species geographical diversity patterns (Rota et al., 2016; Sévêque et al., 2020; Wang et al., 2015; Wisz et al., 2013). Competition between sympatric carnivore species is a consequence of exploiting shared resources, resulting in reduced densities or range restriction of subordinate carnivores due to intraguild predation or inter-specific competition (Atwood et al., 2011; Caro & Stoner, 2003; Donadio & Buskirk, 2006; Fedriani et al., 2000; Newsome et al., 2017). Subordinate carnivores have adapted through exhibiting temporal avoidance, dietary partitioning and spatial segregation (Gosselink et al., 2003; Prange & Gehrt, 2004; Šálek et al., 2015), but in some cases, competition might eventually lead to local extinction (Pamperin et al., 2006; Pimm, 1991; Schuette et al., 2013). To measure the influence of interspecific and intraguild competition and prey availability on species occupancy, I used capture success (number of species captures per 100 trap nights) as a variable. I calculated the capture success of four prey species to test with all carnivores and the capture success of the Caracal and Red Fox to test exclusively with Blanford’s Fox at each camera location.

Figure 8. Traditional farming activities and date farms in the reserve buffer zone

Habitat is mainly dominated by low profile scrubland during winter, while towards the end of the summer, the mountains become barren with sparse vegetation, small bushes and scattered trees (Feulner, 2016). Wadi beds have a higher vegetation density in areas where water emerges or comes closer to the surface (Fig. 9). I calculated the Euclidian distance to wadi and distance to freshwater resources using the spatial analysis tool in ArcGIS 10.2.2 (ESRI, 2014). Additionally, I included two binary variables for cameras locations inside a wadi or on the mountain slope to test species preference for these habitats.

Figure 9. A typical freshwater habitat showing a permanent water pool fed by the static water running under the gravels in the wadi bed (*Arundo donax* left and right with *Typha domingensis* in the middle)

Elevation is another critical variable as it influences water and climate, as rainfall increases linearly with elevation across the Hajar Mountains (Kwarteng, 2009; Lomolino, 2001). Aspect and slopes can influence plant growth in arid regions, and mountain areas, mainly since evaporation varies, affecting soil moisture and vegetation cover (Brinkmann et al., 2009; Deil & al Gifri, 1998; Kidron & Zohar, 2010). To measure the impact of both the aspect and slope, I calculated the heat load index to estimate the impact of radiation (McCune & Keon, 2002). I used satellite-derived Digital Elevation Models at 5 m resolution to extract the values of elevation, aspect and slope (Jenness, 2013).

Vegetation can also be considered a proxy for prey availability (Mueller et al., 2008) and provide services such as cover and food to mesocarnivores. I assessed the impact of vegetation cover (Fig. 10) on carnivores occupancy by calculating the Euclidean distance to four areas of different vegetation cover (vegetation cover <10%, 10-30%, 30-50% and >50%). I extracted the Euclidian distance from the land use land cover map LULC (Fig. 11) developed by the Satellite-based Wetland Observation Service SWOS* (Weise et al., 2020). I also used the mean NDVI (Normailzed Difference Vegetation Index) value within 150m buffer area surrounding the camera trap using Landsat imagery from November 2014 (30x30m resolution).

Figure 10. Mountain slopes and vegetation cover after a good rainy season (© Sami Allah Majeed)

* SWOS project provided a spatial map and characterisation of the vegetation classes in the natural dry habitats depending on the annual average of the vegetation cover. The LULC and vegetation cover map is extracted from 17 images from 12 months between January 2014 to February 2015. NDVI value of 0.15 was used as a threshold to define a "densely vegetated grassland" in such an arid region (knowing that theoretically all NVDI positive values correspond to a presence of vegetation and more they are close to 1, higher the vegetation cover and biomass are).

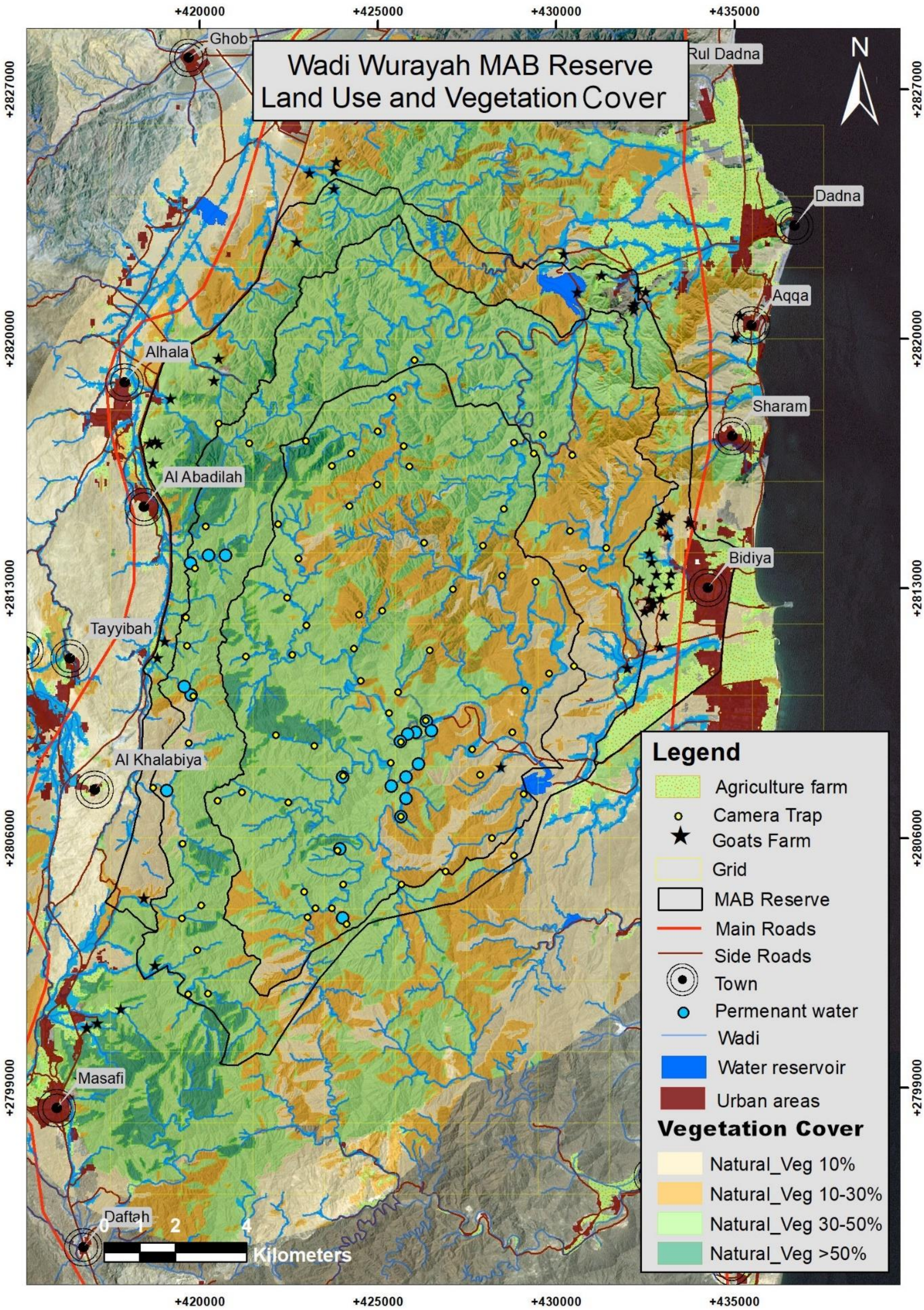

Figure 11. Land use and vegetation cover in Wadi Wurayah Man and Biosphere Reserve and the surrounding area.

Occupancy modelling

Occupancy modelling estimates the probability of a species occupying a site during a given survey period. Occupancy models can account for imperfect detection by incorporating the detection probability and the occupancy of the targeted species. Occupancy models are likelihood-based and modelled depending on the selected research hypothesis and variables (Bailey et al., 2007; Mackenzie et al., 2005; MacKenzie et al., 2017; Nicholson et al., 2009). Single-season occupancy models were used to make inferences on habitat selection (Figel et al., 2019; MacKenzie et al., 2017). To investigate single-season occupancy, I extracted the detection history (Presence/absence data) of each of the three carnivores species from the sub-set sample of the camera traps within the targeted seasons and ran it in PRESENCE software (Hines, 2006; Mackenzie, 2012). To account for the species imperfect detection, I constructed a unique (global) detection model for each species and combined it with the best-fitted occupancy models to answer the research questions (Burnham & Anderson, 2004). I repeated this process for two seasons, summer and winter, as habitat utilisation when food resources and anthropogenic effects are expected to change and thus affect the occupancy (Fuller & Sievert, 2001).

I had to consider several factors when selecting the most suitable seasons and data set between 2013-2018. Considering this, I looked into the limiting factors such as low species detection to maintain relevant results and improve the precision of the occupancy models (Mackenzie & Royle, 2005; Shannon et al., 2014). Targeting rare carnivores with low detection probability can limit the outcomes of single-season occupancy (Burton et al., 2012). Furthermore, studying medium to large mammals with a relatively long life span, I selected the maximum survey length of six months for one season following the recommendation of Wearn et al., (2017). Extended periods for survey length are recommended in rare species for more repetition and to determine habitat use (Gálvez et al., 2016; Mackenzie, 2005; Shannon et al., 2014). The number of sampling locations can be considered another limiting factor, where 30-60 sites are reasonable for many common species (Shannon et al., 2014), but more than 100 sites are optimal for very rare species (O'Brien, 2010). In general, more sites surveyed is preferable within the set limits of 60-90 sites when rare species exist (Mackenzie & Royle, 2005; TEAM Network et al., 2011).

Finally, to improve the detection probability history of the selected seasons, I pooled every seven trap nights to one occasion to increase detections within the detection history matrix (Tobler et al., 2008a).

I extracted species detection history based on independent photo captures, maintaining a 60-minute threshold interval between two independent photos (Bahaa-el-din et al., 2016; Tobler et al., 2008). For single-season occupancy modelling, data were divided into six months, and the summer season extended from 1st April to 30th September, whereas the winter season was from 1st October to 31st March. To select the most appropriate consecutive summer and winter seasons, I only selected seasons with operational sites of 60 to 90, excluding camera traps with less than 60 days of effort for consistency.

Modelling approach

I used single-season occupancy models to test the species occurrence hypothesis and assess the impact of different predictor variables while controlling for imperfect detection (i.e., when a species is present but not detected; Long et al., 2011; MacKenzie et al., 2017). Occupancy modelling can be used to assess the influence of individual variables at the given sites (ψ; probability of the species occupying a site), using the most suitable detection model for each species (p; probability of the species being detected if present).

Each species' binary detection histories were extracted for two seasons (1 for detection and 0 for no detection). To increase species detection probability in each sampling period without violating the closure assumption, I collapsed every seven days into one sampling occasion, and occupancy was assumed constant (MacKenzie et al., 2002; Rich et al., 2016). Every seven camera trap days were considered a repeated survey, resulting in two seasons of 26 sampling periods (weeks with less than four camera trap days and sites with less than 30% of effort were excluded).

Prior to modelling, environmental variables were tested for correlation to avoid multicollinearity that could lead to inappropriate inferences in the final models (Graham, 2003; MacKenzie et al., 2017). I used Pearson correlation coefficient to test for variables correlation, pairs with correlation value > 0.45 were identified, and only the best fitting variable was used in the final models when correlation existed (Ross et al., 2017).

Model fitting and variable selection process might lead to prediction bias when too many variables are tested arbitrarily, leading to well-fitted models by chance (MacKenzie et al., 2017). To avoid misleading variables and minimise model overfitting (when models perform poorly beyond the data used to create them), I followed an *a priori* approach assuming that each variable would affect occupancy differently. This approach also helped limit the number of variables tested in models to the noncorrelated and biologically meaningful ones (Liddle et al., 2009; Long et al., 2011; Vitekere et al., 2020). To develop both the detection and occupancy models, I grouped the predictor variables under five *a priori* model sets belonging to three criteria; Anthropogenic effects (Human disturbance), biotic (competition and predation), and habitat (Habitat and landscape). Only variables specific to carnivore species and that can strongly influence model parameters for both detection (p) and occupancy (ψ) models were selected (MacKenzie et al., 2017). The final list of variables contained only high prediction potential for the carnivore guild, including a few exploratory variables such as vegetation cover (used due to the lack of species-specific regional habitat references). Variables were used to develop one global model for detection that included the best representative variables from all the categories, while occupancy models included combining the best representative variables under each of the five sub categories (Table A1).

To capture seasonal variability in both the occupancy and in detection probability due to the changes in the use of resources, I developed two sets of variables for each season (summer and winter) and followed the same method of variable selection to provide inferences about the changes in the influence of variables between summer and winter (Fuller & Sievert, 2001; Morrison et al., 1998). Variables and detection histories were fitted using Software PRESENCE V 12.7.

Akaike Information Criterion "AIC" was used to compare and rank models (Richards et al., 2011). To extract the most parsimonious model, I used a stepwise backwards-selection approach to identify uninformative variables in the final models by eliminating the least important ones determined by the minimum absolute value of model parameter estimate and standard error (Pagano & Arnold, 2009). If the variable removal did not change the model AIC rank, I considered this variable uninformative and removed it (Arnold, 2010). Additionally, variables with a 95% confidence interval of parameter estimate that overlapped 0 were eliminated; I continued this approach until no additional variable could be removed without leading the AIC value to increase.

The best *a priori* detection model for each species was developed first (Global detection model) and then combined with each candidate *a priori* model representing the three occupancy models categories. I used models ΔAIC and weight "wi" values to assess model fit (Burnham & Anderson, 2004). The most parsimonious models set were considered the best candidate to describe species occupancy patterns (Burnham, & Anderson, 2002; Richards, 2008; Richards et al., 2011). To assess the goodness-of-fit of the top models, I used parametric bootstrapping to calculate the dispersion parameter C-hat ($\hat{c}$) and the 95% confidence intervals CI by generating 10000 parametric bootstraps (MacKenzie et al., 2004). Models with $\hat{c}$ values of ~ 1 were considered adequate for interpretation, whereas models with $\hat{c} > 2$ suggested that models may have overdispersion issues (Liddle et al., 2009).

I reported all models with wi≥0.05 for each species in each season (Arnold, 2010; Richards et al., 2011). Models with ΔAIC≤2 were considered representative of the species occupancy. For the additional models with ΔAIC≤6 and wi≥0.05, I provided a general interpretation of variables to understand habitat use patterns as long as the 95% CI does not overlap with 0 (Richards, 2005, 2008; Richards et al., 2011). Variables were considered to strongly influence detection and occupancy if the 95% confidence interval of the parameter did not overlap or slightly overlap with 0. I back-transformed effects and reported odds ratios to assess each variable's relative importance in the final models. A null model without covariates and constant ψ and p (i.e. $p(.)$, $\psi(.)$) was included in the candidate model set for reference against baseline conditions.

Results

Season selection

I selected the data set of summer and winter of 2016 with the highest number of operational sites with 77 and 79 sites, respectively.

