Assessing Habitat Use and Anthropogenic Threats of Temminck's Pangolin (*Smutsia temminckii*) in southern Kenya

By

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Abstract

All eight pangolin species are threatened and are collectively considered the most trafficked mammal group in the world. Temminck's pangolin (*Smutsia temminckii*; hereafter "pangolin") are an elusive and low-density species that are undergoing population decline due to poaching for traditional medicine uses, spiritual purposes, and bushmeat consumption. They also experience road mortalities caused by vehicular collisions, as well as electrocutions on electric fences. There are significant knowledge gaps in pangolin ecology, including habitat use and how it relates to these anthropogenic threats. The current research utilised field studies, citizen science, and remote sensing in Kenya and South Africa to address these gaps.

There has been limited ecological research on this species in East Africa to date. To investigate small-scale habitat use within home ranges, burrow choice of pangolins was monitored through camera trapping and radio-tracking in Masai Mara National Reserve, Kenya. Pangolins utilise burrows created by aardvarks (*Orycteropus afer*) rather than create their own. This means aardvark burrow presence is likely important for determining pangolin habitat use in Kenya. Five characteristics of aardvark burrows were evaluated for pangolin preference. Pangolins were generalists when it came to utilisation based on these characteristics, although burrows with large entrances were avoided due to presumed predator evasion. These results were the first in East Africa to evaluate pangolin burrow use and additionally provided aardvark distribution and burrow density data.

In addition to burrow presence, there are likely other environmental factors that influence pangolin distribution and habitat use. To evaluate wider-scale pangolin habitat use, habitat suitability models were generated using remotely sensed environmental variables and citizen science reports. This was conducted for both Narok County and all of Kenya, and revealed that moderate rainfall, topography above 1500 m, and eight soil types were the main predictors of distribution. This is the first study to generate such models for pangolins outside of South Africa. Further, a risk model (the first created for pangolins) was generated using anthropogenic variables to predict areas of high threats, which indicated areas with close proximity to roads and human populations as the largest potential threats within Kenya. Fences were indicated as a lesser threat, whereas they are known to cause numerous mortalities in South Africa. This difference between Kenya and South Africa is likely due to a lower amount of electric fencing in East Africa.

To assess fences as a threat to pangolins in South Africa, an online citizen science questionnaire was used to investigate electrocution frequency and which fence types are most prone to cause these mortalities. Mortalities of fourteen taxa were recorded, with pangolins being the second most frequently killed species, after tortoises. The most mortalities occurred on fences with low-level electric wires, indicating that mitigation to reduce deaths on these fences is needed.

Collectively, these findings contribute to our understanding of pangolin ecology, including: habitat use, distribution factors, and anthropogenic threats. This information is vital for conservation planning, and will aid conservation practitioners and stakeholders in developing effective conservation strategies.

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List of Acronyms

CITES	Convention on International Trade in Endangered Species
CSA	Cross Section Area
HSM	Habitat Suitability Model
IUCN	International Union for Conservation of Nature
LEK	Local Ecological Knowledge
MaxEnt	Maximum Entropy
NDVI	Normalized Difference Vegetation *I*ndex
PP	The Pangolin Project
PAR	Perimeter-Area-Ratio
SBD	Sampling Bias Distance
SDM	Species Distribution Model
SRTM	Shuttle Radar Topography Mission
SSC PSG	Species Survival Commission Pangolin Specialist Group

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Author’s declaration

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

Signed: Leandra Stracquadanio

Dated: 27/09/2023

Author contribution statement

<u>Chapter 3</u>: The study concept for this chapter was conceived by The Pangolin Project (PP), a conservation charity in Kenya, and further developed by Leandra Stracquadanio. PP designed the methodology, collected the majority of the data for this study and conducted most of the fieldwork, with Leandra Stracquadanio assisting when possible. Leandra Stracquadanio analysed the data and conducted the writing for this chapter. Feedback on the chapter draft was given by Dr Bryony Tolhurst, Dr Samuel Penny, and Dr Niall Burnside. Dr Rachel White and Dr Maureen Berg reviewed this work as part of University of Brighton Annual Progression Reviews.

<u>Chapter 4:</u> The concept for this chapter was conceived by Leandra Stracquadanio. PP designed the citizen science reporting system and ambassador activities, and along with their volunteers, collected all of the data for this study and conducted all fieldwork. Leandra Stracquadanio analysed the data and conducted the writing for this chapter. Feedback on the chapter draft was given by Dr Tolhurst, Dr Penny, and Dr Burnside. Dr White and Dr Berg reviewed this work as part of University of Brighton Annual Progression Reviews.

<u>Chapter 5:</u> The concept and methodology for this chapter were designed by Leandra Stracquadanio, with methodology feedback from Dr Tolhurst, Dr Penny, and Prof Andre Ganswindt. Leandra conducted all data collection, analysed the data, and conducted the writing for this chapter. Feedback on the chapter draft was given by Dr Tolhurst, Dr Penny, Prof Ganswindt, and Dr Burnside.

Dr White and Dr Berg reviewed this work as part of University of Brighton Annual Progression Reviews.

COVID-19 impact statement

This research presented in this thesis experienced disruptions due to the COVID-19 pandemic. The original research plan, which was developed in early 2020, aimed to study electrocutions of Temminck's pangolins in South Africa. This was planned to include extensive fieldwork throughout 2021 – 2023. International travel restrictions imposed by the UK government and University of Brighton did not allow travel for fieldwork to commence and by August of 2021 it was uncertain when or whether this would be permitted. During this time, an online questionnaire was used to gather data for Chapter 5 remotely. It was unclear when travel would be allowed thus, 12 months into this PhD, the researcher sought an external collaboration with The Pangolin Project in Kenya. This collaboration involved a near complete change of the research direction of this thesis to focus on pangolin distribution, population estimation, and spatial ecology in Kenya. The initial intention of this collaboration was for the researcher to combine elements of existing data already collected by The Pangolin Project with original field data collection. Whilst fieldwork was undertaken by the researcher in Kenya over April 2022, which augmented existing data, unforeseen logistical restrictions meant that this data collection period was cut short. Unfortunately, this necessitated further changes in the research focus of the PhD, as The Pangolin Project needed to pause field operations for an unforeseen amount of time. This involved a redesign of the research leading to the researcher utilising pre-existing data from The Pangolin Project to form Chapters 3 and 4 of this thesis. In summary, this PhD research had two major changes in project design as a result of COVID-19, one direct and one indirect.

Chapter 1 - Introduction

All eight pangolin species are collectively considered the most trafficked mammals globally due to poaching for traditional medicine practices in Asia and Africa (Challender, Waterman and Baillie, 2014; Gaubert et al., 2018) and urgent action is required to reduce the unsustainable population declines that they are experiencing. They are one of the few orders in which every species is threatened with extinction, making them a high conservation priority (Challender et al., 2020a). Additionally, they face other anthropogenic threats such as habitat loss and deaths on fences and roads, which has further accelerated their decline (Pietersen, McKechnie and Jansen, 2014a; Pietersen et al., 2020). Pangolins are elusive and understudied. Evaluating threats to their populations and planning conservation action to mitigate negative population trends is challenging due to numerous knowledge gaps regarding their biology and ecology (Heighton and Gaubert, 2021).

Most existing research has focused on the Asian pangolin species, as these experience the highest level of trafficking. In general, the African species including Temminck's pangolin, have been researched the least for this reason, and most of this research has taken place in South Africa (Pietersen et al., 2020; Pietersen and Challender, 2020; Heighton and Gaubert, 2021). However, in recent years as Asian populations have become depleted there has been a shift towards trafficking of the African species (Challender et al., 2020a). There is a considerable lack of knowledge on Temminck's pangolin; a systematic review by Heighton and Gaubert (2021) found large knowledge gaps pertaining to general ecology, perceptions and awareness of local communities, and anthropogenic threats (excluding poaching).

In 2014, the International Union for Conservation (IUCN) Species Survival Commission (SSC) Pangolin Specialist Group created an Action Plan to determine the most critical research and conservation targets necessary for all pangolin species (Challender et al., 2014b). This encompassed four categories: 1) Conservation Research, which included monitoring, conservation breeding, and genetic studies; 2) Pangolin Strongholds, which entails identifying priority countries in which to focus conservation and demand reduction efforts; 3) Policy Recommendations, including CITES recommendations, the examination of legislation gaps, and the enforcement of protection laws; and 4) Demand Reduction, behaviour change and awareness raising, which includes reducing the demand for meat and scales, and raising the profile of pangolins globally. Within the Conservation

Research category, developing monitoring protocols to estimate abundance, defining habitat suitability for each species, and understanding the ranging behaviour and distribution of all species, were considered priorities (Challender et al., 2014b).

Overall, our understanding of pangolin ecology for all species urgently needs improvement, in particular for regions outside of southern Africa, and in regards to population estimates and monitoring (Pietersen and Challender, 2020). It is particularly important to improve our understanding of habitat use, as it informs conservation planning and can be used to evaluate the impact of various threats on pangolin populations. The majority of research on Temminck's pangolin has focused on ecological data, including distribution, density, habitat use, reproductive and movement behaviour, and predation. However, collectively these topics encompass only 16 scientific papers (Heighton and Gaubert, 2021) and most of this research has been restricted geographically to southern Africa. There is a lack of knowledge on all topics for any other range state or region and it is probable that pangolin ecology will differ across range countries due to variation in environmental factors, as this species is known to exhibit different mating, dietary selection, and home ranging behaviour in different regions (Pietersen et al., 2020). Additionally, few scientific papers have evaluated anthropogenic threats that are not illegal trade related, and again this has primarily been in South Africa. There has been little research into threats within East Africa as a whole, and even less investigation into threats in Kenya. This means there is a gap in how these threats impact pangolin populations and relate to their ecology in all other countries. Additionally, little is known about how dietary selection influences pangolin distribution (Pietersen and Challender, 2020).