Carnivore summer survey results

The summer season covered 183 days from 1st April to 30th September 2016. During this season, 77 camera traps were operational for more than 60 days and produced 3933 records of the three targeted carnivore species during 12453 trap nights (mean = 162 days; SD = 30). Out of these records, 1019 were independent captures divided as follows; 896 pictures of the Red Fox (87.92%), 68 pictures of Blanford's Fox (6.67%) and 55 of Caracal (5.39%).

Camera traps were distributed in 29 wadis and 48 mountain slopes locations during this season, covering a total area of 158.49km^2. One site violated the minimum distance of 500m between camera deployment locations with 347m (between sites 103_02 and 113_01). This violation of spatial independence role was ignored considering that all other sites had a minimum of 547m distance between with an average of 736m.

The summer season had an average richness of 1 carnivore per site. Out of 77 camera trap locations, the Red Fox had the highest naïve occupancy of 0.5 (39 locations) compared with Blanford's's Fox 0.26 (20 locations) and the Caracal 0.26 (20 locations). Red Fox had the highest capture success (7 captures per 100 trap nights), followed by Blanford's Fox (0.5) and then the Caracal with 0.44 (Table 2). The eastern area of the park had the highest number of detections, but Red Fox were the only species recorded (Fig. 12).

Species	Naive occupancy	Total locations and habitat (WD/MS)	Location with records (WD%/MS%)	Independent Photos	Capture success	min/max altitude
Blanford's Fox	0.26	77(29/48)	20 (35/21)	68	0.55	285/666
Red Fox	0.51	77(29/48)	39 (31/63)	896	7	117/666
Caracal	0.26	77(29/48)	20 (28/25)	55	0.44	303/721

Table 2. Summary statistic of naïve occupancy and camera traps independent records of carnivores during summer 2016, including variation between wadis (WD) and mountain slopes (MS)

There was a high overlap (60%) between Blanford's Fox and Caracal detections at camera sites. Red Fox sites had only 30% and 28.2% overlap with the other two carnivores, respectively (Table 3).

Species	Camera captured out of (77)	Blanford's Fox (% overlap)	Red Fox (% overlap)	Caracal (% overlap)
Blanford’s Fox	20		12 (60%)	12 (60%)
Red Fox	39	12 (30%)		11 (28.2%)
Caracal	20	12 (60%)	11 (55%)	

Table 3. Carnivores sites overlap during the summer season

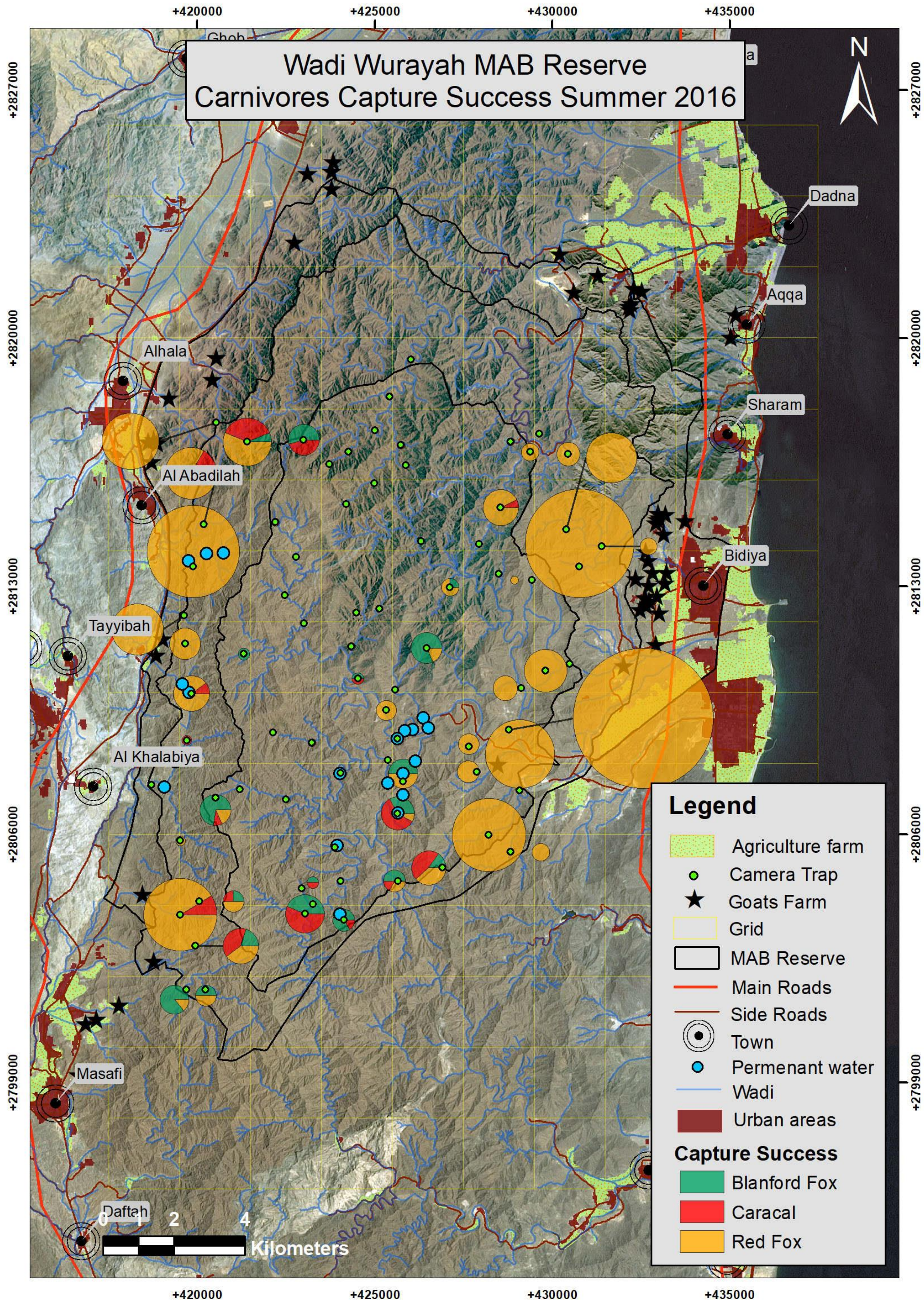

Figure 12. Carnivore captures success for summer 2016, showing all operational camera trap locations

Prey Summer Survey Results

Domestic goats (*Capra aegagrus hircus*) had a high naïve occupancy of 0.96 as they were recorded in 74 locations out of 77 during this season. Camera traps recorded 3055 independent photos capture of domestic goats with an average capture success of 24.5 per 100 trap nights across all sites (Fig. 13).

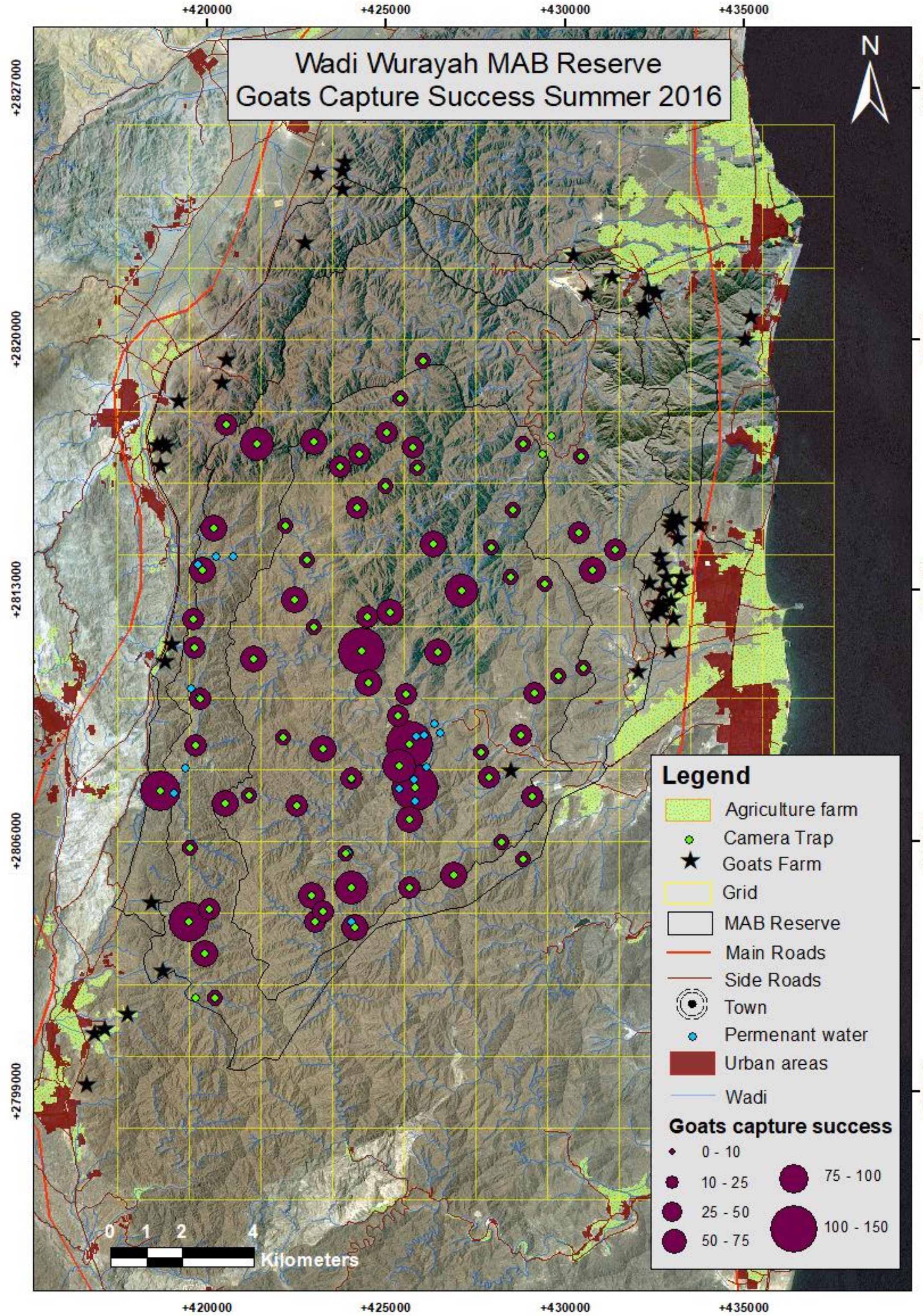

Figure 13. Domestic goats capture success at camera traps locations during summer 2016

In addition to Domestic goats, three other species were identified as potential prey for carnivores, including Brandt's Hedgehog (*Paraechinus hypomelas*), Sand Partridge (*Ammoperdix heyii*) and various small mammals (small mammals records were grouped under one category since species identification is almost impossible in most cases). Due to the low number of photo records during summer 2016, I pooled the summer records of these three species between the years 2010 to 2017 (Table 4). Sand Partridge had the highest number of independent records of 253 in 26 locations with naïve occupancy of 0.34, followed by Brandt's Hedgehog with 26 independent records in 7 locations and a naïve occupancy of 0.09 and finally, small mammals with only 16 independent records in 3 locations and naïve occupancy of 0.04 (Fig. 14).

Species	**Naive occupancy**	**Camera out of (77)**	**Habitat (WD/MS)**	**Independent Photos**	**Capture success**
Domestic goats Summer 2016	0.96	74	29/45	3055	24.5
Brandt's Hedgehog Summer 2010-2017	0.09	7	1/6	26	0.02
Sand Partridge Summer 2010-2017	0.34	26	14/12	253	0.76
Small mammals Summer 2010-2017	0.04	3	2/1	16	0.05

Table 4. Summary statistic of prey species independent camera trap captures during summer season 2016

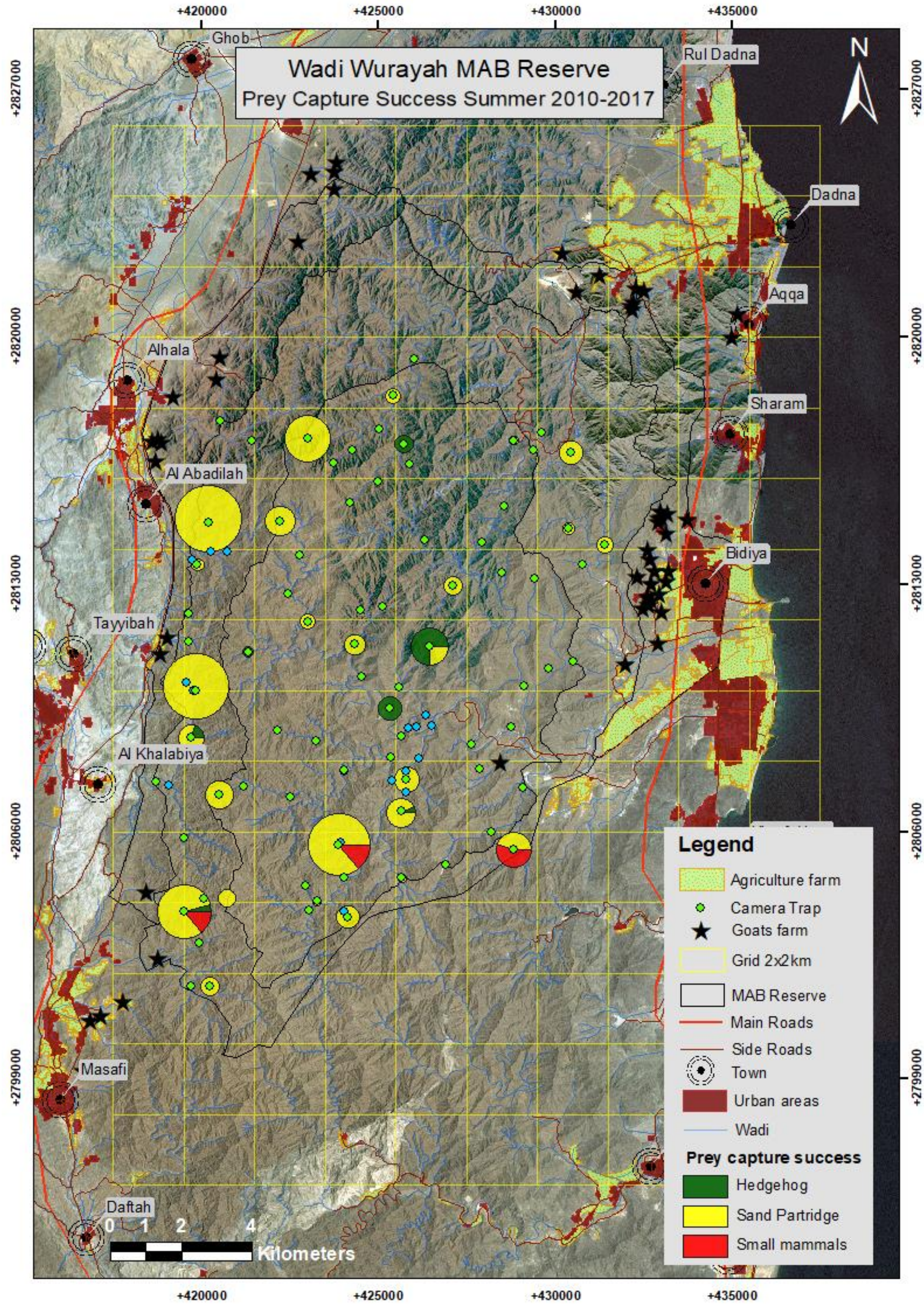

Figure 14. Relative prey capture success at camera traps locations during summer seasons (2010-2017)

Carnivore Winter Survey Results

The Winter season covered 182 days from 1st October 2016 till the 31st March 2017. During this season, 79 camera traps were operational for more than 60 days and produced 5436 records of the three targeted carnivores during a total of 13588 trap nights (mean = 172 days; SD = 27). Out of these records, we had 1397 independent capture events divided as follows: 1080 pictures (77.3%) of the Red Fox, 193 pictures (13.8%) of Blanford's Fox and 124 pictures of the Caracal (8.9%). The winter season had an additional 10% camera trap effort compared to the summer season and yielded an increase of 30% in detection.