This thesis will investigate several knowledge gaps for Temminck's pangolins in both Kenya and South Africa. It will research two of the priorities identified by the IUCN SSC Pangolin Specialist Group; namely defining habitat suitability, and understanding pangolin distribution and ranging. This thesis aims to address the lack of data found on anthropogenic threats, and relating to pangolin habitat use at different spatial scales, which are fundamental for effective conservation action. Specific research aims are outlined in Section 1.7.

1.1. Ecological knowledge

1.1.1. Pangolin biology

Pangolins are a morphologically unique set of mammalian species and the only members of the order Pholidota (Gaudin et al., 2020). There are eight species of pangolin, four of which are found in Asia and four in Africa (Figure 1.2). The four Asian species are: Indian pangolin (*Manis crassicaudata*), Philippine pangolin (*Manis culionensis*), Sunda pangolin (*Manis javanica*), and Chinese pangolin (*Manis pentadactyla*). The four African species are: Black-bellied pangolin (*Phataginus tetradactyla*), White-bellied pangolin (*Phataginus tricupsis*), Giant pangolin (*Smutsia gigantea*), and Temminck's pangolin (*Smutsia temminckii*). The Sunda, Philippine, white-bellied and black-bellied species are arboreal (Chong et al., 2020; Gudehus et al., 2020; Hoffman et al., 2020; Jansen et al., 2020), while the Indian, Chinese, giant ground and Temminck's ground species are terrestrial (Mahmood et al., 2020; Pietersen et al., 2020; Schoppe et al., 2020; Wu et al., 2020).

All pangolins have epidermal keratin scales, which give them a unique appearance unlike any other mammal (Figure 1.1). This has led to them being referred to as "scaly anteaters" because they are the only mammals that possess true scales, and because their diet is comprised of ant and termite species. However, they are not closely related to this group evolutionarily, nor to Armadillos, which also possess scales but differ in appearance and are composed of osteoderms rather than keratin (Vickaryous and Hall, 2006; Gaudin et al., 2020). Establishing the evolutionary history of pangolins has proven difficult as they do not have teeth, the most well-preserved part of most mammalian skeletons. Teeth are often used to elucidate relatedness between mammal species thus their place on the evolutionary tree has historically been debated (Ungar, 2010; Gaudin et al., 2020). Their occurrence at low density has also resulted in a sparse fossil record. Previously, they have been grouped closely with Xenarthra, which includes armadillos, and in Carnivora. However now it has been established that they are in a separate order of their own, Pholidota. Pholidota likely originated from Laurasia, a small mammal group from the early Palaeocene in Europe, with its two closest relatives being Carnivora and Palaeanodonta from North America (Flynn and Wesley-Hunt, 2005; Rose et al., 2005; Gaudin et al., 2020). This evolutionary distinctness combined with their unique morphology and high level of vulnerability to anthropogenic threats means that they are now classified as an Evolutionarily Distinct and Globally Endangered (EDGE) priority species. EDGE species are of important research and conservation focus (Park, 2014).

Pangolin scales cover their entire dorsal region including the tail. Interestingly, their keratin composition is homologous with that of primate fingernails (Spearman, 1967; Tong et al., 1995; Gaudin et al., 2020). Pangolin scales act as protective armour from predators and when threatened a pangolin will curl into a ball to maximise protection from their scales (Gaudin et al., 2020). Due to this behaviour, pangolins do not have many natural predators; they are only occasionally predated on by lion (*Panthera leo*), leopard (*Panthera pardus*) or spotted hyaena (*Crocuta crocuta*). However, their scales do not protect against ant or termite bites which may deter them from feeding on certain species (Heath and Hammel, 1986; Gaudin et al., 2020). Although pangolins do not have teeth, they do have extended tongues of 40 – 60 cm. This is due to their very specific diet of ants and termites, known as myrmecophagy (Gaudin et al., 2020). This tongue, along with their specialised claws for burrowing, allow them to easily penetrate insect mounds (Gaudin et al., 2020), and similar traits are found in South American anteaters. Pangolins have relatively poor eyesight and enhanced senses of smell for detecting prey, which is common amongst insectivores (Soewu and Sodeinde, 2015; Pietersen et al., 2020). All pangolins are exceptionally species-specific with their diet and will typically only predate a few of the available ant or termite species in their ranges, even if numerous species are present (Sweeney, 1956; Chao, Li and Lin, 2020; Panaino et al., 2022). All species possess powerful forelimbs with claws, and in arboreal species these claws are curved and hindfeet are longer to assist with moving on branches (Gaudin et al., 2020). In terrestrial species, the front claws are longer, straighter, and often more worn from digging than in the arboreal species. All pangolin species have a muscular tail that can be used in defence against predators, as a counter balance when walking for the bipedal Temminck's pangolin, or as a prehensile appendage for climbing for arboreal species (Gaudin et al., 2020). Temminck's pangolins have between 11 and 13 scale rows on their bodies, with a total of 340 – 420 scales (Pietersen et al., 2020). Scales are absent from their underbellies and heads, and they have very sparse hair on their abdomens and limbs (Pietersen et al., 2020). Temminck's pangolin are water independent and most of their water consumption comes from their diet, although they will opportunistically drink from available water sources (Stuart, 1980; Pietersen et al., 2016b).

Most pangolin species are predominately nocturnal, with the exception of the black-bellied pangolin which is diurnal (Gudehus et al., 2020). Nocturnal behaviour can vary depending on the time of year and the weather. This may depend on prey availability and season, for instance in South Africa in the summertime, Temminck's pangolin is known to be nocturnal to avoid high temperatures, whereas in winter they may be diurnal to avoid cold night temperatures (Swart, 2013; Pietersen, McKenchie and Jansen, 2014b; Pietersen et al., 2020). They are a solitary species that only meet during mating periods (Chao et al., 2020). All pangolin species are seldom seen and have primarily been recorded at low density (Sweeney, 1956; Pietersen et al., 2014b; Willcox et al., 2019) hence the paucity of behavioural and ecological data relating to them. Their predicted lifespan is long, at up to 20 years, and have slow reproductive outputs with one pup every two years, with a gestation period of 105 – 140 days (Pietersen et al., 2016a; Pietersen et al., 2020). If primarily adults are poached this means the rapid decline of mature individuals is contributing to quick population reductions since less individuals can reproduce. This has been seen with African forest elephants (*Loxodonta cyclotis*), which also have a slow population growth rate and have undergone extensive poaching in Central Africa. Turkalo, Wrege and Wittemyer (2016) estimate that it would take 4 – 6 decades for this elephant population to recover. Pups ride on their mother's tail during the early stages of life and become independent at approximately four months. It is likely that pups and juveniles experience a high mortality rate as their scales are still soft and developing (Pietersen et al., 2016a). Adult Temminck's pangolins weigh on average 9 – 10 kg and have a body length up to 140 cm, although these measurements vary across their range, e.g., a male in Sudan was recorded weighing 21 kg. There is no sexual dimorphism although males weigh slightly more than females (Pietersen, 2013; Pietersen et al., 2020).

Figure 1.1 Adult Temminck's pangolins with fully developed scales. Both are foraging, one on a fallen tree (top) and one on grass (bottom). Photos taken by Leandra Stracquadanio.

1.1.2. Temminck's pangolin habitat use, distribution, and populations

Distribution of all pangolin species is determined primarily by prey distribution, temperature, and occasionally, water access (Figure 1.2; Chao et al., 2020). Temminck's pangolins have the largest range of all pangolin species and are present in a variety of habitats, including woodland, arid and mesic savannah, desert, and semi-arid habitats. They are notably absent from closed-canopy forests, coastal regions and agricultural crop areas (Coulson, 1989; Heath and Coulson, 1997; Pietersen et al., 2016a; Pietersen et al., 2020). Overall, they do not show strong habitat selection within their home or core ranges and their presence within a region is presumed to be subject to the availability of prey species and dens for shelter (Pietersen et al., 2016a; Pietersen et al., 2020). Pangolins from different regions feed on different species and if moved to a new region will not feed on unfamiliar species (Pietersen et al., 2020). It is unknown if this arises from learned experience or whether it is socially learned or an innate biological trait. This species is one of five myrmecophagous species in southern Africa (aardvark (*Orycteropus afer*), bat-eared fox (*Otocyon megalotis*), aardwolf (*Proteles cristatus*), and Miller's mongoose (*Rhynchogale melleri*), and is the only one to feed solely on ant and termite species (Pietersen and Robertsen, 2023). Temminck's pangolins occur within climatic conditions of 250 – 1400 mm of rainfall annually and their altitude upper limit is ~1700 m (Coulson, 1989; Pietersen et al., 2020). The overall factors that influence pangolin distribution, such as climate, resources and habitat, are not fully understood thus it is challenging to predict their occurrence, which is necessary for understanding their ecology and for conservation planning.

The focal countries for this thesis are South Africa and Kenya. Temminck's pangolins are found throughout Eastern and Southern Africa, although distribution in these regions can be fragmented (Pietersen et al., 2020; Figure 1.2). It is thought that overexploitation has caused local extinctions in some regions (Pietersen et al., 2020). The northernmost presence of the species has been recorded in Chad, while the eastern and western most records are from Ethiopia and Namibia, respectively. They are widely distributed in East Africa and their range extends southernly down to South Africa. This species is absent from northern, western and most of central Africa, including the Democratic Republic of Congo. This is presumably due to their niche requirements not being met, however further study is needed to investigate this. They are found throughout most of Kenya except in the north-eastern regions of the country (Swynnerton and Hayman, 1950; Foley et al., 2014; Pietersen et al., 2020). Their population once did occur easterly to the coast of Kenya, however anthropogenic habitat use has reduced their range (C. Okell, personal communication, 2022). There is very little information on the ecology of this species in Kenya due to a lack of published research outside of southern Africa. Their southernmost distribution is in the Northern Cape of South Africa (Pietersen et al., 2016a; Pietersen et al., 2020). Within South Africa, Temminck's pangolin are found in the Northern Cape, Limpopo, North-West Province, Mpumalanga and the northern regions of KwaZulu-Natal. The species was once known to be widespread but low density in KwaZulu-Natal in 1983 (Kyle, 2000), however there have been presumed local extinctions there caused by *muthi* practices (local traditional medicine) and bushmeat consumption (Pietersen et al., 2014a; Pietersen et al., 2016a).

Much of this species is confined to managed or protected areas in South Africa (Pietersen et al., 2016a). Population estimates for Temminck's pangolin are absent throughout most of the species' range due to its elusive and nocturnal nature. Most research on Temminck's pangolins has been conducted in South Africa and current population estimates for South Africa are between 0.12 – 0.16 reproducing individuals per km² and 0.23 – 0.31 total individuals per km² (Pietersen et al., 2014b). From these predicted population densities it is estimated that in South Africa there are 7,002 – 32,135 mature individuals, with a more likely range of 16,329 – 24,102 (Pietersen et al., 2016a). There is little difference in range size recorded between males and females. Home range size differs between regions in South Africa, with the north-eastern ranges varying from 1.3 – 7.9 km², and eastern regions estimating 9.28 – 22.98 km² (van Aarde et al., 1990; Swart, 2013). Home ranges within the Kalahari of South Africa are estimated at 10 km² for adults and 7.1 km² for sub-adults. This variation in home range size may be due to habitat type, population density, or sex. Males have generally been found to have slightly larger home ranges than female (Heath and Coulson, 1997; Pietersen et al., 2020). Social structures are not well understood, and the overlap of male and female home ranges also varies depending on locale, with different regions indicating either monogamous or polygamous mating interactions (Prediger, 2020; Pietersen et al., 2020; Pietersen and Challender, 2020). In Zimbabwe, home ranges are estimated to be between 0.17 – 23.4 km², with males having the largest ranges and temporarily overlapping several female ranges (Heath and Coulson, 1997). There appears to be a large disparity in range size depending on region, which may be due to habitat type, climate, or social interactions between pangolins, as individuals of the same sex do not often have overlapping home ranges (Pietersen et al., 2020). Unfortunately there are no estimates for any other areas of the species' range and the decline of this species is presumed based on perceived threats (Pietersen et al., 2020). Males may be territorial with an intolerance for other males in their home ranges, which can result in wrestling battles (Swart, 2013; Pietersen et al., 2020). Within their home range, pangolins utilise burrows as a form of shelter and for predator avoidance, and move in an apparent unplanned manner between burrows (Health and Coulson, 1997; Swart, 2013). This species uses burrows created by other species such as aardvarks rather than digging their own. When they are not foraging, pangolins spend the majority of time resting in burrows (Swart, 2013; Pietersen et al., 2020). They change burrows often and occasionally revisit previously used burrows, indicating that numerous are needed throughout their habitat (Pietersen et al., 2020). The mechanisms behind burrow selection are not well understood and likely depend on a combination of biological and social factors. Understanding how this choice occurs would provide valuable insights into pangolin habitat use and distribution. This thesis investigates the burrow characteristics that influence pangolin burrow use. By understanding burrow use, we can better evaluate how pangolins move and utilise habitat within their home ranges and core areas.

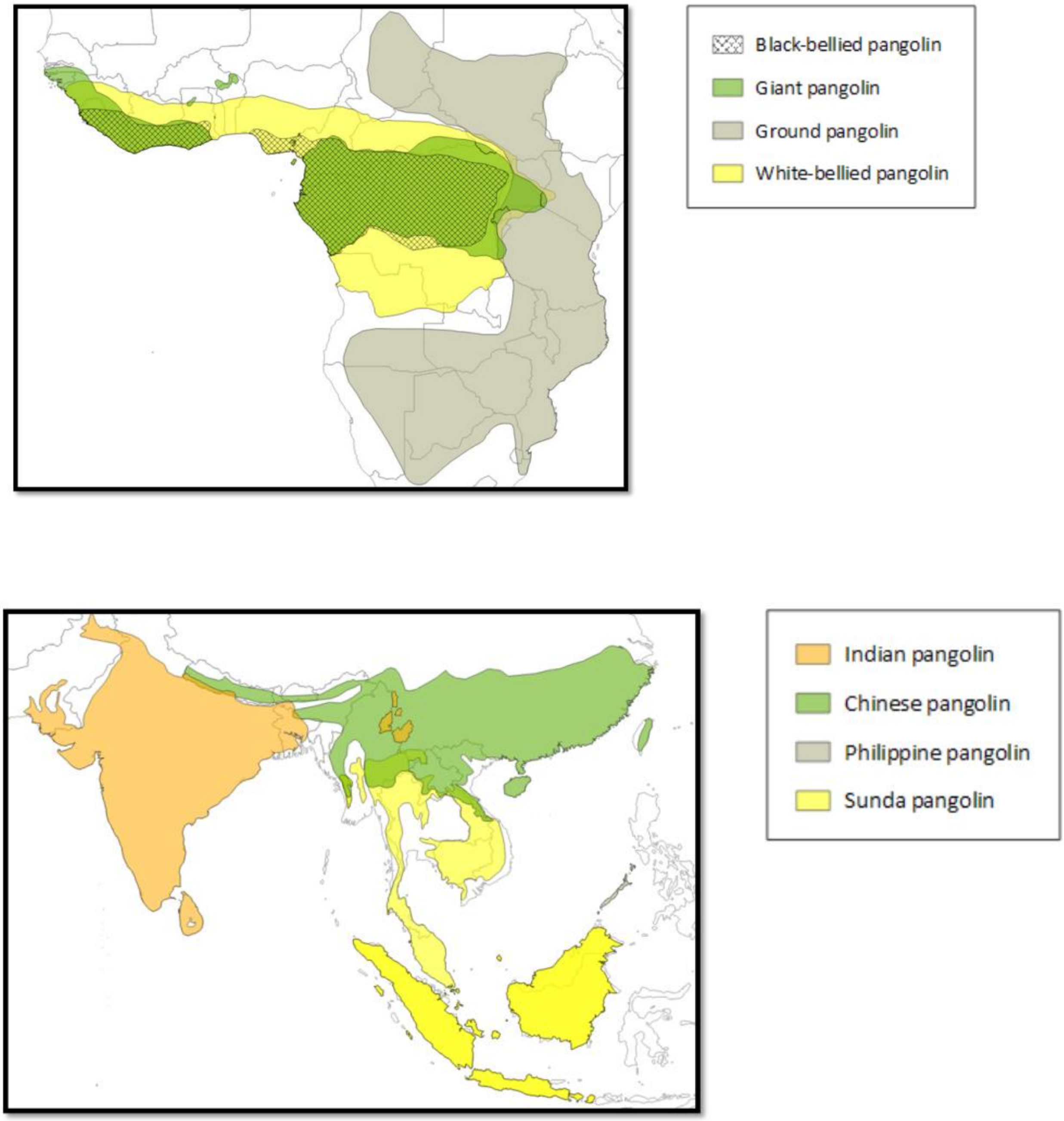


Figure 1.2 Map illustrating the ranges of all pangolin species in Africa (top) and Asia (bottom). Temminck's pangolin are shown on the top in grey. Adapted from the Scaling Up Pangolin Conservation, IUCN SSC Pangolin Specialist Group Conservation Action Plan (Challender, Waterman and Baillie, 2014).

1.2. Ecological, cultural and socio-economic value of pangolins

Some pangolin species, including the Chinese pangolin, are potentially thought to regulate ant and termite populations and contribute to habitat construction by digging burrows that other animals use (Chao et al., 2020). Prey are consumed at all stages of life despite heavy prey selectivity. In Taiwan, the Chinese pangolin consumes several species, including the yellow crazy ant (*Anoplolepis gracilipes*) which is invasive to the country (Chao et al., 2020). The regulation of social insects provided by pangolins likely influences local ecosystems by controlling insect abundance and distribution. Ants are vital as decomposers in ecosystems while termites play an important role by digesting cellulose, and although important these roles must be regulated (Chao et al., 2020). Additionally, if uncontrolled, ants and termites can become pests to humans through building and crop damage, therefore pangolins are an important aspect of ecosystem services and thus contribute to humans economically (Del Toro, Robbins and Pelini, 2012; Sileshi et al., 2005; Chao et al., 2020). It is estimated that one pangolin can consume several million insects each year. This ecological value is established for the Chinese pangolin, however, similar quantification is required for other pangolin species. Given the low abundance of all pangolin species further research is needed to evaluate their contribution to ecosystem services.