One site violated the minimum distance of 500m between camera deployment locations with 347m; all other sites had a minimum separation of 547m and an overall average of 728m. Camera traps were distributed in 31 wadis and 48 mountain slopes. The camera network covered a total area of 158.12km^2.

The winter season had an average richness of 1.3 carnivores per site. Across the 79 camera trap locations, the Red Fox had the highest naïve occupancy of 0.59 (47 locations), Blanford's Fox had a naïve occupancy of 0.42 (33 locations), and the Caracal had a naïve occupancy of 0.3 (24 locations). Red Fox had an average capture success of 7.9 captures per 100 trap nights, which was less than summer, but the highest of all carnivores during this season. Blanford's Fox had a higher capture success rate of 1.42 per 100 trap nights than the summer season, followed by the Caracal with 0.91 per 100 trap nights (Table 5). The eastern area of the park had the highest number of detections, where Red Fox is the only species recorded (Fig. 15).

Species	Naive occupancy	Total locations and habitat (WD/MS)	Location with records (WD%/MS%)	Independent Photos	Capture success	min/max altitude
Blanford's Fox	0.42	79(31/48)	33(77.4/18.8)	193	1.42	223/666
Red Fox	0.59	79(31/48)	47 (41.9/70.8)	1080	7.9	117/666
Caracal	0.3	79(31/48)	24 (41.9/22.9)	124	0.91	259/721

Table 5. Summary statistic of naïve occupancy and camera traps independent records of carnivores during winter 2016, including variation between wadis (WD) and mountain slopes (MS)

In winter, we noticed a change in the distribution pattern from the summer season. Red Fox was recorded in 60% of Blanford's Fox and Caracal distribution sites, almost similar to summer. The Caracal sites overlap with Blanford Fox decreased by 20%, while Red Fox overlap with Blanford’s Fox sites increased by 20%. This change in pattern can be related to a change in habitat use patterns and exploiting the same resources. It is also possible that aggression between the Fox species is less in the more productive winter season, promoting more tolerance (Table 6).

Species	Camera captured out of (79)	Blanford's Fox (% overlap)	Red Fox (% overlap)	Caracal (% overlap)
Blanford’s Fox	33		24 (60%)	13 (39.4%)
Red Fox	47	24 (51.1%)		15 (31.9%)
Caracal	24	13 (54.2%)	15 (62.5%)	

Table 6. Carnivore site overlap during the winter season

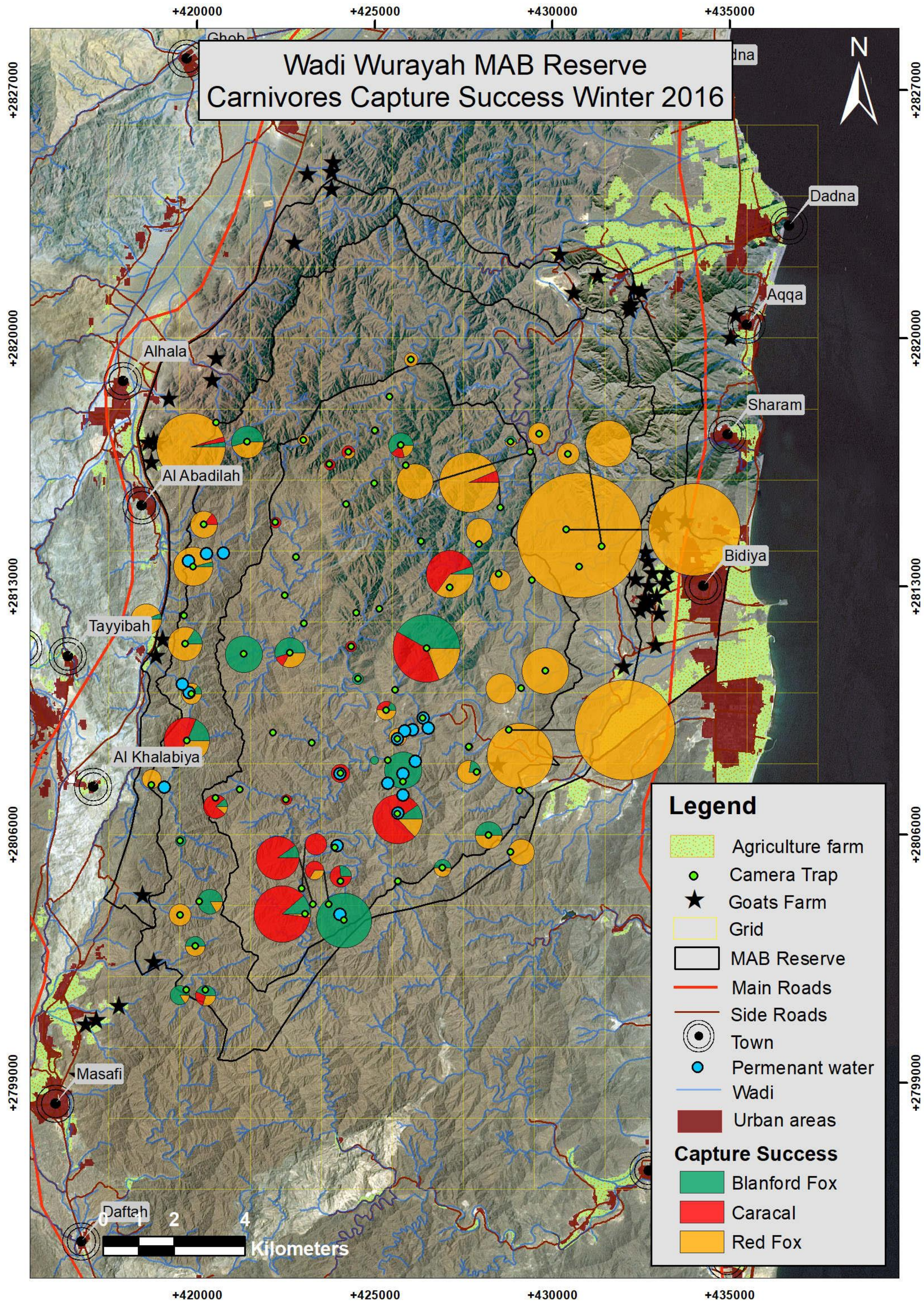

Figure 15. Carnivore capture success per camera location for winter 2016

Prey winter survey results

Domestic goats *Capra aegagrus hircus* had a high naïve occupancy of 0.97 as they were recorded in 77 locations out of 79 during the winter season of 2016 (Fig. 16). Camera traps recorded 2254 independent records with a total capture success of 8.3 per 100 trap nights.

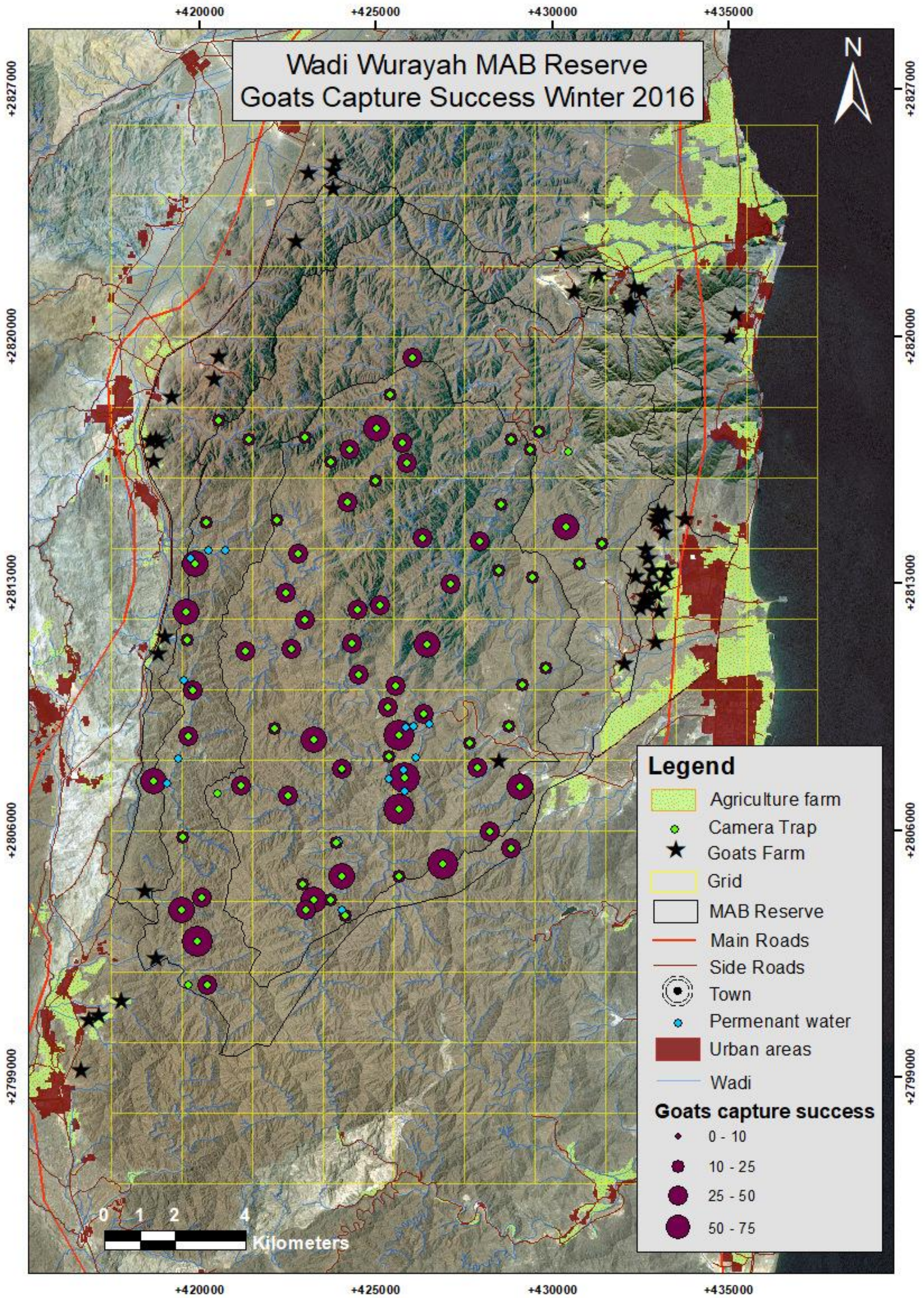

Figure 16. Domestic goats capture success at camera traps locations during winter 2016

The three additional species identified as potential prey for carnivores are Brandt's Hedgehog *Paraechinus hypomelas*, Sand Partridge *Ammoperdix hey*, and small mammals. All these prey species were captured at fewer sites and on fewer occasions during the winter of 2016. To compensate for the low detections, I used winter historical records from 2010 to 2016 to calculate capture success to account for the small numbers (Fig. 17). Sand Partridge had the highest number of independent records of 76 in 26 locations with naïve occupancy of 0.33, followed by Brandt's Hedgehog with 29 independent records in 14 locations and 0.18 naïve occupancy and finally, the small mammals with 27 independent records in 6 locations and naïve occupancy of 0.08 (Table 7).

Species	**Naive occupancy**	**Camera captured out of (79)**	**Habitat (WD/MS)**	**Independent Photos**	**Capture success**
Domestic goats Winter 2016	0.97	77	31/48	2254	8.3
Brandt's Hedgehog Winter 2010-2016	0.18	14	4/10	29	0.11
Sand Partridge Winter 2010-2016	0.33	26	12/14	76	0.28
Small mammals Winter 2010-2016	0.08	6	2/4	27	0.1

Table 7. Summary statistic of prey naïve occupancy and camera traps independent records during winter season

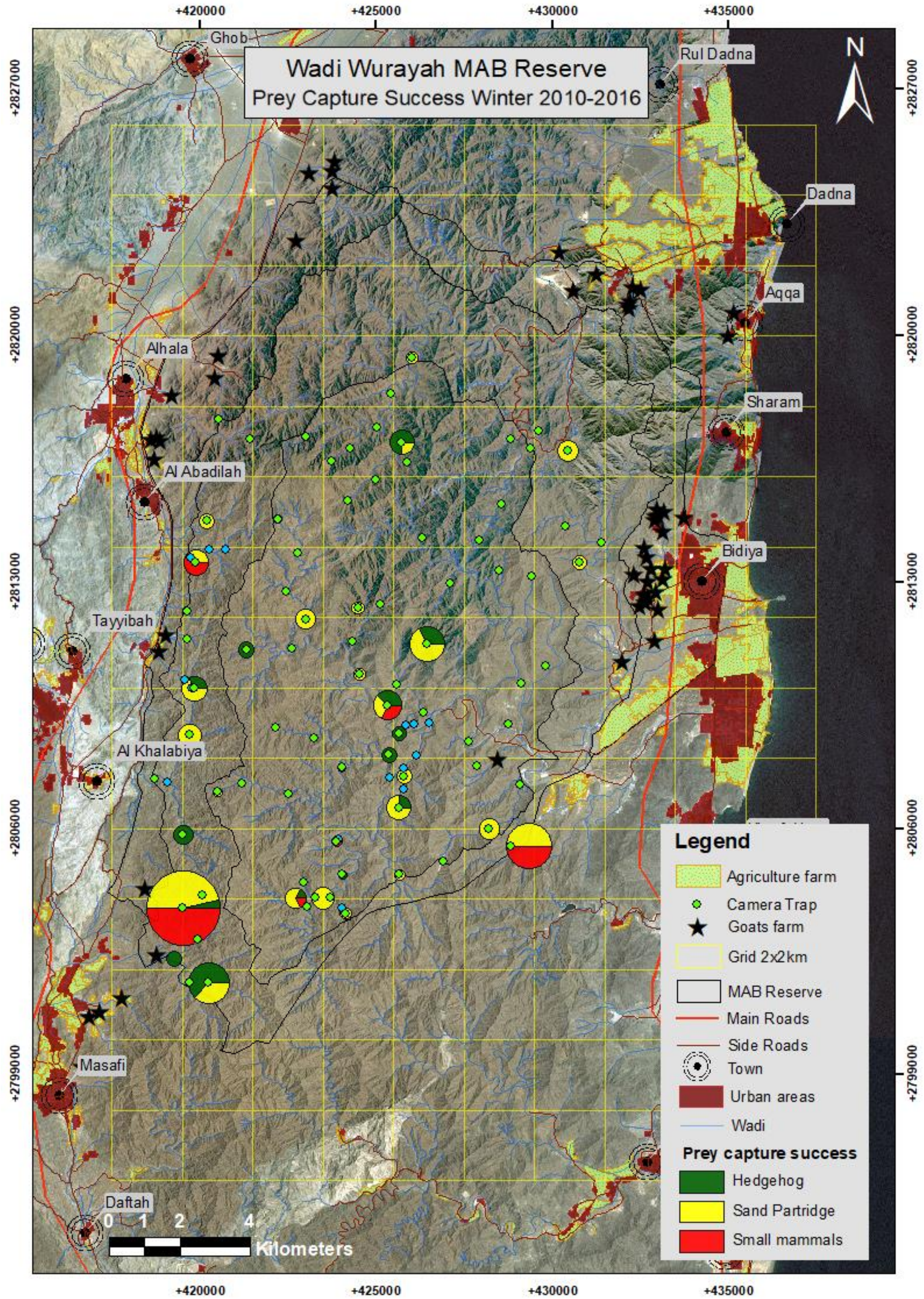

Figure 17. Relative prey capture success at camera traps locations during winter seasons between 2010-2016

Occupancy Models

Summer Occupancy Models

1. Blanford's Fox Summer Models

1.1 Blanford's Fox Summer Models (No Biotic variables)

The habitat model, including distance to permanent water, was the most parsimonious, with a wi of 0.68 and ΔAIC≤2 suggesting that permanent water availability positively influenced Blanford's Fox occupancy over the summer (Table 8). Odds ratios suggested that for every 1000m closer to permanent water, there was a 14.8% increase in the odds of Blanford's Fox occupancy. The anthropogenic effects and landscape categories models were less supported with ΔAIC≤6. Anthropogenic and landscape variables impacted Blanford's Fox occupancy less than habitat models since w_i >0.05, and the 95% confidence intervals did not overlap 0 (Table 9). Blanford's Fox occupancy is influenced positively by closer distances to goat farms (GtFarm) and negatively by the increasing ruggedness (Rugg500) and mountain slope habitat.

Blanford's Fox Summer Season Models (No Biotic variables)	AIC	K	ΔAIC	W_i	Ĉ
Occupancy (Detection kept constant)					
Habitat					
1. ψ (PW),p(NDVI+Veg3050)	352.24	5	0	0.68	0.14
2. ψ (MS),p(NDVI+Veg3050)	355.69	5	3.45	0.12	0.12
3. ψ (NDVI),p(NDVI+Veg3050)	357.08	5	4.84	0.06	0.11
Anthropogenic effects					
4. ψ (GtFarm),p(NDVI+Veg3050)	356.69	5	4.45	0.07	0.14
Landscape					
5. ψ (Rugg500),p(NDVI+Veg3050)	356.84	5	4.6	0.07	0.13
No effects					
1 group, Constant P	367.52	2	15.28	0.0004	0.48
1 group, Survey-specific P	390.41	23	38.17	0.00	19.90

Table 8. Blanford's Fox summer single-season occupancy models (with no biotic variables), including AIC values, delta AIC (ΔAIC), AIC weight (w_i), number of parameters (K), and C-hat (Ĉ).

Variable	β	95% CI
Occupancy (Detection kept constant)		
PW	-0.29	-0.08, -0.5
MS	-0.97	-0.13, -1.81
NDVI	-11.39	-0.42, -22.35
Anthropogenic effects		
GtFarm	-0.16	-0.01, -0.31
Landscape		
Rugg500	-0.54	-0.03, -1.06
Detection global model		
NDVI	-29.21	-18.77, -39.65
Veg3050	-22.1	-4.36, -39.85

Table 9. Logistic parameter estimates (β) and 95% confidence intervals (95% CI) estimates for occupancy models no.1, 2, 3, 4 and 5 and the global detection model variables hypothesized to influence the occurrence and detection probabilities of Blanford's Fox during the summer season with no biotic variables (higher impact variables on top).

Based on the global detection model of Blanford's Fox, detection increased during the summer season in areas with lower vegetation indicated by a negative association with NDVI. A negative association with distance to areas with vegetation cover of 30-50% (Veg3050) indicate that Blanford's Fox detection probability increases closer to areas with vegetation cover of 30 to 50% (Table 9). Based on that, we can expect that Blanford's Fox detection probability would increase as we move towards the higher elevation areas of the park where there is a higher incidence of vegetation cover 30-50%. The detection probability of Blanford's Fox also decreased in lower vegetation, as indicated by (NDVI).

1.2 Blanford's Fox Summer Models (Biotic variables included)

Blanford's Fox occupancy showed no sensitivity towards prey variables but was affected by competition variables. The competition model was the top-ranking model with w_i=0.98. The model included Caracal and Red Fox capture success variables (Table 10). Other models were not supported, indicating that sympatric competition and/or habitat partitioning within the carnivore guild is the most likely driver for Blanford's Fox occupancy during the summer season. A one-unit increase in the Red Fox capture success (RF-Succs) per trap night resulted in a 38.5% reduction in the odds of the Blanford's Fox occupancy. Whereas the Caracal capture success variable (Ca-Succs) had a higher impact on the occupancy of Blanford's Fox, but a slight overlap in 95% confidence interval value indicating some variability in effect (Table 11). A one-unit increase in Caracal capture success per trap night resulted in a 488% increase in the odds of Blanford's Fox occupancy.

Blanford's Fox Summer Season Models (Biotic variables included)	AIC	K	ΔAIC	W_i	Ĉ
Occupancy (Detection kept constant)					
Biotic (Competition)					
1.ψ(RF-Succs+Ca-Succs),p(NDVImn +Veg3050+ HG)	416.77	7	0.00	0.98	0.05
No effects					
1 group, Constant P	442.75	2	25.89	0	2.17
1 group, Survey-specific P	463.31	27	46.54	0	11.82

Table 10. Blanford's Fox summer single-season occupancy models (using biotic variables), including AIC values, delta AIC (ΔAIC), AIC weight (w_i), number of parameters (K), and C-hat (Ĉ).

Variable	**β**	**95% CI**
Occupancy (Detection kept constant)		
Competition		
Ca-Succs	1.77	3.79, -0.24
RF-Succs	-0.49	-0.03, -0.94
Detection global model		
NDVI	-29.53	-20.83, -38.22
Veg3050	-31.10	-15.93, -46.27
HG-Succs	0.49	0.86, 0.13

Table 11. Logistic parameter estimates (β) and 95% confidence intervals (95% CI) estimates for occupancy model no.1, and the global detection model variables hypothesized to influence the occurrence and detection probabilities of Blanford's Fox during the summer season using biotic variables (higher impact variables on top).

Detection probability was positively associated with Brandt's Hedgehog capture success (HG-Succs) and negatively with vegetation index NDVI. Additionally, moving closer to areas of vegetation cover 30-50% increased the detection probability of Blanford's Fox based on the negative association with the distance to these areas.

2. Red Fox Summer Models

2.1 Red Fox Summer Models (No Biotic variables)

The landscape model based on AIC ranking with a w_i value (0.71) emerged as the top occupancy model (Table 12) with variables 95% confidence interval not overlapping with 0 (Table 13). The landscape model included two variables, elevation (Elev) and ruggedness within a 700 m radius (Rugg700). This model suggested Red Fox occupied habitats of lower elevation in rugged terrain. Every 100 m increase in the elevation corresponds to a 74% decrease in the odds of Red Fox occupancy. At the same time, every 0.1 step increase in ruggedness corresponds to a 260% increase in the odds of occupancy of the Red Fox.

Based on the AIC ranking, the anthropogenic effects model came second and had two variables, including the distance to towns centre (Town), which had a higher impact than the distance to roads (Rds) variable. With every 1000m closer to the town's centre, Red Fox occupancy decreased by 64%. In contrast, the negative value of the distance to roads variable (Rds) suggested that Red Fox odds of occupancy increase by 49% with every 1000m closer to roads, indicating that Red Fox may use roads for travel. Both variables suggest that Red Fox odds of occupancy would increase as we move closer towards the peripheral areas of the towns.

The Habitat model contained only one occupancy variable, distance to areas with vegetation cover 30-50% (Veg3050). This model suggested that the odds of Red Fox occupancy decreased as we moved closer to areas with a vegetation cover of 30-50%.

Red Fox Summer Season Models (No Biotic variables)	AIC	K	ΔAIC	W_i	Ĉ
Occupancy (Detection kept constant)					
Landscape					
1.ψ(Elev+Rugg700),p(Urban+WD+NDVI+Veg3050+HL3+Rugg100)	874	10	0.00	0.71	0.20
Anthropogenic effects					
2.ψ(Town+Rds),p(Urban+WD+NDVI+Veg3050+HL3+Rugg100)	877	10	2.99	0.16	0.22
Habitat					
3.ψ(Veg3050),p(Urban+WD+NDVI+Veg3050+HL3+Rugg100)	877.29	9	3.28	0.14	0.19
No effects					
1 group, Constant P	1116.32	2	242.31	0.00	236.98
1 group, Survey-specific P	1148.86	27	274.85	0.00	220.95

Table 12. Red Fox summer single-season occupancy models (with no biotic variables), including AIC values, delta AIC (ΔAIC), AIC weight (Wi), number of parameters (K), and C-hat (Ĉ).

The global detection model of the Red Fox (Table 13) suggests that Red Fox detection probability increases away from the central areas of the park where vegetation cover of 30-50% occur. At the same time, there is a positive correlation between Red Fox detection probability and ruggedness. The increase of NDVI and heat load (HL) values negatively affected the detection probability of Red Fox compared with the distance to urban areas (Urban), where detection probability increases as the distance decrease. The Wadi habitat (WD) negative association indicated that Red Fox used wadis less frequently in the summer season, prioritizing mountain slopes. Variable of selected occupancy and detection models did not overlap 95% confidence interval giving higher confidence of the results (Table 13).

Variable	β	95% CI
Occupancy (Detection kept constant)		
Landscape		
Rugg700	3.3	4.03, 2.57
Elev	-0.007	-0.005, -0.01
Anthropogenic effects		
Town	0.49	0.88, 0.1
Rds	-0.67	-0.15, -1.19
Habitat		
Veg3050	4.88	9.47, 0.29
Detection global model		
Veg3050	1.84	2.44, 1.23
Rugg100	1.78	2.49, 1.06
NDVI	-15.57	-4.67, -26.48
WD	-1.24	-0.73, -1.75
Urban	-0.66	-0.49, -0.84
HL	-0.48	-0.12, -0.85

Table 13. Logistic parameter estimates (β) and 95% confidence intervals (95% CI) estimates for occupancy models no.1, 2, 3 and the global detection model variables hypothesized to influence the occurrence and detection probabilities of the Red Fox during the summer season with no biotic variables (higher impact variables on top).

2.2 Red Fox Summer Models (Biotic variables included)

No additional occupancy models emerged during the summer season after using biotic variables. Only one additional variable to report in the global detection model.

Domestic goats capture success seemed to correlate positively with Red Fox's detection probability.

3. Caracal Summer Models

3.1 Caracal Summer Models (No Biotic variables)

The landscape model had the highest AIC rank with a w_i value of 0.68. Two additional but less supported models emerged under habitat and anthropogenic effects, suggesting attraction towards permanent water resources and towns (Table 14). These two variables have 95% confidence intervals overlapping 0, suggesting a minor effect on the occupancy of Caracal (Table 15).

The landscape model is the only representative model of the caracal occupancy with two variables, elevation (Elev) and ruggedness within a 250 m radius of the camera location (Rugg250). The landscape model suggests that a 100 m increase in elevation corresponded to a 67% increase in the odds of Caracal occupancy. In addition, every unit increase in ruggedness corresponded to a 94% decrease in the odds of occupancy of Caracal.

Caracal Summer Season Models (No Biotic variables)	AIC	K	ΔAIC	Wi	Ĉ
Occupancy (Detection kept constant)					
Landscape					
1.ψ(Elev+Rugg250),p(GtFarm+Veg3050+Veg50+PW)	375.72	8	0.00	0.68	0.43
Habitat					
2.ψ(PW),p(GtFarm+Veg3050+Veg50+PW)	378.27	7	2.55	0.19	0.23
Anthropogenic effects					
3.ψ(Town),p(GtFarm+Veg1030+Veg3050+PW)	379.00	7	3.28	0.13	0.26
No effects					
1 group, Constant P	395.89	2	20.17	0.00	56.53
1 group, Survey-specific P	417.33	27	41.61	0.00	873.24

Table 14. Caracal summer single-season occupancy models (with no biotic variables), including AIC values, delta AIC (ΔAIC), AIC weight (W_i), number of parameters (K), and C-hat (Ĉ).

The Caracal global detection model suggested that Caracal detection probability decreases closer to areas with vegetation cover higher than 50% in summer; these areas occur mainly in the western part of the park at higher elevations. Conversely, Caracal detection probability increases as we move closer to areas with vegetation cover 30-50% (Veg3050), Domestic goats (GtFarm) farms and permanent natural water resources (PW).

Variable	β	95% CI
Occupancy (Detection kept constant)		
Landscape		
Rugg250	-2.97	-2.296, -3.636
Elev	0.01	0.009, 0.005
Habitat		
PW	-0.16	0.04, -0.36
Anthropogenic effects		
Town	-0.07	0.04, -0.17
Detection global model		
Veg50	1.64	2.55, 0.73
Veg3050	-18.5	-2.69, -34.32
GtFarm	-0.73	-0.5, -0.97
PW	-0.22	-0.03, -0.4

Table 15. Logistic parameter estimates (β) and 95% confidence intervals (95% CI) estimates for occupancy model no.1, 2, 3 and the global detection model variables hypothesized to influence the occurrence and detection probabilities of the Caracal during the summer season with no biotic variables (higher impact variables on top).

3.2 Caracal Summer Models (Biotic variables included)

Introducing the biotic variables into the Caracal occupancy modelling produced the prey occupancy model. The prey model with two variables came as a top-ranking model with a wi value of 0.85 (Table 16). The high rank and wi value of the biotic model suggested that prey availability has a higher impact on the occupancy of the Caracal than habitat. The prey model suggests that a one-unit increase in Sand Partridge capture success would result in a 265% increase in the odds of the Caracal occupancy. In contrast, one unit increase in Domestic goat capture success per 100 trap nights would result in a 2.5% reduction in the odds of the Caracal occupancy. Sand Partridge capture success variable (SP-Succs) had a higher impact on the occupancy of the Caracal, but a slight overlap in 95% confidence interval value indicated some variability in effect (Table 17).

Caracal Summer Season Models (Biotic variables)	AIC	K	ΔAIC	W_i	Ĉ
Occupancy (Detection kept constant)					
Biotic (Prey)					
1.ψ(Gt-Succs+SP-Succs),p(GtFarm+Veg3050+Veg50+PW)	371.46	8	0.00	0.85	0.21
Landscape					
2.ψ(Elev+Rugg250),p(GtFarm+Veg3050+Veg50+PW)	375.72	8	4.26	0.10	0.43

Table 16. Caracal summer single-season occupancy models for (biotic variables included), including AIC values, delta AIC (ΔAIC), AIC weight (Wi), number of parameters (K), and C-hat (Ĉ).