In addition to ecological values, most pangolin species are of high importance to local communities due to cultural, medicinal and spiritual beliefs (Boakye et al., 2014) and these cultural values are at risk if poaching and bushmeat hunting continue to cause severe population decline. Pangolins are a common bushmeat food source in many range countries. Many communities in Central Africa view them as a preferred bushmeat species (Boakye et al., 2016; Soewu et al., 2020). There are also several spiritual beliefs related to pangolins. In Central and East Africa, they are associated as icons of romantic attraction. Throughout much of eastern Africa, they are seen as symbols of an abundance of rain and food, signifying that they are generally a good omen (Walsh, 1995; Soewu et al., 2020). However, different communities hold varying beliefs. They are often considered to be revered and sightings are taken in a serious manner (Baiyewu et al., 2018). Some communities in Kenya and South Africa view them as good luck, while some view them as bad luck. Pangolins therefore hold numerous cultural values, and their decline would certainly have an impact on these communities. In terms of economic importance, pangolins may contribute to tourism income throughout their range countries (Di Minin and Hausmann, 2020). At least one tourist lodge in the Masai Mara National Reserve of Kenya, Sala's Camp, advertises the known presence of pangolins in the area to tourists (Steyn, 2015). Phinda Reserve in KwaZulu-Natal, South Africa offers tourists the opportunity to join a researcher in the field for a pangolin monitoring experience using telemetry tracking (AndBeyond, 2023). Di Minin and Hausmann (2020) found that there is a high interest in seeing pangolins amongst eco-tourists in southern Africa and that these tourists are willing to spend more money to see pangolins. This has the potential to bring more donations to eco-tourism projects and revenue to local communities that support pangolin conservation. However, not many pangolin-focused tourism projects exist so the development of these should be considered (Di Minin and Hausmann, 2020).

1.3. Population trends

Population of all eight pangolin species are currently declining due to anthropogenic threats. There are few population estimates for all pangolin species so it is difficult to assess declines quantitatively for individual species. All existing estimates are summarised below in section 1.3.1. Range distribution of each species can be seen in Figure 1.2. The lack of population estimates derive in part from a paucity of ecological knowledge necessary for designing appropriate monitoring methods. All species are naturally low-density, solitary, and elusive, making counting them difficult (Morin, et al, 2020). Pangolins are also habitat generalists (Morin et al., 2020), which can hinder our understanding of where they are and where to focus research. Additionally, resources in range countries are often limited and bureaucracy for research permits can be complicated (IUCN SSC Pangolin Specialist Group, 2018). Most monitoring has been conducted on observable species, such as the terrestrial Temminck's pangolin, but there is a need to improve research techniques so the less visible arboreal species can be monitored.

1.3.1. Species-specific population trends

Chinese pangolin: This species was once widespread throughout China and declined sharply, up to 94%, between 1960 – 1990. This species is present in Vietnam and Nepal and populations are presumed to have dramatically declined in both (Wu et al., 2004; Newton et al., 2008; Thapa, 2013; Wu et al., 2020). It also occurs in Hong Kong but there are currently no accurate population estimates. It is thought that this may be one of the only regions where this species is not in decline, however it is difficult to assess this without a population estimate. There is no data for any other range countries for this species (Table 1.1; Wu et al., 2020).

Indian pangolin: There is very limited abundance data for this species and no population estimates (Table 1.1). In Pakistan the species is estimated to have declined 79% between 2010 and 2012 (Irshad et al., 2015). There have been no assessments in India, Nepal or Bangladesh (Mahmood et al., 2020).

Sunda pangolin: Population estimates are lacking for most range states but are expected to be declining in most regions (Table 1.1). Myanmar and Thai populations are thought to be in decline due to illegal exportation to China and habitat loss (Anon, 1999; Nijman, Zhang and Shepherd, 2016). The species is considered extremely rare throughout much of its range in Southeast Asia, where there have been large declines of up to 99% (Duckworth, Salter and Khounboline, 1999; Chong et al., 2020). Lao PDR and Vietnam reported severe declines from 1990 – 2000. Malaysian populations are also thought to be declining (Chong et al., 2020).

Philippine pangolin: There is not much known about this species' population size and it inhabits a very small range in the Philippines. The species is very rare and evidence suggests it is in decline and located sporadically across its range (Schoppe et al., 2020). The species is not evenly spread across its range and has declined sharply since the 1960s, between 85 – 95% (Acosta and Schoppe, 2018; Palawan Council for Sustainable Development Staff, 2020; Table 1.1).

Black-bellied pangolin: To date, there have been no estimates of population size for this species (Table 1.1). This species is the least frequently reported which may reflect its low density (Kingdon and Hoffman, 2013; Gudehus et al., 2020).

White-bellied pangolin: This species is thought to be the most frequently seen pangolin species and occurs in high densities in suitable habitat, however there are no current population estimates at national or global levels (Table 1.1; Jansen et al., 2020). Most reports suggest the species is declining, however local hunters in the Volta Region of Ghana consider them common (Emieaboe et al., 2014). In Benin, Uganda, Guinea and Nigeria the species is thought to be declining (Bräutigam et al., 1994; Djagoun and Gaubert, 2009; Soewu and Adekanola, 2011; MTWA, 2018; Jansen et al., 2020).

Giant ground pangolin: Overall this species appears to be uncommon and rare, and there are predicted reductions in population sized based on camera trap data. There are no true population estimates for this species (Hoffmann et al., 2020; Table 1.1). There have been several camera trap studies on this species across a few range countries and their success has varied greatly but the overall capture rate indicates they are rare and in decline (Foley et al., 2014; Bruce et al., 2018; Khwaja at al., 2019).

Temminck's ground pangolin: Population estimates are lacking for most range countries apart from South Africa (Table 1.1). Populations of this species are thought to be declining across their wide range (Pietersen et al., 2016a; Pietersen et al., 2020) but this is challenging to assess due to the lack of research taking place outside of South Africa.

Table 1.1 Summary of the current population abundance and density estimates for each pangolin species (Wu et al., 2002; Akpona et al., 2008; National Forestry Administration, 2008; Pabsara et al., 2015; Pietersen et al., 2016a; Mahmood et al., 2018; Kao et al., 2019; Chong et al., 2020; Gudehus et al., 2020; Jansen et al., 2020; Mahmood et al., 2020; Pietersen et al., 2020; Schoppe et al., 2020; Wu et al., 2020).

Species	**Population and density estimates**	**Location**	**Date**
Chinese pangolin	64,000	China	1990
	50,000 – 100,000	China	2002
	0.043/km²	Guangxi, China	2008
	12 – 13/km² and 15,000	Taiwan	2019
Indian pangolin	0.00044 – 0.37/km²	Pakistan	2012 – 2018
	5.69/km²	Sri Lanka	2015
Sunda pangolin	1046	Singapore	2019
Philippine pangolin	2.5 – 4/km²	Philippines	2020
Black-bellied pangolin	0.015 – 0.26/km²	Cote d'Ivoire	2019
White-bellied pangolin	0.84/km²	Benin	2008
Giant pangolin			
Temminck's pangolin	0.23 – 0.31/km² and 16,000 – 24,000	South Africa	2016

1.4. Threats

As with many threatened species, all threats to pangolin populations are believed to be anthropogenic (Pietersen et al., 2014a). Temminck's pangolin face both domestic and international trade demands, which cause high levels of illegal poaching and trafficking. "Domestic demand" here refers to poaching for bushmeat and local medicinal practices within range states, while "international demand" describes export of pangolin or pangolin products to a non-range state. In addition to trafficking, this species is threatened by habitat loss, fence mortalities, and mortalities caused by road collisions (Pietersen et al., 2014a). Within South Africa, the combination of these threats has led to a predicted 30% decline in Temminck's pangolin populations over 3 generations, or approximately 27 years (Pietersen et al., 2016a).

1.4.1. Local demand, cultural beliefs, and drivers of consumption: African pangolin species

The use of animal products for medicinal purposes impacts numerous species. However, the difference between pangolins and other species is the large demand across local communities, in combination with demand for products exported in the illegal wildlife trade. This makes the extent of the problem unique to pangolins as a taxon because they are impacted both locally and internationally (Soewu et al., 2020; Pietersen et al., 2020). In many countries across Africa, pangolin products from all four species are extensively used in traditional African medicine practices, traditional ceremonies, and for bushmeat (Boakye et al., 2016; Soewu et al., 2020). Often pangolin meat is considered a delicacy (Wildlife Justice Commission, 2020a). They are popular due to their taste and are commonly sold at many restaurants throughout Nigeria, Botswana, Ghana, Sierra Leone, Zimbabwe and Mozambique (Soewu et al., 2020; Wildlife Justice Commission, 2020a). In West Africa, the white-bellied, black-bellied, and giant pangolin species are present and all have historically been consumed as bushmeat (Boakye et al., 2016; Bräutigam et al., 1994; Soewu and Ayodele, 2009). Central Africa is home to the same three pangolin species, which are all considered a preferred bushmeat source throughout the region.

In West Africa, traditional medicine is the most common form of healthcare and pangolin use is widespread for a variety of ailments including leprosy and mental illness (Soewu et al., 2020). Specific body parts of the pangolin are used to cure different diseases. Many spiritual beliefs (both positive and negative) surround pangolins in Central Africa, including relating to fertility (Soweu et al., 2020; Walsh, 2020). In East Africa, there has been little research into bushmeat consumption or medicinal use, but it has been recorded sporadically, primarily in Tanzania (Wright, 1954; Walsh, 2020). Throughout East Africa pangolins are referred to as "Mister Doctor", meaning they carry a spiritual and possibly medicinal use (Wright, 1954; Pietersen et al., 2020). Scales are thought to aid with pregnancy ailments and treating nose bleeds (Kingdon, 1974). Pangolins also hold numerous cultural beliefs, which can be positive or negative depending on the locale. In much of Tanzania, Temminck's pangolins are used as sacrifices to predict rainfall and pangolin products are often used as protection and good luck charms to ward off bad luck (Mbilinyi, 2014). Conversely, in south-western Tanzania, they can be seen as a sign of oncoming drought if the animal does not shed tears during ritual ceremonies (Walsh, 1995; Walsh, 2020). There has been almost no investigation into these threats in Kenya but as it borders Tanzania the uses of pangolin products and the beliefs behind this may be similar.