Variable	β	95% CI
Occupancy (Detection kept constant)		
Biotic		
SP-Succs	1.29	2.608, -0.02
Gt-Succs	-0.03	-0.002, -0.048
Landscape		
Rugg250	-2.97	-2.3, -3.64
Elev	0.01	0.01, 0

Table 17. Logistic parameter estimates (β) and 95% confidence intervals (95% CI) estimates for occupancy model no.1, and the global detection model variables hypothesized to influence the occurrence and detection probabilities of the Caracal during the summer season using biotic variables (higher impact variables on top).

The global detection model for Caracal was consistent as it did not change or improve with the addition of biotic variables during the summer season.

Winter Occupancy Models

1. Blanford's Fox Winter Models

1.1 Blanford's Fox Winter Models (No Biotic variables)

Only one model emerged as a representative of Blanford's Fox occupancy during the winter season under the habitat category (Table 18). Habitat model came as the top-ranking based on the AIC rank with 0.99 wi value with both variables having 95% confidence intervals that did not include 0 (Table 19). The habitat model included two variables, natural permanent water resources and mountain slope habitat. Based on winter season outcomes, we can confirm that Blanford's Fox Occupancy during both seasons, summer and winter, depends on freshwater resources and its associated habitat. Every 1000 m closer to permanent water increased occupancy odds of Blanford's Fox by 38.6%. The positive correlation with mountain slopes (MS) indicates that Blanford Fox odds of occupancy increased by 38% in mountain slopes habitat.

Blanford's Fox Winter Season Models (No Biotic variables)	AIC	K	ΔAIC	W_i	$\hat{C}$
Occupancy (Detection kept constant)					
Habitat					
1.ψ(PW+MS),p(Veg10+Veg3050+Veg50+Rugg900+ MS+Dist-WD)	780.38	10	0	0.996	0.7
No effects					
1 group, Constant P	794.13	2	13.75	0.001	423.12
1 group, Survey-specific P	823.49	27	43.11	0.00	708.02

Table 18. Blanford's Fox winter single-season occupancy models (with no biotic variables), including AIC values, delta AIC (ΔAIC), AIC weight (Wi), number of parameters (K), and C-hat ($\hat{C}$).

All variables affecting Blanford's Fox detection probability during the winter season are mainly habitat-related variables (Table 19). Blanford's detection probability corresponded to vegetation cover at different elevations. The detection probability increased as we moved closer to areas with vegetation cover 30-50%; meanwhile, it decreased moving closer to areas with vegetation cover higher than 50% and 10% at higher and lower elevations. Ruggedness and distance to wadis negatively impacted Blanford's Fox detection probability as it decreased as we moved closer to wadis and rugged areas. Mountain slopes seem to be favourable for Blanford's Fox during the winter season as it positively affects its detection.

Variable	**β**	**95% CI**
Occupancy (Detection kept constant)		
PW	-0.49	-0.23, -0.75
MS	1.94	3.13, 0.75
Detection global model		
Veg3050	-3.55	-0.93, -6.17
Rugg900	-2.11	-1.51, -2.71
Veg50	0.52	0.88, 0.16
Veg10	0.4	0.84, -0.04
Dis-WD	0.34	0.62, 0.07
MS	0.10	0.58, -0.38

Table 19. Logistic parameter estimates (β) and 95% confidence intervals (95% CI) estimates for occupancy model no.1, and the global detection model variables hypothesized to influence the occurrence and detection probabilities of Blanford's Fox during the winter season with no biotic variables (higher impact variables on top).

1.2 Blanford's Fox Models (Biotic variables included)

No additional occupancy models emerged during the winter season using biotic variables. Two additional variables emerged in the global detection model: the Sand Partridge capture success (SP) and the Red Fox capture Success (RF). These two variables (Table 20) suggest that Blanford's Fox detection probability is positively associated with the increase of Sand Partridge capture success and negatively with Red Fox capture success.

Variable	β	95% CI
Detection global model		
Veg10	1.07	1.62, 051
Veg50	0.82	1.24, 0.4
SP-Succs	0.74	1.06, 0.43
Veg3050	-3.89	-0.95, -6.83
Rugg900	-3.1	-2.35, -3.86
Dist-WD	0.62	0.92, 0.31
MS	0.53	1.04, 0.02
RF-Succss	-0.07	-0.03, -0.11

Table 20. Logistic parameter estimates (β) and 95% confidence intervals (95% CI) estimates for the global detection model variables hypothesized to influence the occurrence and detection probabilities of Blanford's Fox during the winter season using biotic variables (higher impact variables on top).

2. Red Fox Winter Models

2.1 Red Fox Winter Models (No Biotic variables)

Landscape variables continued to be the main driver behind the occupancy of the Red Fox in winter. The landscape model with two variables (model no. 1), elevation (Elev) and ruggedness (Rugg900), had the highest impact with a wi value of 0.78 and Ĉ=0.58 (Table 21). Two additional models under the habitat category (models 2 and 3) were less supported with a ΔAIC ≤2 but had variables with 95% confidence intervals that did not include 0 (Table 22). The top-ranked model under the landscape category suggests that a 100m increase in elevation decreases 60% in the odds of Red Fox occupancy, which means that Red Fox moved to a lower elevation compared to the summer season. Increased ruggedness within a 900 m radius of the camera trap location positively impacted Red Fox occupancy. For every 0.1 step increase in ruggedness, there is a 290% increase in the odds of Red Fox occupancy.

Red Fox winter Season Occupancy Models (No Biotic variables)	AIC	K	ΔAIC	W_i	Ĉ
Occupancy (Detection kept constant)					
Landscape					
1.ψ(Elev+Rugg900),p(Urban+NDVImn+Dist-WD+WD+PW+HL2)	1376.29	10	0	0.78	0.58
Habitat					
2.ψ(PW),p(Urban+NDVImn+Dist-WD+Hbt-WD+PW+HL2)	1379.32	9	3.03	0.17	0.63
3.ψ(Veg3050),p(Urban+NDVImn+Dist-WD+Hbt-WD+PW+HL2)	1381.73	9	5.44	0.05	0.61
No effects					
1 group, Constant P	1556.17	2	179.88	0	1025.97
1 group, Survey-specific P	1583.59	27	207.3	0	1003.08

Table 21. Red Fox winter single-season occupancy models (with no biotic variables), including AIC values, delta AIC (ΔAIC), AIC weight (Wi), number of parameters (K), and C-hat (Ĉ).

Habitat models have a ΔAIC<6 with a variables confidence interval of β coefficient that does not overlap 0 and Wi value higher than 0.05, thus, we can use habitat models to provide general inferences on the Red Fox occupancy. Both habitat models and variables suggest that

Red fox occupancy increases as the distance to permanent water and areas with a 30-50% vegetation cover increase.

The Red Fox global detection model(Table 22) suggests that NDVI (vegetation coverage), closer distance to urban areas, and heat load positively affect detection probability. In contrast, wadi habitat, distance to a wadi, and distance to water resources negatively affected Red Fox detection.

Variable	Β	95% CI
Occupancy (Detection kept constant)		
Landscape		
Elev	-0.007	-0.005, -0.009
Rugg900	3.4	4.13, 2.67
Habitat		
PW	0.29	0.48, 0.09
Veg3050	5.6	10.96, 0.23
Detection global model		
NDVImn	7.43	14.01, 0.84
Urbn	-0.56	-0.46, -0.67
Hbt.WD	-0.52	-0.14, -0.89
Dist-WD	0.29	0.50, 0.09
HL	0.20	0.36, 0.04
PW	0.16	0.22, 0.10

Table 22. Logistic parameter estimates (β) and 95% confidence intervals (95% CI) estimates for occupancy models no.1, 2, 3 and the global detection model variables hypothesized to influence the occurrence and detection probabilities of the Red Fox during the Winter season with no biotic variables (higher impact variables on top).

2.2 Red Fox Winter Models (Biotic variables included)

Using biotic variables did not result in additional viable occupancy models. The only outcome to report was the additional variables introduced to the global detection model (Table 23). Brandt's Hedgehogs capture success negatively influenced red Fox detection probability. There was also a positive impact of Caracal and Domestic goats capture success on the Red Fox detection probability.

Variable	β	95% CI
Detection global model		
NDVImn	6.85	14.04, -0.34
Urbn	-0.75	-0.63, -0.87
Hbt.WD	-0.65	-0.25, -1.04
HG- Succs	-0.59	-0.15, -1.04
WD	0.29	0.51, 0.08
PW	0.24	0.30, 0.17
Ca-Succs	0.20	0.27, 0.13
HL	0.17	0.34, 0
Gt- Succs	0.01	0.02, 0

Table 23. Logistic parameter estimates (β) and 95% confidence intervals (95% CI) estimates for the global detection model variables hypothesized to influence the occurrence and detection probabilities of the Red Fox during the winter season using biotic variables (higher impact variables on top).

3. Caracal Winter Models

3.1 Caracal Winter Models (No Biotic variables)

The top-ranking occupancy model for caracal was a habitat-based model with a slightly high Ĉ value indicating overdispersion. (Table 24). The top model suggests that for every 1000 m closer to areas with vegetation cover 30-50%, there is a 100% increase in the odds of the Caracal occupancy. The second variable in the habitat model suggests that Caracal occupancy decreased by 1409% for every 1000m closer to areas with vegetation cover 10-30%. These results suggest a specific habitat preference by the Caracal favouring the medium vegetation cover areas on higher elevations' higher vegetation cover areas. Vegetation cover 10-30% had 95% confidence intervals slightly overlapping 0, suggesting a minor effect on the occupancy of Caracal (Table 25).

Caracal winter Season Occupancy Models (No Biotic variables)	AIC	K	ΔAIC	W_i	Ĉ
Occupancy (Detection kept constant)					
Habitat					
1.ψ(Veg1030+Veg3050),p(Veg1030+Veg3050+ Veg50+Urban+PW+ Dist-WD)	509.85	10	0	0.998	2.14
No effects					
1 group, Constant P	594.4	2	84.55	0	422.98
1 group, Survey-specific P	610.76	27	100.91	0	1019.3

Table 24. Caracal winter single-season occupancy models (with no biotic variables), including AIC values, delta AIC (ΔAIC), AIC weight (Wi), number of parameters (K), and C-hat (Ĉ).

The global detection model (Table 25) suggested that caracal detection probability increases moving away from areas with vegetation cover of 30-50% and above 50%. While the association with the distance to areas of vegetation cover 10-30% was negative, indicating that the detection probability of Caracal in lower elevation areas, mainly in the areas with less vegetation cover, is higher than in the areas of higher elevation and higher vegetation cover. Other anthropogenic and habitat variables that positively impacted detection included being closer to wadis, permanent water, and urban areas.

Variable	β	95% CI
Occupancy (Detection kept constant)		
Veg3050	-17.66	-2.34, -32.99
Veg1030	2.71	6.06, -0.63
Detection global model		
Veg3050	15.14	25, 5.28
Veg1030	-3.04	-1.43, -4.66
Veg50	0.65	1.13, 0.16
Dis-WD	-0.9	0.05, -1.86
PW	-0.42	-0.23, -0.61
Urban	-0.26	-0.14, -0.37

Table 25. Logistic parameter estimates (β) and 95% confidence intervals (95% CI) estimates for occupancy model no.1, and the global detection model variables hypothesized to influence the occurrence and detection probabilities of the Caracal during the winter season with no biotic variables (higher impact variables on top).

3.2 Caracal Winter Models (Biotic variables)

Caracal occupancy showed no sensitivity towards the four prey variables in winter, except for Brandt's Hedgehog capture success, which positively correlated with the Caracal detection probability.

Discussion

This research confirms the feasibility of using non-invasive monitoring methods to develop occupancy models depending on one year of detection/non-detection histories for three carnivore species in an arid area. Single season occupancy was used to understand carnivore ecology better, seasonal variation in habitat use and the influence of anthropogenic, biotic, and habitat resource variables. Occupancy models indicated that habitat use varied between the three sympatric carnivores and was influenced by the interactions between the three sympatric species, prey availability and habitat composition. This study demonstrated that the survey method and sample size was adequate to develop occupancy models and provide a baseline of the influencing variables.

Habitat variables were the main contributors to the Red Fox occupancy models, while the influence of biotic variables was evident for Blanford's Fox and the Caracal. Blanford Fox habitat use was influenced by the detection of the other two predators, whereas for the Caracal, it was influenced by prey availability in the summer season. The Red Fox occupancy was constant across seasons with a stable occupancy pattern. Anthropogenic disturbance variables represented in various land use activities were correlated, and thus, any effect of one land use can be attributed to the others in general. In some cases, I interpreted the results based on the existing literature and personal experience, knowing that further studies and research are required, particularly in the reserve buffer and transitional zones due to the risk of human-wildlife conflict and the niche overlap between the three carnivore species. These findings could contribute significantly to future management planning and guide carnivore conservation in the reserve in the long term.

Blanford Fox

Sites occupancy by Blanford's Fox was consistent with the distance to freshwater resources (Free water) and its associate habitat in both seasons with some variation in the magnitude. Blanford's Fox's attraction towards areas with free water was higher during the winter season (2.5 times higher than in the summer) despite the abundance of seasonal water pools in the reserve during winter.

In addition to distance to water, occupancy was positively associated with mountain slope during the winter. These findings are consistent with others from the region, confirming the association of Blanford's Fox with mountain slopes where water resources are scarce (Cunningham & Wronski, 2009; Geffen et al., 2009). This association of Blanford's Fox with permanent water resources is not necessarily an indication of the need for water; Blanford's Fox can survive in arid areas with intermittent water resources, it is physiologically adapted and can compensate for the loss of water by eating insects and plant material (Geffen et al., 2009; Geffen et al., 1992a). The higher occupancy closer to free water, in general, may be attributed to the abundance of food resources such as fruits, invertebrates and other prey species associated with the moister conditions surrounding permanent water sources (Fig. 18).

Figure 18. Plants diversity around the permanent water

Other factors might contribute to the higher occupancy of Blanford's Fox during the winter season closer to water resources and on mountain slopes. Based on published literature, Blanford's Fox cubs are entirely dependent on the mother's milk after being born until they start foraging for food (Geffen & MacDonald, 1992). The higher dependency on free water and mountain slopes during the winter season can be attributed to the den location selection and the mothers higher dependency on the free water during the lactation period to compensate for water loss (Cain et al., 2006; Geffen & MacDonald, 1992). The higher occupancy of Blanford's Fox on mountain slopes and closer to free water seems to contribute to a higher detection probability on mountain slopes and closer to wadis during winter.

While during the summer season, the higher occupancy closer to free water is not surprising, although water is not essential for a highly adapted desert species such as Blanford's Fox (Atwood et al., 2011; Geffen et al., 2009; Schuette et al., 2013). Access to free water can enhance the species fitness by reducing the physiological stresses associated with foraging (Brawata & Neeman, 2011). The lesser association of the Red Fox with permanent water resources and the higher detection rate of the Caracal closer to water resources also likely influence Blanfords association with the freshwater habitats. Sympatric competition with Red fox and the likely provision of domestic goat carrion by Caracals that prey on domestic goats is likely services Blanford's Fox gain from using these areas (Brawata & Neeman, 2011; Moehrenschlager et al., 2007). The positive correlation between Blanford Fox occurrence and the higher capture success of the Caracal could theoretically be influenced by intra-guild competition, but this would require further investigation. In other words, the higher detection of the Caracal near to water resources during the summer season may deter the Red Fox for the benefit of Blanford's Fox (Haswell et al., 2020; Levi & Wilmers, 2016; Newsome et al., 2017; Prugh et al., 2009; Wang et al., 2015).

Other models emerged in the summer suggesting additional influencing environmental and anthropogenic variables. Blanford's Fox is highly adapted to rocky areas and arid climates (Geffen et al., 1992b; Smith et al., 2003). Their diet is specialised but variant as they are known to be insectivorous and frugivorous. Plant material seems to have a high percentage in their faeces, explaining their lower dependency on water (Cunningham & Howarth, 2002; Geffen et al., 1992, 1992a). Blanford's Fox is also a scavenger (Stuart & Stuart, 2003); It was recorded repeatedly feeding on goat carcasses and foraging at night in wadi beds and on mountain slopes with scree in the reserve. Higher occupancy closer to goat farms and urban areas in the summer season is confirmed and can be associated with scavenging behaviour as farmers dump dead animals, carcass remains and organic waste behind their farms in the wadis or at mountain base (Fig. 19). Additional influencing variables suggest a higher occupancy closer to wadis, areas of lower vegetation coverage and lower occupancy in highly rugged areas during summer. Based on the summer capture success map (Fig. 12), we can assume that Blanford's Fox is attracted to goat farms in the western area of the reserve rather than the eastern, as Red Fox capture success is lower than in the eastern area. The higher sensitivity of Blanford's Fox occupancy towards a variety of anthropogenic, habitat and landscape preferences may be explained by the lack of resources during the summer season and probably the active avoidance of the Red Fox (Prange & Gehrt, 2004).

Figure 19. Blanford’s Fox with a goat carcass in the buffer zone in proximity to farms area

Blanford’s Fox occupancy is positively associated with the wadi habitat during the summer. This association can be explained by Blanford's Fox's diet and foraging behaviour. Wadis, in particular, are the most favourable foraging ground for Blanford's Fox; they host a variety of microhabitats, and due to that, higher density of small mammals and other smaller biota such as arthropods (Geffen et al., 2009; Geffen et al., 1992a; Geffen & MacDonald, 1992). Falling fruits of *Ficus salicifolia* and *Ziziphus spina-christi* during the summer season is another attraction and could be another reason behind the higher occupancy of Blanford's Fox in wadis (Jongbloed et al., 2003; C. T. Stuart & Stuart, 2003).

Occupancy models, including predator variables, came as the top-ranking models in summer. These Biotic variables had a higher effect on Blanford's Fox occupancy than habitat variables. Habitat selection of subordinate species can result from niche segregation influenced by prey selection and the avoidance of other predators (Gosselink et al., 2003; Prange & Gehrt, 2004; Šálek et al., 2015). As the resources become more scarce during the summer season, competition between sympatric carnivores increases, and in some cases, leads to local extinction of the subordinate ones (Pamperin et al., 2006; Pimm, 1991; Schuette et al., 2013). Using biotic variables revealed that summer occupancy of Blanford's Fox is highly influenced by intraguild and intraspecific relations between the three carnivores. Blanford's Fox occupancy decreased in camera trap locations with a high capture success of the Red Fox and increased in locations with a higher capture success of Caracal. These findings coincide with a photo record of a Red Fox carrying Blanford's Fox carcass captured in the reserve (Fig. 20). Although we have no evidence of direct aggression between the two foxes species from the region, we can assume it might exist based on the competitive encounter record from the reserve and other reports of a Red Fox killing Arctic Fox and restricting its access to specific habitats during the scarce season in Alaska (Elmhagen et al., 2002; Pamperin et al., 2006). The competition between the two Fox species was reported from UAE and Oman, referring to a replacement of Blanford's Fox by the Red Fox (Smith et al., 2003; A. Spalton, 2002; Spalton et al., 2006).

Figure 20. Red Fox carrying Blanford's Fox carcass in Wadi Wurayah MAB Reserve

On the contrary to the negative impact of the Red Fox on Blanford's Fox occupancy, the increase in Caracal detection had a positive impact on Blanford's Fox occupancy. In the past few decades, human activities such as hunting have replaced the apex predator, the Arabian leopard (*Panthera pardus nimr*), with the Caracal in many areas of the Hajar Mountains (Spalton et al., 2006a). The niche overlap between Blanford's Fox and the Caracal can be related to several reasons. It may be that the species use similar resources or find prey in similar habitats, but it could also be due to Caracal providing some security to Blanford's through its suppressing the Red Fox; and additionally, Caracal may provide carrion from leftover prey (Haswell et al., 2018, 2020; Levi & Wilmers, 2016; Newsome et al., 2017; Wang et al., 2015). Although we can not explain how Blanford's Fox can co-exist with the Caracal based on the research outcomes, we can only suggest that Blanford's Fox maintains temporal segregation with the Caracal or micro spatial adjustments to avoid direct encounters. Successful co-existence between the two species can also be related to the low abundance of Blanford's Fox combined with the Caracal's larger home range contributing to lesser interaction opportunities between the two species. Accordingly, we can assume that Blanford's Fox habitat selection of areas closer to free water seems to benefit and increase its fitness by reducing the possibility of getting into a deadly confrontation with the Red Fox.

Based on the competition and avoidance relation between the two foxes species, we can further explain Blanford's Fox's habitat selection, particularly in the summer season. The positive association of Blanford's Fox occupancy with wadis is associated with a negative detection probability of the Red Fox in wadis, and the negative association of Blanford Fox occupancy with ruggedness in summer is also correlated with the increase in the occupancy of the Red Fox in rugged areas in the summer season. The use of wadis and less rugged areas by Blanford Fox can be related to the active avoidance of the Red Fox and other factors related to habitat requirement and specialized diet. Based on this, we can conclude that Blanford's Fox's habitat preferences during the summer season are a coexistence mechanism to promote avoidance by spatial segregation, forage efficiently given each species specializations, and access to other essential resources and life requirements (e.g. den sites, and breeding opportunities).

Both foxes species seem to be attracted to goat farms during the summer season; Blanford's Fox occupancy increases, and the capture success of the Red Fox in areas closer to goat and agriculture farms. As the spatial overlap increases, the interaction opportunities increase, contributing to increased aggression or deadly encounters near suburban areas in the reserve buffer zone and particularly in the park's western side.

The detection probability of Blanford's Fox was correlated with habitat variables in both seasons. The global detection models of both summer and winter suggest an increase in detection probability closer to areas of sparse vegetation cover of 30-50%. The summer detection model also suggests a negative association with areas of high vegetation coverage (NDVI). The Winter global detection model suggests a higher detection probability on mountain slopes, which can correlate with Blanford's Fox routine movement to its denning areas. Winter global detection model included other environmental variables, such as ruggedness (negative correlation), distance to wadi and areas of less than 10% vegetation cover at lower elevations and 50% vegetation cover at higher elevations (positive correlation). The sensitivity towards these variables is probably related to a higher activity movement pattern during the winter season in the central areas of the reserve rather than the higher elevation and the lower elevation areas in the buffer and transitional zone. Higher detection in low ruggedness areas, closer to wadis and areas of vegetation cover 30-50%, may be related to feeding preferences or the active avoidance of the Red Fox as both species are nocturnal (Mueller et al., 2018).

Blanford's detection showed a positive correlation with the Hedgehog's capture success in the summer, which is probably due to habitat overlap as both species are insectivorous

(Goodarzi & Azarhoosh, 2016). It also showed a positive correlation with Sand Partridge capture success in winter. This positive correlation may be due to predator/prey relation or habitat overlap between the two species. Blanford's Fox is a nocturnal species, while the Sand Partridge is diurnal, which makes the Sand Partridge an occasional prey during the winter season (Geffen & Macdonald, 1993; Kam et al., 1987).

Red Fox

Red Fox occupancy was consistent during both seasons, with the landscape occupancy model including two variables, elevation and mountain ruggedness, being the most explanatory. Two additional but less supported models emerged in each season. The summer season suggested that Red Fox occupancy increases closer to urban areas based on the distance to town centres and roads. While the additional models from winter suggested a decrease in occupancy as we moved closer to areas of sparse vegetation of 30-50% cover and permanent water resources inside the reserve core zone.

Several underlying effects have probably led to the current habitat preferences of the Red Fox. Although elevation and ruggedness seem to influence the occupancy strongly, other underlying factors could be the driver, such as anthropogenic effects, intra-guild competitive exclusion, and other behavioural traits behind the Red Fox occupancy preferences. Anthropogenic effects impose a cascade effect on the carnivore guild and alter the ecosystem processes (Ritchie & Johnson, 2009). Species adjustment and adaptation to these effects might lead sub-ordinate species to isolation like Blanford's Fox, while others are expected to benefit from the new situation, such as the Red Fox and the Caracal (Crooks et al., 2011; Rich et al., 2017). The Red Fox is a cursorial predator, and its higher occupancy in the lower elevation areas (reserve peripheral area) can be attributed to its behavioural traits and the need for open areas for hunting. The Arabian Gazelle *Gazella gazella cora* herds were still occupying the mountain slopes and Acacia plains around the reserve up to the wadis and mountain foothills until the early 90's (Saeed Al Hamoudi, personal communication); these areas coincided with the current occurrence area of Red Fox (Mendelssohn et al., 1995). During that period, the Arabian leopard and the Caracal mainly occupied the mountainous areas in the UAE (Edmonds et al., 2013). At the same time, the hunting intensity increased, forcing the Arabian Gazelle, Arabian Leopard, and the Arabian Tahr *Arabitragus jayakari* to extirpation (Tourenq & Launay, 2008). Despite the change in species dynamic, the Red Fox continued to utilise the lower elevation areas around the reserve, benefiting from date farms and fishing activities along the coast for food supplements.

Both Foxes in the reserve tends to be generalist omnivore; their diet includes fruits and vegetables whenever available (Huey, 1969; Lenain et al., 2004; Stuart & Stuart, 2003). The Red Fox is a highly adapted and opportunistic species; its diet consists mainly of small mammals, invertebrates, and fruits; it is also known to be a scavenger (Lenain et al., 2004; Vilella et al., 2020). The high occupancy areas of the Red Fox during the summer season corresponds to the lower elevation, highly rugged, and peripheral city areas closer to roads. These areas are close to agricultural farms and goat farms, including one landfill site on the eastern side of the reserve; Red Fox is an opportunistic feeder and can find various food resources in these transitional and semi-urban areas (Díaz-Ruiz et al., 2013). The landscape and habitat preferences of the Red Fox, and the attraction towards the peripheral urban areas, seems to correspond to the other findings from the UAE and arid areas (Dell'Arte & Leonardi, 2009; Macdonald et al., 1999; Stuart & Stuart, 2003). Interestingly, the Red Fox occupancy model did not show any relation with the natural water resources inside the reserve as expected based on the existing literature (Najafi et al., 2019). Thus, we assume that Red Fox probably depends on alternative water resources from semi-urban areas or compensates for the lack of water by feeding actively on particular food and prey species such as insects and fruits (Dell'Arte & Leonardi, 2009).

While other carnivores might avoid high ruggedness as it can be associated with higher energetic costs and lower productivity (Cristescu et al., 2019). The Red Fox occupancy seems to increase in highly rugged areas. These areas are preferably less disturbed by humans and optimal for rest during the day (Macdonald et al., 1999). In addition, Red Fox could be actively avoiding the Caracal by selecting the lower elevation and highly rugged areas less occupied by the Caracal during the summer season. The Red Fox is known to utilise areas in proximity to human development as a spatial refuge to reduce encounters with predators with less tolerance to human disturbance, such as the Caracal (Gosselink et al., 2003; Mueller et al., 2018; Schuette et al., 2013).

Winter season occupancy models included two additional but less supported variables suggesting that Red Fox occupancy is lower as we move closer to areas of sparse vegetation cover of 30-50% and permanent water resources. Red Fox habitat associations may well be related to the active avoidance of the Caracal as its occupancy increased closer to areas with a 30-50% vegetation cover and a higher detection closer to water during winter. Although we have no direct evidence of the Caracal killing a Red Fox, the Caracal can suppress the Red Fox through harassment and fear of injury, competition on den sites and dietary opportunities (Haswell et al., 2018; Newsome et al., 2017).

Based on the habitat occupancy modelling outcomes, I assume that avoidance through niche segregation is utilised in both seasons as a co-existence mechanism. The habitat segregation during the summer season was the most obvious, with the Red Fox occupying lower and highly rugged areas where the Caracal occupancy increased as we moved to higher areas with lower ruggedness. While during the winter, a less supported occupancy model of the Red Fox suggested a decrease in the occupancy closer to areas of 30-50% sparse vegetation cover where the Caracal occupancy increased. Based on these findings, I assume that Caracal probably excluded the Red Fox from its high-density prey areas during the summer and higher vegetation cover areas during the winter.

Due to the same routes' daily foraging routine, Red Fox detection probability increased closer to urban land in summer and winter. Shuttle movement between the sub-urban and low mountain profile areas in the core zone was observed. Additionally, Red Fox cubs were recorded between March to April; adults and the young sub-adults using their parents range probably contributed to the higher detection rate closer to urban areas in both seasons. Caracal showed a similar pattern of higher detection probability closer to goat farms in summer and urban areas in winter. This positive detection probability of the two predator species closer to urban areas might be related to scavenging behaviour (Stuart & Stuart, 2003).

The lower detection of the Red Fox closer to areas of 30-50% sparse vegetation cover and in low ruggedness areas correlate negatively with the Caracal high occupancy in Wadis and high capture success closer to 30-50% sparse vegetation cover areas. This pattern can be attributed to the avoidance relationship during the summer season. The Red Fox detection probability was higher closer to wadis during the summer and negatively correlated with NDVI and heat load (HL). On the contrary, the detection probability increased with higher NDVI and HL during the winter.

Using biotic variables indicated an increase in Red Fox occupancy correlated with higher capture success of goats and Caracal during winter. This positive correlation can be related to the spatial overlap between the three species in the reserve buffer zone closer to urban areas. At the same time, global detection models for both the Red Fox and the Caracal showed a contrasting pattern, where the Red Fox showed a lower detection closer to wadi habitat and moving away from free water, the Caracal showed the opposite pattern of detection in summer. In contrast, Red Fox detection probability decreased closer to areas with 30-50% vegetation cover in winter and inversely for the Caracal.