Temminck's pangolin is the only pangolin species in southern Africa, and has been reported as bushmeat in South Africa, Zimbabwe, Mozambique, and Botswana, but less so than in West and Central Africa. In South Africa, pangolins are commonly used for traditional medicine practices and are one of the most in-demand species in local commercial markets (Cunningham and Zondi, 1991). This is typically where scale and bone products can be purchased but they are not widely available. However, a study by Baiyewu et al (2018) found that only 55.5% of community members had knowledge of pangolin cultural or medicinal uses in South Africa. Pangolin products are regarded as highly effective medicine in Zimbabwe and are also found in medicinal markets in Namibia and Mozambique. Many different body parts are prescribed by practitioners, each for different ailments. In addition to medicinal beliefs, there are many spiritual beliefs around this species (Soewu et al., 2020). For example, in South Africa and Zimbabwe, pangolins are often associated with good omens and seen as valuable gifts for chiefs. In much of South Africa, they are also seen as indicators for rainfall and if a pangolin is killed it is believed a drought will occur. However, the AmaZulu tribe believes the opposite, i.e., if a pangolin is seen, a drought will ensue unless the animal is killed (Kyle, 2000). Contradictory beliefs are also seen in Mozambique, where pangolin sightings can be regarded either as a sign of abundance or famine, depending on the ethnic group. There are many rituals surrounding pangolins to bring good luck, ward off evil, or for cleansing (Soewu et al., 2020).

Current local trade rates indicate an increasing demand for African pangolin products, which will impact Temminck's pangolin populations (Pietersen et al., 2016a). Local hunting was once considered sustainable but this is no longer the case. For example, the KwaZulu-Natal Province of

South Africa has undergone depletion of most populations such that pangolins are now locally extinct in some areas (Pietersen et al., 2016a). Local demand is challenging to manage because cultural beliefs are often ingrained into community practices, making them difficult to change.

1.4.2. International wildlife trade: all pangolin species

For centuries pangolin products (primarily scales) from the Asian species, have been harvested throughout Asian range countries for traditional medicine practices, food sources, and decorative ornaments. This has been known to occur in every range country for the four Asian pangolin species and is particularly prevalent for traditional Chinese medicine (Xing et al., 2020). Much of the illegal trade is facilitated by corruption throughout both pangolin range states and consumer states, which can include organised crime and law enforcement (van Uhm and Moreto, 2018; Wildlife Justice Commission, 2020a). An estimated 1 million pangolins have been removed from the wild in the last decade, with 206.4 tonnes of scales confiscated from 52 seizures between 2016 – 2019 and two-thirds of these in 2018 – 2019 (Challender et al., 2014a; Baiyewu et al., 2018; Wildlife Justice Commission, 2020b). One kilogram of pangolin scales can vary from $52 – 739 (~£42 – 606; Wildlife Justice Commission, 2020b). An estimated 895,000 pangolins and their derivatives were trafficked between 2000 and 2019, based on 1474 seizures (Pantel and Anak, 2010; Challender et al., 2020a). It is likely that the majority of pangolin products are not intercepted and thus the actual number is much higher. In general, seized wildlife products represent a small proportion of actual numbers of animals poached (Eliason, 2003).

Pangolin products are used for a wide variety of reasons that differ between regions in Asia. In South Asia, pangolins are commonly consumed for subsistence and the scales from the Indian and Chinese pangolins are used for medicinal purposes (Acosta-Lagrada, 2012; Mohapatra et al., 2015; Perera et al., 2017; Xing et al., 2020). Scale products are worn by women to alleviate reproductive issues, treat haemorrhoids, and prevent pneumonia. In much of Nepal the scales are used to protect babies from diseases, however in some regions of the country scales are used to as a symbol of good luck (Soewu and Adekanola, 2011; Aisher, 2016). In Southeast Asia, which includes Chinese, Philippine, and Sunda pangolin ranges, pangolins are primarily hunted for meat, and some communities in Sumatra and Java believe this meat can heal skin conditions (Anon, 1999). The commercial value of pangolins is so high that pangolins are often sold into the illegal trade rather than consumed by the hunter thus there has been a reduction in subsistence consumption. Pangolin meat is often the most expensive meat in high-end restaurants (Challender et al., 2015; Xing et al., 2020). In terms of cultural medicinal beliefs, which does not include evidence-based medicine, in Southeast Asia they are used to treat digestive problems, encourage blood circulation, treat ulcers and skin rashes, to improve lactation in women, and to protect from disease such as prostate illnesses (Xing et al., 2020). In East Asia only the Chinese pangolin is present. Meat consumption here has been documented for over one thousand years and the meat is considered a "tonic" to prevent diseases and remove toxins from the body. Traditional Chinese medicinal use of pangolins was first recorded around 500 CE in an ancient Chinese herb book and pangolin scales were used to improve ant bite reactions. In later centuries, scales were used to cure malaria, promote lactation, reduce blood clots, and improve circulation (Xing et al., 2020) and have also been used to treat many gynaecological issues. Across all regions, scales and meat are consumed in a variety of ways including as pangolin wine, or scales ground down, boiled, or sun-dried (Xing et al., 2020).

All Asian pangolin species are in steady decline due to Chinese medicinal practices (Xing et al., 2020). This continued domestic demand has depleted pangolin populations in Asia and has led to all Asian pangolin species being classified as Endangered or Critically Endangered by the IUCN Red List. Additionally, up until the early 2000s the United States was the biggest importer of Asian pangolin scales and leather which were commonly used for fashion accessories due to the unique appearance of the leather (Heinrich et al., 2016). The high demand for pangolin products from Asia has remained despite the decline in Asian pangolin populations. The need for a new source to meet this demand has caused a knock-on effect which has resulted in an increase in trafficking of African pangolin species (Figure 1.3). These species are now poached and are exported to Asia, which is a practice that has increased steadily over recent years (Pietersen et al., 2016a). Prior to 2008, no African species had been recorded as trafficked to Asia but this is no longer the case, with all four now found in the illegal trade to varying degrees (Heinrich et al., 2016). An estimated 585,000 African pangolins were trafficked between 2016 – 2019 (Challender et al., 2020a). From May – August 2017, there were six seizures of African pangolins in Malaysia, weighing 6695 kg (Krishnasamy and Shepherd, 2017). These involved at least seven export and transit countries including Kenya. The total importation into Malaysia since 2014 is estimated to be 8000 kg of African pangolin scales

(Krishnasamy and Shepherd, 2017). This exploitation has begun to impact Temminck's pangolin, although it is considered the least trafficked of all pangolin species, having not been recorded in the trafficking trade until approximately 15 years ago. The TRAFFIC wildlife trade database reports only 35 incidents of Temminck's seizures between 2008 – 2022, with 32 individual pangolins and numerous scales seized (TRAFFIC International, 2023). However, between 2008 – 2019 there was an increase reported in Temminck's pangolin poached for international exportation (Challender and Hywood, 2012; Shepherd et al., 2017), with at least 144 individuals seized although the actual number is likely much higher as a high proportion are not intercepted (Challender et al., 2020a; Pietersen et al., 2020).

There has been little recorded international exploitation of pangolins from South Africa, rather the poaching is almost entirely for local use (Pietersen et al., 2020). TRAFFIC has records of 24 incidents in South Africa, 23 which have taken place since 2018 (TRAFFIC International, 2023). The primary exporters within Africa appear to be Nigeria, the Democratic Republic of Congo, and Cameroon (Wildlife Justice Commission, 2020b). In Kenya, the main threat to pangolin populations is thought to be the illegal wildlife trade (Kenya Wildlife Service, 2016). As the Asian species have been depleted, increasing numbers of pangolins have been poached from the wild in Kenya and exported, with the first incidents reported to TRAFFIC in 2011 (TRAFFIC International, 2023). From 2014 – 2015, just one case of pangolin trafficking was seized at Jomo Kenyatta International Airport in Nairobi, while from 2021 – 2022 more than 20 cases of pangolin trafficking were seized (Africanews, 2023). Kenya ranks 7th highest of all African countries involved in the illegal trade of pangolin scales, with 1,398 kg of scales intercepted from 2015 – 2018 (Environmental Investigation Agency [EIA], 2020). Kenya is a known exportation hub for pangolins, likely both for locally poached pangolins and for those being trafficked from Cameroon, the Democratic Republic of Congo, Senegal and Central West African Republic (EIA, 2020). This trade is appears to be increasing but the extent to which exported pangolins originate from Kenya versus transiting from other countries via Kenya is currently unknown (Soewu et al., 2020).

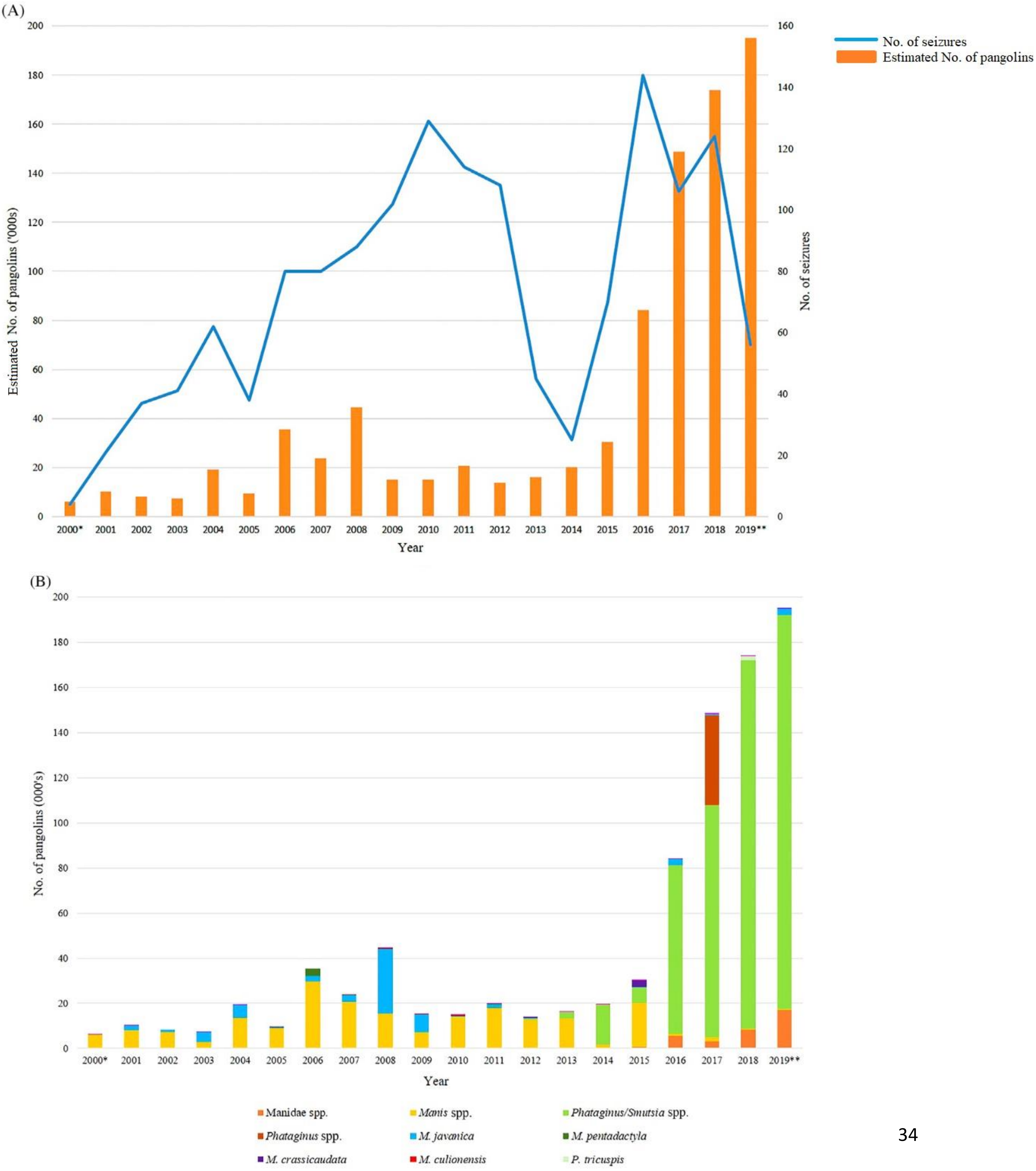


Figure 1.3 Figure adapted from Challender et al., 2020a. (A) Estimated number of pangolins illegally traded and number of seizures between August 2000 and July 2019. (B) Estimated number of pangolins illegally traded between August 2000 and July 2019 by species, genera, or presented as Manidae spp., inferred from available seizures data. (A and B) Source: open source and pangolin range state government data. Trade volumes based on seizures and illegal trade records. For full methods see Challender, Harrop and MacMillan (2015). Orange bars=estimated no. of pangolins; blue line=no. of seizures. *Seizures from August-December 2000 only. **Seizures from January July 2019 only.

1.4.3. Habitat loss: Temminck's pangolin

Temminck's pangolins are known to utilise a variety of habitats but they are notably absent from commercial and crop agricultural land, likely due to human disturbance (Pietersen et al., 2020). As human presence increases so do agricultural practices and land development, which can lead to extensive habitat fragmentation. Additionally, increased human presence likely leads to areas with higher levels of poaching due to close proximity of pangolins and people. Matrix habitats caused by fragmentation are unlikely to be suitable to pangolins if there is a high level of human activity and disturbance in the area (Pietersen et al., 2020). Edge habitats may be more suitable, depending on the availability of prey and shelter resources, however any proximity to human activity or agriculture will reduce the suitability of these areas for pangolins (Pietersen et al., 2020). Loss of pangolin habitat is likely to be widespread across Africa, however this is understudied and without a full understanding of pangolin habitat requirements it is difficult to determine how this will impact pangolin distribution and populations. Temminck's pangolins in Kenya are believed to have experienced habitat loss in recent decades due to forest clearance for logging (Kirui, 2022). Their historic range once extended to the eastern coastal regions and higher north but due to human expansion these habitats have decreased (C. Okell, personal communication, 2022). Currently Temminck's pangolins are only thought to inhabit less than 50% of Kenya, with much of this predicted range being throughout fragmented habitat (C Okell, personal communication, 2022). This range loss has also occurred in some provinces of South Africa as human settlements have expanded. Research is needed to understand pangolin distribution at the patch and landscape scale so that we can fully evaluate how habitat loss is impacting this species and prioritise conservation of areas containing suitable habitat. It is also suspected that Temminck's pangolins are susceptible to pesticide poisoning in agricultural areas (Bräutigam et al., 1994; Baiyewu et al., 2018). This thesis will evaluate and discuss the environmental and anthropogenic characteristics that impact Temminck's pangolin distribution at different spatial scales within their range in Kenya.

1.4.4. Fences mortalities: Temminck's pangolin

Fences are known to impact a variety of species globally by halting dispersion as they are a linear, and often impermeable barrier, that reduce the availability of movement corridors and increase habitat fragmentation (Gregory et al., 2021). Additionally, fences are known to cause mortalities by direct physical entanglement and electrocution (Beck, 2009). Pangolins in South Africa (Temminck's) are considered to be severely impacted by mortalities on fences, due to electrocution on electric fences, and general entanglement on wires. Temminck's pangolins are bipedal and thus their underbelly is exposed as they walk. This, in combination with their poor eyesight, makes it easy for them to accidentally walk into fences (Pietersen et al., 2014a). Many fences feature a low-level electrified tripwire, which delivers a shock to their exposed abdomen. Since pangolins curl into a ball as a defence mechanism they can inadvertently curl around the wire and get shocked continuously, often resulting in severe injury or death. This threat is thought to primarily impact pangolins in South Africa where fences are most prevalent (Pietersen et al., 2014a). Pietersen et al (2014a) estimated 19,033 km of electric fencing across pangolin range in South Africa. The true extent of this threat is not known but electric fences are estimated to be the largest threat to pangolins in South Africa currently, with 1 individual electrocuted per 11 km of fence per year (Beck, 2009; Pietersen et al., 2014a). This threat is not limited to electric fences, if a pangolin walks into a non-electrified fence their scales can become caught on the wiring and they become entangled and unable to free themselves. Little is known about the fence characteristics that cause most mortalities and their prevalence. To accurately assess this threat, it will be necessary to investigate the issue further to inform targeted mitigation. There are currently no effective methods for reducing this threat on a widescale, although practices such as raising trip-wire height have been considered (Pietersen et al., 2014a). This thesis will explore this further and quantify pangolin electrocutions in Chapter 5.

1.4.5. Road mortalities: Temminck's pangolin

Road mortalities are an additional understudied threat that impacts Temminck's pangolin. This threat has not been widely reported and incidents are often sporadically recorded. Pietersen et al (2014a) recorded four mortalities on the same road in five years in South Africa. With 8056 km of road predicted across the species' range in South Africa this extrapolates to a potential 280 deaths per year. This may appear to be minor, but may be significant when scaled up across range states. It would be beneficial to assess the size of the threat posed by roads by examining their extent throughout pangolin range. Additionally, roads may impact territoriality by limiting ranging behaviour. They may also cause a high-level noise disturbance during construction and their subsequent use (Gaughran et al., 2021). Roads are often impermeable barriers that can cause habitat fragmentation and disrupt movement within home ranges (Peaden et al., 2017; Gregory et al., 2021). This can mean corridors are lost and species movement is restricted (Gregory et al., 2021). No studies have focussed on this threat to date. This thesis evaluates the likelihood and magnitude of roads as a threat to pangolins in Kenya.

1.5. Conservation status

In recent years, pangolins have become conservation icons due to their vulnerability to overexploitation (Harrop, 2020). Pangolins are threatened on national and international levels that have now become cross-border problems. Therefore, it is vital to implement regulations in individual countries and throughout entire regions. However, recently regulation schemes are slowing and seemingly unable to keep up with the threats that pangolins face (Harrop, 2013; Harrop, 2020). There are two main organisations involved in international pangolin protection, CITES and the Convention on Biological Diversity (CBD, 2023). Both organisations legislate to preserve species and biodiversity, and when a state becomes a signatory it agrees to implement these regulations within its own borders (Harrop, 2020).