Caracal

Carnivore distribution, in general, is determined by environmental and anthropogenic variables (Rich et al., 2017; Sévêque et al., 2020); at the same time, their distribution is limited by their diet and prey availability (Karanth et al., 2004). The Caracal replaced the Arabian Leopard in the UAE and most of Arabia to become the apex predator (Spalton et al., 2006a; Zafar-ul Islam et al., 2020). Caracal is a generalist feeder with a varied diet that includes mammals, birds, reptiles, and even insects (Hassan-Beigi, 2015; İlemin et al., 2020; Jansen et al., 2019; Van Heezik & Seddon, 1998). Caracal preying on domestic animals was reported from several sources from the Middle East (Moqanaki et al., 2016; Stuart & Hickman, 1991; Ünal et al., 2020). This study gained one photograph of Caracal predating on a Domestic goat and another photo of the Caracal while hunting a young goat during winter season (Fig.s 21 and 22).

Based on published literature, I expected Caracal occupancy to be associated with mountains and ruggedness (Abu Baker et al., 2004; Hassan-Beigi, 2015; Hemami et al., 2018). The Caracal, in particular, is an ambush carnivore and would probably benefit from the increasing ruggedness (Ruth & Murphy, 2010). Instead, Caracal occupancy was correlated with moderate terrain and lower ruggedness in line with other findings (Hemami et al., 2018; Mengüllüoğlu & Ambarlı, 2019; Singh et al., 2014). During the summer season, Caracal occupancy increased with elevation and decreased in highly rugged areas, which might be associated with higher energetic cost and lower productivity considering that domestic goats and Sand Partridge are the main prey species in the reserve (Cristescu et al., 2019).

Figure 21. Caracal carrying the remnant of a domestic goat carcass

Figure 22. Caracal attacking a young domestic goat

Carnivore species can respond differently to landscape features (Burton et al., 2012). The Caracal, in particular, can adapt to different habitats and landscapes (Moqanaki et al., 2016). The elevation factor might affect carnivores occurrence due to habitat structure change and prey availability (Hemami et al., 2018; Melville & Chaber, 2016). Caracal is also known as an opportunistic species targeting the most frequently encountered prey (Melville et al., 2004). The summer occupancy model suggested that higher elevation is positively correlated with higher occupancy of the Caracal. On the other hand, positive association with elevation in summer was not surprising based on the existing literature, the predicted behavioural traits, and occupancy modelling outcomes. Predator occupancy would correlate with elevation in correspondence to prey availability. Consequently, segregation by elevation can occur; for instance, the Persian leopard *Panthera pardus saxicolor* an apex predator from Iran, is restricted to higher elevation areas as a mechanism for niche partitioning in certain seasons (Hemami et al., 2018).

The Caracal occupancy model using biotic variables was the most supported statistically than the habitat model. The summer biotic model suggested a high correlation with the Sand Partridge capture success compared to the Domestic goats capture success. Sand partridges averaged capture success in the reserve was the highest during the summer compared to winter. The concentration of high capture success of the Sand Partridge was at higher elevation in the western area of the reserve, which may explain the increase of the Caracal occupancy with elevation and is in line with other findings from the region. Ground dwelling phasianids such as the Chukar and the Sand Partridge are targeted by the Caracal (Hassan-Beigi, 2015; Mengüllüoğlu & Ambarlı, 2019; Stuart & Stuart, 2007; İlemin et al., 2020). The dominance of the prey model over the habitat and landscape models indicate that prey availability is the main driver of caracal occupancy. Habitat preferences come as a second preference and are probably correlated with favourable routes to hunting areas and other landscape features that could facilitate successful hunting opportunities.

The less supported habitat occupancy models of the Caracal during the summer season shows an increasing occupancy closer to water resources and wadi habitat. The Caracal as an apex predator, is expected to use linear travel routes (wadis) as an indication of predominance (Spalton et al., 2006a). The higher occupancy closer to water resources can be attributed to the Caracal being an ambush predator, which benefits from water holes to ambush prey (Farhadinia et al., 2007). The two main prey of the Caracal has low dependency on water. Domestic goats and Sand Partridge, for instance, are not entirely dependant on free water in the reserve as goats commute daily to their farms, where water is provided, and Sand Partridge are highly efficient in the xeric environment, it can compensate for water loss by consuming green vegetation (Degen et al., 1983). In addition to this, Caracal is a highly adapted species to hot and arid environments, but it still benefits from free water to compensate for water loss during the hot season, not only to ambush prey (DeStefano et al., 2000; Ochoa et al., 2021). These justifications can probably explain the positive correlation of occupancy with water resources but the low AIC rank of the model since the prey species, including the Caracal, are not highly dependent on the free water holes during the summer season.

Winter occupancy models showed a clear preference of the Caracal towards areas with medium vegetation cover. The Caracal occupancy increased closer to areas with 30-50% vegetation cover and decreased closer to 10-30% cover. Vegetation has no direct effect on carnivore species; thus, we can consider it a proxy for prey availability (Mueller et al., 2008), as most carnivores population are correlated with natural vegetation predominates where ecological processes still occur (Noss et al., 1996; Šálek et al., 2015). Although no occupancy models emerged using prey variables for the Caracal in the winter, we can assume that occupancy increased closer to higher vegetation cover due to higher prey abundance. The correlation between Caracal occupancy and areas of 30-50% sparse vegetation cover can be explained by the higher consistency of goats capture success across the central areas of the reserve due to the expansion of pasture land in the winter season (Fig. 16). Sand Partridge and other prey species also showed the same pattern of increase in capture success in the central areas of the park (Fig. 17), particularly in sparse vegetation areas of 30-50% cover.

During winter, the detection probability of the Caracal increased as we moved away from the vegetation cover areas (30% and above) at a higher elevation and increased moving closer to areas with very low vegetation cover (less than 10%) at lower elevations. Detection also increased closer to wadis and urban areas, indicating a regular movement pattern using wadis as preferred routes. Based on the detection model, we can suggest that the Caracal frequently moved from its high occupancy areas with higher vegetation cover towards the peripheral areas of the reserve closer to urban areas. The frequent movement of the Caracal towards urban areas is probably correlated with the domestic goat's daily movement pattern between the farms towards the grazing ground in the mountain and vice versa (Khalifa Abdouly, personal communication). Interestingly, Caracal consumption of livestock increase in the cold is reported in the season between April to September in the Kalahari Desert region (Melville et al., 2004). The same study from the Kalahari Desert supported by others from our region confirmed that Caracal would move into the nearby villages or towns, and other references confirmed finding a Caracal den in proximity to a village and referred these encounters to inexperienced juveniles or exhausted adults encroaching into sub-urban areas during the night (Farhadinia et al., 2007; Ünal et al., 2020). The higher demand for large prey during the winter season can be the reason for the higher detection probability closer to urban areas, or it can be related to the less strict herding system as goat owners try to leave their goats roaming freely to benefit from the green pasture (Sultan Alkaabi, personal communication). We assume that Caracal is aware of the goats movement and frequently uses the same routes to move closer to goats and enhance stalking or ambushing opportunities. We assume that higher demand for food is probably related to Caracal home range expansion due to the favourable climatic conditions during winter season, similarly to other predators from other regions (Wang et al., 2015). This increase in home range correlates with the Caracal being recorded in new locations at lower elevations in the reserve buffer zone (40 m lower in elevation than in summer).

Caracal detection probability increased closer to 30-50% vegetation cover areas during the summer season. This increase in detection can be associated with higher activity of Caracal in the central area of the reserve and closer to free water areas during the breeding season. The Caracal continue to have higher detection closer to urban areas but closer to goat farms during summer. Two records in two separate locations showed an adult Caracal with one kitten in May and one in June (Fig. 23), corresponding to similar findings from the region

Figure 23. Two photos from separate locations of adult Caracal with a kitten during April and May of the same year in different locations

suggest a birth peak in semi-arid areas in April (Farhadinia et al., 2007). The higher detection closer to goat farms is more evident in summer than in winter as goats move less far from their farms. In addition, free-roaming goats tend to give birth in the mountains, and newborn goats hide close to their farms in the bushes until they gain strength, making them more vulnerable to Caracal attacks (Sultan Alkaabi, personal communication).

Caracal detection probability increased closer to water resources and decreased at higher elevations where vegetation cover is higher than 50% in both seasons. Using the biotic variables revealed a positive correlation with the higher capture success of Brandt's Hedgehog. This correlation could be due to the overlap in species' habitat preference as there is no evidence of the Caracal preying on a Hedgehog.

Conclusion

This research provides evidence (and a baseline) of some habitat characteristics influencing the occupancy of the carnivore guild inside the reserve. Habitat use based on occupancy modelling suggests that our three targeted carnivores exhibit greater niche partitioning in the summer than winter. The Red Fox occupies the lower elevation areas with high ruggedness, and its occupancy increases closer to roads and peripheral urban areas. Red Fox's occupancy overlaps with the reserve's transitional and buffer zones where goat farms and agriculture farms are concentrated. By comparison, Blanford's Fox occupancy increased around permanent freshwater resources distributed in the reserve's core zone. Caracal occupancy increased with higher elevations and low ruggedness in summer and medium vegetation cover areas during the winter season.

Differences in variables impact were expected between the three sympatric species and between seasons, considering the difference in body sizes and the levels of specialisation of each carnivore. For instance, variables such as distance to water, ruggedness and elevation had a different seasonal impact on each of the three carnivores.

Blanford's Fox occupancy increased by 2.5 times closer to freshwater habitat in winter compared to summer. Additionally, the habitat utilisation by Blanford's Fox changed from wadis in summer to mountain slopes in winter. This variation in habitat use reflects the importance of customising specific monitoring programs and conservation strategies particular to the ecosystem and the targeted species, reducing cost and increasing detectability (Mattfeldt et al., 2009; Shannon et al., 2014). Water availability also positively influenced Caracal detection probability; meanwhile, the Red Fox occupancy showed no association with the water resources inside the reserve even in summer.

Caracal occupancy increased with elevation in summer almost at the same percentage of the Red Fox occupancy decreased in relation to the same variable, possibly indicating spatial segregation by elevation between the two species. At the same time, the elevation had no direct impact on Caracal occupancy during the winter season; instead, Caracal occupancy was mainly correlated with areas of 30-50% vegetation cover as it probably provides better hunting cover and a higher abundance of prey. Thus, Caracal occupancy during the winter season might vary as vegetation cover changes by season and by elevation depending on the annual precipitation or climate change effects in the long term (El-Keblawy & Editors, 2014).

On the other hand, ruggedness is another variable that supports the spatial segregation assumption between Caracal and Red Fox. This variable has a positive effect on Red Fox occupancy and a negative impact on Caracal during the summer season.

Including biotic variables in the modelling was complementary and allowed additional inferences on habitat use. For instance, the prey capture success of Sand Partridge and domestic goats had the highest impact on the Caracal occupancy during the summer season. Another example of biotic variables impact is the effect of predators' capture success on Blanford's Fox occupancy and its habitat selection preferences. The competition model came as the top-ranking model for Blanford's Fox during the summer season; the model included Caracal and Red Fox trap success variables, indicating that habitat variables selection for Blanford's Fox was probably highly influenced by the competition with the sympatric predators. Blanford's Fox avoided the interaction with Red Fox to increase its fitness. Higher competition on resources between the two foxes during the summer could increase agonistic encounters (Haswell et al., 2020; Reimchen, 1998). At the same time, Blanford's Fox benefitted from the Caracal higher detection near free water. Caracal capture success was higher near to free water, which may have facilitated occupancy of Blanford's Fox through it benefitted from the carrion provided by the Caracal and avoided or reduced the deadly encounters with Red Fox. The positive correlation between Blanford Fox occurrence and the higher capture success of the Caracal can theoretically be explained by the intra-guild cascade effect of the Caracal on the Red Fox, knowing that further investigation is required to confirm this hypothesis. For now, we can assume that Caracal, as the top predator, is probably suppressing the Red Fox for the benefit of Blanford Fox (Haswell et al., 2020; Levi & Wilmers, 2016; Newsome et al., 2017; Prugh et al., 2009; Wang et al., 2015).

Occupancy models proved to be an effective tool for studying species' habitat relationships (MacKenzie et al., 2017). Using PIR camera traps for monitoring inaccessible mountainous areas also proved effective with nocturnal species and reliable in high-temperature weather (Gaidet-Drapier et al., 2006; O'CONNELL et al., 2006). Camera traps combined with occupancy modelling can be utilised successfully for monitoring species occupancy with no unique markings. This monitoring strategy could provide a robust framework for predicting carnivores response to anthropogenic effects and climate change, particularly in the Hajar mountains, to understand species–habitat relationships and to draw basic inferences on future changes at the community level (MacKenzie et al., 2017; Parsons et al., 2019). Species habitat utilisation can be utilised to identify climate refugia and predict how species may react under climate change and urban development scenarios (Charabi, 2013; El-Keblawy & Editors, 2014; Elmhagen et al., 2017; Seddon, 2008).

Conservation Strategies

As towns and other anthropogenic infrastructure continue to expand around the reserve, human disturbance is becoming the most pervasive threat to the carnivore guild and biodiversity in general. This research has provided baseline data from which changes can be measured and a proven method for future studies on sympatric carnivores under anthropogenic pressure. Camera traps proved an effective tool to map and quantify occupancy of the carnivore guild, including elusive species. The same approach could be applied to other protected areas across the country and the eco-region running similar monitoring programs to test hypotheses around the effects of different variables that may influence habitat use of carnivore species.

From a conservation perspective, carnivores provide several ecological services, and their survival is vital for the stability of the natural ecosystems (Ritchie et al., 2012; Roemer et al., 2009). Carnivores extinction would lead to a trophic cascade effect on the community structure and the composition of the ecosystem leading to further effects on other species and ecosystem processes (Estes et al., 2011). Larger carnivores are at a higher risk of extinction in areas of human-wildlife conflict in particular (Webber et al., 2007). The increasing disturbance and habitat fragmentation are additional factors expected to reduce species diversity and impose further pressure on carnivores (Butchart et al., 2010; Treves & Karanth, 2003). The increasing vulnerability of carnivores species combined with their higher detection rate using camera traps makes them an optimal target for monitoring in WWNP (Carroll et al., 2001; Monterroso et al., 2014; Moruzzi et al., 2002).

The research was conducted while the reserve was closed to the public, which supported establishing a baseline for carnivore occupancy with no direct interference from human activities inside the reserve. There were no human or recreational activities permitted during the data collection between 2016-2017 except for research and honey gathering by the local people. Biosphere reserves are considered areas for understanding the interactions between ecosystems and humans and managing conflicts to promote coexistence and solutions to potential issues (Batisse, 1982). One significant challenge facing the reserve in the near future is the increasing intensity of urbanisation in the surrounding area and farming activities in the transitional zone. The current herding pattern of domestic goats creates opportunities for the Caracal to compensate its diet from the lack of large natural prey in the reserve. The Caracal and the Red Fox has probably benefited the most from the anthropogenic food resources provided by the nearby farms; both are generalist species and capable of increasing their niche breadth to accommodate the natural and anthropogenic food resources to increase their competitiveness (Concepción et al., 2015; Verdade et al., 2011). Future expansion of human development will alter the habitat and facilitate the encroachment of the Red Fox towards the core zone of the reserve to compete with Blanford's Fox on its niche (Ordeñana et al., 2010).