The CBD provides suggested acts for states to follow their regulations, but these are not pangolin-specific and are non-binding (Harrop, 2020). CITES focuses on limiting the international wildlife trade and legislation features two appendices, Appendix I which prohibits all trade of a species except in exceptional circumstances (e.g., research) and Appendix II, which allows regulated trade. Temminck's pangolin was added to CITES Appendix I in 1975, with the Chinese and Sunda species on Appendix II, and subsequently all pangolin species were added to CITES Appendix II in 1995, including Temminck's which was downlisted. In 2016, all pangolin species were then moved to CITES Appendix I (CITES, 2023). At the time of inclusion, there was even less known about African pangolin population levels however it was deemed they were at risk due to the decline of the Asian species (Zain and Oldfield, 2017). This was celebrated as a major success of the 17th meeting of the Conference of the Parties to CITES (CoP17; Zain and Oldfield, 2017). Almost all pangolin range states are members of CITES (Harrop, 2020). Each member country is required to implement adequate regulations to protect pangolins. Since pangolin trafficking is considered a global issue, CITES requires all members, not solely range states, to have effective law enforcement (Harrop, 2020).

Appendix I requires permits for any legal international trade with a zero quota for all Asian pangolin species and no commercial trade permitted (Shepherd et al., 2017). However, there are no quotas for the African species and trade is permitted if it follows national laws and CITES requirements (Shepherd et al., 2017). Currently the great majority of their trade is due to illegal trafficking rather than legal CITES-permitted trade (Challender et al., 2020b).

The CITES database lists a total of 44 legal Temminck's pangolin trade incidences between 1985 and 2021, which involved at least 223 in the form of carcasses, specimen, skeletons or live individuals. Additionally, one carving, 1.539 kg of scales, 17 whole scales, and 2 skin pieces were also reported (Table 1.2). The majority of exports were reported by South Africa (38.6%), followed by the US (13.6%) and UK (11.4%). Almost no reports listed the origin of the pangolin products (CITES Trade Database, 2023). Between 1980 – 1992, the majority of CITES declarations included 152 live pangolins exported from Togo to the USA, primarily for zoo use (Bräutigam et al., 1994).

Table 1.2 Summary of legal Temminck's pangolin trade from the CITES database. This includes the purpose of the trade and the origin of the specimen (CITES Trade Database, 2023).

Purpose/use	**Percentage**	**Specimen origin**	**Percentage**
Scientific	48.8	Wild	61.9
Personal collections	19.5	Pre-CITES specimen	14.3
Commercial	9.8	Confiscated	9.5
Education	9.8	Unknown	9.5
Zoo	4.9	Ranched	2.4
Law enforcement	4.9	Captive bred	2.4
Medicinal uses	2.3		

All pangolin species have been added to the International Union for Conservation of Nature (IUCN) Red List, with Temminck's listed with a Vulnerable status due to their predicted population decline of 30 – 40% over a 45-year period (Pietersen, Jansen and Connelly, 2019; Table 1.3).

Table 1.3 IUCN Red List status of each pangolin species (Challender, O'Neill and Willis, 2019b).

Pangolin Species	IUCN Red List Status
Chinese pangolin	Critically endangered
Sunda pangolin	Critically endangered
Philippine pangolin	Critically endangered
Indian pangolin	Endangered
White-bellied pangolin	Endangered
Giant pangolin	Endangered
Black-bellied pangolin	Vulnerable
Temminck's pangolin	Vulnerable

Legal protection and the effectiveness of such legislation for pangolins varies across Africa (Wildlife Justice Commission, 2020b). Some countries have now implemented protection requirements for Temminck's pangolins (Harrop, 2020), including Kenya and South Africa. Within Kenya, they are protected under the Third Schedule of the Kenyan Wildlife Conservation and Management Act of 2013 (Kenya Gazette Supplement, 2013). This prohibits all hunting and trade of pangolins and ensures perpetrators will pay heavy fines or face long imprisonments (Kaii et al., 2015). This species is also listed as Vulnerable on the South African Red List of Mammals, meaning it is of local conservation concern (Pietersen et al., 2016a). Many range countries in Africa do limit wildlife hunting, often with severe fines or imprisonment, however few focus this specifically on pangolins. Penalties in South Africa for poaching pangolins can be up to $760,000 USD (~£620,000) and/or imprisonment (Harrop, 2020). Additionally, there is provincial legislation in several South African provinces (Baiyewu et al., 2018; Table 1.4). In Zimbabwe, pangolins are protected under the Zimbabwe Parks and Wildlife Act, Chapter 20 (Duri, 2017). A person guilty of a pangolin-related offence is given a mandatory nine-year jail sentence for the first offence and 11 years for any subsequent offence (APWG, 2023).

Table 1.4 Provincial legislation regarding pangolin protection status in South Africa. Adapted from African Pangolin Working Group (Baiyewu et al., 2018; APWG, 2023).

Region/Province	Legislation
South Africa	Threatened or Protected (ToPs) Species under the National Environmental Management: Biodiversity Act of 2004
Western Cape	Endangered Wild Animals (Schedule 1) of Western Cape Nature Conservation Laws, Amendment Act 3 of 2000
North West Province	Protected Game (Schedule 2) Section 15 (1) (a) of Transvaal Nature Conservation Ordinance 12 of 1983
Mpumalanga	Protected Game (Schedule 2) Section 4 (1) (b) of Mpumalanga Nature Conservation Act 10 of 1998
Northern Cape	Specially Protected Schedule 1 of Northern Cape Nature Conservation Act 9 of 2009
Limpopo	Specially Protected Wild Animals (Schedule 2) of Limpopo Environmental Management Act 7 of 2003
Gauteng	Protected Game (Schedule 2) Section 15 (1) (a) of Nature Conservation Ordinance 12 of 1983
Free State	Schedule 1 Protected Game (section 2) in Nature Conservation Ordinance 8 of 1969
KwaZulu-Natal	Specially Protected Game (Schedule 3) in Nature Conservation Ordinance 15 of 1974
Eastern Cape	Endangered Wild Animals (Schedule 1) of Cape Nature and Environmental Conservation Ordinance 19 of 1974

1.6. Potential conservation strategies

1.6.1. Reducing poaching demand

The consensus among experts is that the primary way to reduce the illegal pangolin trade is to limit the demand for pangolin products (Challender et al., 2014b). If demand decreases, so will the value of the scales and correspondingly, poaching. Many national parks and reserves implement anti-poaching security, but this is often focused on elephant (*Africana loxodonta*) and rhino species (*Rhinocerotidae spp*.). This also includes general efforts to reduce bush meat hunting by deterring people from entering protected or private areas. Since pangolins are low-density and not regularly observed it is not feasible to use specific anti-poaching teams to protect them. Awareness of the lack of true medicinal effectiveness is key to limiting this demand however there are many challenges along with this, as beliefs are often deeply rooted into culture (Burgess et al., 2020). Before this can be tested, the mentality behind the use of pangolin products needs to be fully understood, as well as who uses these products (Burgess et al., 2020). For example, in Asia, educating the users on alternative medicines may aid in reducing the demand but social research is needed to determine which alternatives would be accepted by users (Broad and Burgess, 2016; Burgess et al., 2020). Several actors and public figures have spoken out about pangolin conservation in an effort to improve education amongst their followers ('t Sas-Rolfes and Challender, 2020). However, simply giving facts to the public may not be the most effective action and hands-on approach may be more appropriate. The use of “participatory action” may be a valuable technique in enhancing local knowledge of pangolin conservation value (Rowe et al., 2013; Skinner et al., 2020). This approach relies on stakeholder engagement, collaboration and discussion to engage local communities, rather than utilising a research perspective. Community members are encouraged to converse with each other rather than people they view as outsiders. This supports local implementation of wildlife protection while also fighting corruption. This has been utilised successfully in the past for elephant (*Loxodonta Africana*) anti-poaching initiatives and may be effective for pangolins (Rowe et al., 2013; Skinner et al., 2020). The IUCN SSC Human-Wildlife Conflict and Coexistence Specialist Group also recommends community involvement as an approach (IUCN, 2023) and states the importance of engaging the general public when planning such action. There is no standard method for undertaking this and each situation needs to be evaluated carefully prior (IUCN, 2023). This sort of approach has commonly been used for large carnivores, including The Lion Guards in Namibia and the Long Shields Lion Guardians in Zimbabwe (Namibian Lion Trust, 2023; WildCRU, 2023). Both programmes involve local people to work as lion ambassadors and reduce conflict within the community by protecting both the lions and community members. The programmes actively protect livestock from predators and subsequently, lions from persecution. They also collect ecological and behaviour data on the lions (Namibian Lion Trust, 2023; WildCRU, 2023). This form of community participation and appreciation of wildlife may be invaluable for future pangolin conservation methods.

1.6.2. Farming

As the demand for pangolin products continues there has been consideration for other methods to meet this demand whilst reducing illegal hunting. With other threatened species, including white rhinoceros (*Ceratotherium simun*; “rhino”), the suggestion of farming has been raised (Kagande and

Musarurwa, 2014; Challender et al., 2019a). This suggestion comes from a need to reduce hunting of wild populations by meeting consumer demand in another way ('t Sas-Rolfes and Challender, 2020). In the case of rhino, horns can be regularly harvested as they grow throughout the animal's life (Kagande and Musarurwa, 2014), whereas pangolins scales are extremely slow growing so this is less feasible (E. de Jager, personal communication, 2022). Legal constraints in most countries do not allow for the farming of pangolins currently, and even if legal in the future this practice would be challenging to manage on a large scale ('t Sas-Rolfes and Challender, 2020). A major barrier to this is the inability to breed pangolins in captivity and on a commercial scale (Challender et al., 2019a). Additionally, they are highly susceptible to stress in captivity and there is a lack of understanding around their dietary requirements. This means that considerations for farms are not likely to keep the animals alive. Challender et al (2019a) considered 17 conditions which should be met to indicate that farming would successfully reduce illegal hunting and pangolin species met only 4 – 6 of these. The study determined that farming would not displace the demand for wild pangolin products and there is unlikely to be successful conservation implications.