Any future management interference to combat overgrazing has to be gradual and supported by reintroduction programs for the Arabian Tahr and the Arabian Gazelle, the natural prey in these mountain areas. I suggest that further investigating current herding activities would be valuable in developing conservation strategies targeting human/wildlife conflict. Developmental encroachment is another issue that needs to be planned considering the sustainability and recovery of the reserve. New challenges include feral animal use of the reserve, including domestic dogs (a threat to potential reintroductions) and cats (resulting in a risk of hybridisation with Gordon's wildcat), with a noticeable increase in their occurrence and detection in the reserve recently. The interaction between the carnivore species in the transitional zone with domestic animals could make transmission of zoonotic diseases an additional challenge to consider by management. This research demonstrates how single-species, single-season occupancy models can effectively monitor anthropogenic effects in a relatively rapid development area (Wang et al., 2015).

The future expansion in the sub-urban areas around the reserve would impact the apex predator home range and alter its occupancy, potentially resulting in a cascading effect on the ecology of the carnivore guild (Fisher et al., 2021; Levi & Wilmers, 2016; Prugh et al., 2009). Carnivores and humans can co-exist in proximity; Such an interaction has benefited the Red Fox and, to a lesser degree, the Caracal, as domestic goats are now part of Caracal diet, but further development might imbalance the fragile equilibrium in the carnivore community. The reserve buffer and transitional zone are equally vital for the long term viability of these sympatric species. The fact that the most vulnerable species, Blanford's Fox and the Caracal, are not actively avoiding urban development areas and the higher detection of the Caracal closer to urban areas is worrying and could be a sign of an ecological trap (Fig. 24) (Isaac et al., 2014; Lamb et al., 2017). Larger carnivores are known to be more vulnerable to extinction in areas of human-wildlife conflicts (Haswell et al., 2017).

The reserve is one of the last strongholds for conservation in the country, and it has the last three species of carnivores thriving in the wild in the UAE. Maintaining the ecosystem services provided by the mountain ecosystem and safeguarding its landscape is crucial for preserving the carnivore guild. Based on occupancy modelling and habitat use outcomes, maintaining a pristine environment in the reserve's core zone is critical for the carnivores guild. Additional attention should be given to areas with 30-50% vegetation cover, freshwater ecosystems, and associated habitats.

Figure 24. (Top) A pair of Red Foxes *Vulpes vulpes* hanging from a tree near Alkhalbiya village near the reserve's western borders. (Bottom) Stuffed Red Fox inside a car bought from labours working in goat farms

Recommendations and Future Studies

As for now, the reserve is protecting its natural habitat effectively, including the freshwater habitat, a key supporting habitat for carnivores and their prey. However, it is important to point out that the results are insufficient to assess the effectiveness of the current species conservation strategies, considering the low detection rate of Blanford's Fox and the Caracal. The current status of these two species could indicate a decline in the population, knowing that carnivores, in general, are persecuted and killed outside of the borders of the reserve. For the future, conducting further research to assess the population viability of these two species is recommended (Ben-Ami et al., 2006). Integrated population models (IPM) combining several data sets such as a mark-recapture estimate of the population, telemetry or satellite tagging of carnivores to assess the population viability supported with further investigation on the nature of human/wildlife interaction around the reserve would be essential for the management (Saunders et al., 2018; Wang et al., 2017; Wittemyer et al., 2008). Mammals and carnivores are considered a good indicator of a healthy ecosystem (Crooks, 2002; Ritchie et al., 2012); thus, I recommend considering Blanford's Fox and the Caracal as flagship species for conservation in the UAE, giving their habitat requirements the priority for protection.

The interaction between the three sympatric species was expected where the presence of one species could influence the detection or the presence of another. However, I still consider these results preliminary and require further investigation. Occupancy modelling can provide inferences on population dynamics. Using multi-species occupancy models to expand on the sympatric relationships between the three species can further enhance our understanding of the complex relationships of the carnivores guild (Fedriani et al., 2000; Haswell et al., 2020; Mackenzie et al., 2004). Although there is no competition on water resources between desert carnivores, interactions between species are higher in these areas between species and mainly when resources are scarce as larger carnivores may use these areas to ambush prey (Golightly & Ohmart, 1984). Blanford's Fox occupancy is highly correlated with water areas; thus, further investigation would explain the high dependency on freshwater habitats and the avoidance mechanism Blanford's Fox used to exploit these resources and increase its fitness by avoiding the Caracal successfully at the same time (Najafi et al., 2019).

This research has revealed some primary feeding strategies based on how habitat association and prey variables impacted occupancy. Prey variables effect came as a reflection of the positive relationship between each carnivore and its most accessible prey. Some results did not reflect reality due to a lack of reliable outcomes. The small mammal's detection variable did not correlate with carnivore occupancy due to the low detection rate by camera traps. This gap in our knowledge has limited the inferences on the correlation of carnivores occupancy with particular habitats or landscapes, knowing that small mammals are one of the main overlapping diet components between the three carnivores. Further investigations and more comprehensive research with different methodologies are recommended in the future, focusing on habitat association, seasonal variation, and prey biomass such as Sand Partridge *Ammoperdix heyi*, and expanding to small mammals at a later stage could complement our understanding of carnivore carrying capacity in the reserve (Hayward et al., 2007). Through scat collection and analysis, further research on carnivore diet would provide more information regarding feeding strategies and improve our predictions on habitat relationships and the nature of competition among the three sympatric carnivores (Carvalho & Gomes, 2004; Fedriani et al., 2000).

Considering the current pattern of urban areas intrusion and the speed of habitat loss. Impact on species with large home range such as the Caracal and other effects such as the increasing competition between the sympatric carnivore species is inevitable. Habitat suitability maps are used to identify hot spots for carnivore conservation, protected areas expansion and possibly identify other mountain areas that require further protection or can support reintroduction programs (Smith et al., 2016; Tan et al., 2017). For this, developing a preliminary habitat suitability map for the reserve and the larger mountain area in the UAE is a priority (Cristescu et al., 2019; S. Ross et al., 2017). The outcomes of habitat suitability modelling using this research's highly dependent occupancy models can be utilised among other tools to identify the most fragile areas where most human/carnivore conflict mitigation is required (e.g. Harihar & Pandav, 2012; Winterbach et al., 2014). The occupancy modelling results supported by habitat suitability modelling can also support developing corridors or a network of mountain protected areas for the country. Such an initiative is crucial for preserving the last carnivore and their prey species, particularly the charismatic species with a large home range such as the Caracal (Ashrafzadeh et al., 2020). Establishing a network of mountain reserves between the three neighbouring emirates of Fujairah, Sharjah, and Ras Al Khaimah could ensure the conservation of these predators. Considering these areas are inaccessible and not yet developed, the mountainous areas of this region could provide many conservation opportunities for Arabian biodiversity.

Given the increasing intensity of threats, once the reserve is open for the public compared with the small size of the reserve, I stress the importance of maintaining the ecological integrity of the reserve through regulations enforcement and developing further guidelines for the activities within the transitional zone and land use, traditional and commercial activities, including the recreational ones (Stottlemyer, 1987; Taylor & Knight, 2003; Watson et al., 2016). In the past, park management strategy has been successful in law enforcement, particularly in prohibiting hunting activities. However, these outcomes can be deceiving and fragile unless compensation measures for the locals supported by systematic public awareness and outreach campaigns are in place.

I also recommend improving and maintaining the existing monitoring program of carnivores in the reserve for its potential application in tracking climate change effects on carnivores, such as habitat loss, range restriction and prey changes (Dar et al., 2021; Khorozyan et al., 2015; Khosravi et al., 2021). The Mountain ecosystem is sensitive to climatic changes, and the reserve can be one of the few locations in the country to provide biological refugia and a case study of the impact of a changing climate (Ashrafzadeh et al., 2019; Radhi, 2009). Future changes in the hydrological cycle and vegetation cover would affect carnivore ecology and social structure (Rabaiotti & Woodroffe, 2019). Occupancy models can predict future changes based on habitat change not only by climate but also by the induced anthropogenic factors such as land use transformation or management interference (King et al., 2020).

Further Improvements and Gaps

Several potential important factors were absent from our model or were not measured at a fine scale. Weather variables, for instance, was absent as available data were too coarse, showing only slight variation between monitoring sites at the reserve scale. Roads are another example; all roads were combined in one network with no differentiation between fast roads and side roads (Dean et al., 2019; Santos et al., 2018). At the habitat scale, I considered the mountain terraces as part of the mountain slopes and combined small gorges with wadis to establish a baseline for occupancy status. Further investigation to prioritise habitats at a smaller scale might provide further inferences. Similarly, freshwater habitats were merged under one category due to their scarcity (e.g., extensive reed bed riffle, isolated gravel pool, bedrock riffle). Additionally, I would recommend increasing the sample size in the future and expanding beyond the protected area borders into the nearby mountain areas considering that rare species occupancy modelling would perform better with higher sample size and in order to study the impact of protection by measuring the difference in occupancy between areas inside the reserve and the surrounding mountains areas in general.

Appendix A

Appendix A1. Environmental variables used in the definition of occupancy models. Type refers to whether the variable was included as an explanatory variable in occupancy-focussed (Ψ) or detection-focussed (p) models.

S	Unit	Predictor variables	Type	Abbreviation	Description	References
A		**Anthropogenic effects**				
1		**Human disturbance**				
1.1	m	Distance to agriculture farm	Ψ, p	Agri	Euclidian distance between camera trap locations and agriculture farm extracted from LULC map (SWOS project).	(Rich et al., 2017), (Sarmento et al., 2011), (Ramesh & Downs, 2015), (Wang et al., 2015), (Šálek et al., 2015), (Burton et al., 2012), (Schuette et al., 2013), (Curveira-Santos et al., 2019), (Nicholson et al., 2009)
1.2	m	Distance to a domestic goat farm	Ψ, p	GtFarm	Euclidian distance between camera location and domestic goat farms (52 farm) in the vicinity of the park extracted from DEM map of 5x5 resolution	
1.3	m	Distance to roads	Ψ, p	Rds	Euclidian distance between camera trap locations and main roads inside and around WWNP extracted from DEM map of 5x5 resolution	
1.4	m	Distance to town	Ψ, p	Town	Euclidian distance between camera trap locations and the nearest town extracted from DEM map of 5x5 resolution	
1.5	m	Distance to urban area	Ψ, p	Urban	Euclidian distance between camera trap locations and urban areas extracted from LULC map (SWOS project).	
B		**Biotic interactions**				
2.1		**Competition**				
2.1.1		Red Fox trap success	Ψ, p	RF-Succs	Number of independent photo captures per 100 trap nights (calculated for two seasons)	(Bender et al., 2017), (Sarmento et al., 2011), (Sollmann et al., 2012), (Atwood et al., 2011), (Fedriani et al., 2000), (Elmhagen et al., 2017), (Atwood et al., 2011), (Pamperin et al., 2006), (Donadio & Buskirk, 2006), (Wang et al., 2015), (Šálek et al., 2015), (Gosselink, T. E., T. R. Van Deelen, R. E. Warner, 2003),
2.1.2		Caracal trap success	Ψ, p	Ca-Succs	Number of independent photo captures per 100 trap nights (calculated for two seasons)	

						(Rota et al., 2016), (Caro & Stoner, 2003), (Schuette et al., 2013), (Haswell et al., 2018)
2.2		**Prey effect**				
2.2.1		Goat trap success	Ψ, p	Gt-Succs	Number of independent photo captures per 100 trap nights (calculated for two seasons)	(Sarmento et al., 2011), (Rich et al., 2017), (Bender et al., 2017), (Sarmento et al., 2011), (Ramesh & Downs, 2015), (Fedriani et al., 2000), (Lozano et al., 2003), (Burton et al., 2012), (Rota et al., 2016), (Curveira-Santos et al., 2019)
2.2.2		Hedgehog trap success	Ψ, p	HG-Succs	Number of independent photo captures per 100 trap nights (calculated between 2009 to 2018)	
2.2.3		Sand partridge trap success	Ψ, p	SP-Succs	Number of independent photo captures per 100 trap nights (calculated between 2009 to 2018)	
2.2.4		Small mammals trap success	Ψ, p	SM-Succs	Number of independent photo captures per 100 trap nights (calculated between 2009 to 2018)	
C		**Habitat variables**				
3.1		**Habitat**				
3.1.1	m	Distance to permanent water	Ψ, p	PW	Euclidian Distance between camera trap locations and permanent water resources (20 locations) inside WWNP extracted from DEM map of 5x5 resolution	(Rich et al., 2017), (Bender et al., 2017), (Sarmento et al., 2011), (Sollmann et al., 2012), (Atwood et al., 2011), (Rich et al., 2017), (Ramesh & Downs, 2015), (Sollmann et al., 2012), (Gosselink, T. E., T. R. Van Deelen, R. E. Warner, 2003), (Lozano et al., 2003), (Burton et al., 2012), (Mangas et al., 2008), (Schuette et al., 2013), (Curveira-Santos et al., 2019)
3.1.2	m	Distance to water reservoir	Ψ	Reserv	Euclidian Distance between camera trap locations and seasonal water reservoir (4 locations), extracted from LULC map (SWOS project).	
3.1.3	m	Distance to Wadi	Ψ, p	Dis-WD	Euclidian Distance between camera trap locations and wadi lines inside WWNP extracted from DEM map of 5x5 resolution	
3.1.4	m	- Distance to vegetation cover <10% - Distance to vegetation cover 10-30% - Distance to vegetation cover 30-50% - Distance to vegetation cover >50%	Ψ, p	Veg10, Veg10-30, Veg30-50, Veg50	Euclidian distance between camera trap locations and areas of vegetation cover density (<10%, 10-30%, 30-50%, >50%). Vegetation cover extracted from LULC map (SWOS project).	
3.1.5	1 unit	Normalized Difference Vegetation Index	Ψ, p	NDVI	NDVI mean value of a 150m radius buffer area around the camera trap location extracted from 30	

					m resolution Landsat 8 imagery from November 2014	
3.1.6	Binary	Wadi Habitat Mountain Slope Habitat	P Ψ, p	WD MS	WD is a binary variable where 1 represents a camera installed in the wadi bed. MS is a binary variable where 1 represent a camera installed on a mountain slope (This variable used only used with Blanford's Fox)	
3.2		**Landscape variables**				
3.2.1	m	Elevation	Ψ	Elev	Elevation at camera trap location extracted from DEM map of 5x5 resolution	(Bender et al., 2017), (Curveira-Santos et al., 2019)
3.2.2	1 unit	Heat load index	Ψ, p	HL	Heat Load Index, indicating the influence of sunlight on surface temperature calculated using the equation of (McCune & Keon, 2002)	(Bender et al., 2017)
3.2.3	1 unit	Ruggedness (Mean surface ratio)	Ψ	Rugg100-250-500-750-900-1000	The mean surface ratio of a 100m, 250m, 500m, 750m, 900m, 1000m radius buffer area around the camera trap location (5x5m resolution)	(Bender et al., 2017), (Sarmento et al., 2011), (Atwood et al., 2011)

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