1.6.3. Rescue and rehabilitation

Since pangolins are protected throughout most range states, there are regular seizures of pangolin products and live animals from the illegal trade. Additionally pangolins are also retrieved from entanglement or electrocutions on fences (Beck, 2009; Pietersen et al., 2014a; Wright and Jimerson, 2020). These are the two most common causes for pangolin admission to rescue and rehabilitation centres in South Africa. Temminck's pangolins are sensitive to stress and are often recovered when dehydrated and emaciated, thus rehabilitation is needed. There are several designated pangolin rehabilitation centres in South Africa but it is not uncommon for conservationists in remote areas to undertake the rehabilitation process (Wright and Jimerson, 2020). Initial stabilisation of each animal is the most important step, and a full veterinary assessment is required, although diagnostic tools for pangolins are currently limited. Husbandry for pangolins has notoriously been difficult. Despite being kept in captivity over the last 150 years, the majority do not survive past the first six months (Chin and Tsao, 2015; Zhang et al., 2017; Wicker, Lourens and Hai, 2020). There is a lack of knowledge of their nutritional and husbandry requirements and the rehabilitation process has proven to be a learning curve amongst conservationists (Clark, Nguyen and Phuong, 2009; Hua et al., 2015; Perera et al., 2017; Wicker et al., 2020). Temminck's pangolins in captivity are known to require temperatures of 18 – 35 °C and a humidity of approximately 59% (Zhang et al., 2017; Wicker et al., 2020). These pangolins will not feed in captivity so must be fed via tube or walked outside to feed naturally each day. Once the pangolin has recovered from injury and is a healthy weight, the release process can begin (Wright and Jimerson, 2020). Soft release is preferable to reduce stress and involves a slow introduction of the pangolin to a new environment while being carefully observed. As it is often difficult to know where a pangolin originated from, a new release site is chosen based on suitable habitat, however pangolins do not always take well to new environments and occasionally need to be recalled for further rehabilitation. This emphasises the importance of researching and understanding pangolin ecological needs and habitat selection so that suitable release sites can be chosen. Once released, radio/GPS telemetry is typically used to monitor each pangolin for a year period. This process has been conducted since the early 2000s and numerous pangolins have been successfully released in South Africa via this process (Wright and Jimerson, 2020). However, the impact of these releases on population size is unknown.

1.6.4. Monitoring methods

Developing successful and effective monitoring methods is a main objective when it comes to pangolin research and conservation, identified by the IUCN SSC Pangolin Specialist Group (Challender et al., 2014b). There is an urgent need to fill baseline information gaps that will aid in future conservation efforts, such as accurate population estimates, distribution, and the impact of threats. All of these can be aided by effective population monitoring methods. Few methods have been consistently tested but these include social research amongst community members, and camera trapping studies (Matthews et al., 2022). Burrow counts, citizen science, telemetry tracking, and detection dogs, have also been utilised and may be applicable to numerous pangolin species (IUCN SSC Pangolin Specialist Group, 2018). Other methods such as non-invasive genetic sampling, acoustic monitoring, and eDNA have not been widely tested but are thought to have potential applications for all pangolin species. Further testing of these methods with strategic scientific protocols are needed to establish if any are viable monitoring solutions (IUCN SSC Pangolin Specialist Group, 2018). From this, it will hopefully be possible to estimate population, density, occupancy, and distribution. Effective monitoring methods will also improve our ability to collect and understand ecological data for pangolins such as, habitat suitability prediction to identify future release sites (Challender et al., 2014b).

Citizen science is a proposed monitoring method that has the potential to be effective for all pangolin species, including Temminck's pangolin (IUCN SSC Pangolin Specialist Group, 2018). This is a method of data collection for research that involves members of the public, including experts, the general public, students and various stakeholders, that may have an interest in a research topic (Santori et al., 2021). Participants may be used to report sightings along with ecological and behavioural data. Over the last two decades, new forms of citizen participation have been developed and refined in many scientific fields, making it a very common practice (Bonney et al., 2016). This increase in use is primarily due to its ease of implementation, generally inexpensive cost, and the high amount of data it can produce (Zhang, 2019; Henckel et al., 2020). Citizen science can be used to monitor a species' distribution based on sighting reports, which can then inform on habitat use and behavioural ecology. For rare species, such as pangolins, citizen science can provide contextual ecological information that is not possible to gather otherwise, as reports can come from those who witness pangolins occasionally in the wild. Citizen science has not been widely used to study pangolin species however this method is becoming increasingly common. For example, Sompud et al (2023) utilised informal surveys to evaluate the distribution of Sunda pangolins in Malaysian Borneo.

Citizen science data can also be used to create predictive species distribution (SDM) and habitat suitability models (HSM). SDMs and HSMs evaluate species presence points with environmental variables to predict distribution and habitat use (Henckel et al., 2020). This form of modelling can provide valuable insights into pangolin spatial ecology, habitat use, and threats, which may otherwise be difficult to collect data on. Pietersen et al (2021) combined citizen science database records with field data and literature searches to generate a species distribution model for Temminck's pangolin in South Africa. Citizen science data for this modelling can either be collected opportunistically or systematically (Henckel et al., 2020), and can include presence/absence or presence-only data. This thesis employed citizen science data in Kenya to assess Temminck's pangolin predicted distribution and habitat suitability in Chapter 4.

1.6.5. Reducing fence mortalities

Modifying fences with the aim of reducing electrocutions and entanglements would likely be an effective way to limit this threat. By investigating which fence types cause the most mortalities and their extent it will be easier to plan mitigation accordingly. There have been suggestions of raising low-level trip wires, creating physical rock barriers in front of low wires, and alternating when power is on/off between night and day (Pietersen et al., 2014a). These suggestions may prove useful in the future once we can prioritise which fences to modify, however this would need to be done on a large-scale to see a noticeable reduction in mortalities. Additionally, any modification would need to be affordable so that landowners are incentivised to implement them. These solutions may reduce the level of electrocutions that occur however they would not necessarily reduce general entanglements on fences, which is likely also a source of mortalities. Future research should focus on the mechanisms that cause mortalities and then aim to design pangolin-friendly fencing that reduces overall mortalities. This thesis presents to use of an online citizen science questionnaire to evaluate fences as a threat to pangolins and assess the effectiveness of current mitigation methods in South Africa in Chapter 5.

1.7. Research aims and thesis outline

The considerable anthropogenic threats that pangolins face are believed to have led to sharp population declines throughout their range. This is further exacerbated by the large knowledge gaps relating to their ecology and overall biology. Despite sometimes being considered an iconic species, there is a lack of awareness of their existence which hinders conservation efforts because they do not receive as much attention or research focus as other species. An understanding of their general ecology is necessary for successful threat mitigation. This thesis aims to investigate Temminck's pangolin habitat use and distribution, and quantify specific anthropogenic threats (namely, fence mortality) to inform future conservation action in alignment with the IUCN SSC Pangolin Specialist Group Action Plan.

This thesis is divided into five subsequent chapters. Chapter two describes the general methods used for data collection, and chapters three to five present the findings of the research. Chapter six discusses the collective findings and their implications for conservation action, along with recommendations for future research priorities.

The aims of this thesis were:

1) To examine the drivers of Temminck's pangolins burrow use within their home range and explore the burrow characteristics that affect this (Chapter 3). Chapter Three utilised telemetry tracking and camera traps to establish pangolin burrow presence and determine the microhabitat variables that influence burrow use and distribution of pangolins in the Masai Mara National Reserve, Kenya.

2) To determine the wider-scale habitat and climate variables that influence Temminck's pangolin distribution throughout Kenya (Chapter 4) by generating habitat suitability and risk models. Chapter Four employed citizen science reports of pangolin sightings in Narok County to predict habitat suitability distribution for pangolins in relation to environmental variables and anthropogenic risk. Remotely sensed anthropogenic risks were modelled with pangolin distribution and habitat suitability to assess the main threats to pangolins in this region.

3) To utilise citizen science to investigate the threat posed to Temminck's pangolins by electrocution on electric fences in South Africa (Chapter 5). Chapter Five employed a quantitative questionnaire to assess fences as an overall threat to pangolins and other wildlife. This aimed to investigate which fence types cause mortalities, how widespread these fences are, if perimeter-area-ratio influences mortalities, and determine where pangolins are most at risk of fence mortality.

Chapter 2 - General Methodology

This chapter summarises the general methods and site details used for this research. Specific methods and data analyses for each research section are outlined in subsequent chapters. Chapter 3 investigated pangolin use of aardvark burrows and which characteristics affect this, to enhance our understanding of habitat use in Kenya. Chapter 4 utilised citizen science data to explore the availability of suitable habitat for pangolins and examine how habitat characteristics influence their distribution. This chapter also evaluated how habitat suitability relates to anthropogenic threats in Kenya. In Chapter 5, this thesis investigated fences as a threat to Temminck's pangolin (hereafter termed "pangolin") by employing a questionnaire to determine which fence types cause mortalities, and how widespread they are in South Africa.

2.1. Study sites

2.1.1. Kenya (Chapters 3 and 4)

Temminck's pangolins range stretches from eastern to southern Africa, across a variety of countries and habitats. Within Kenya, they are found throughout most southern, western, and eastern regions (Figure 2.1; Pietersen et al., 2020). They are absent from the northeastern regions. Their historic range was once widespread to the northern and coastal regions; however, habitat loss and bush meat poaching have reduced their range (C. Okell, personal communication, 2022). Their true distribution is not known, nor is their population size within the country. No studies have been conducted to estimate population size or distribution within Kenya and most records are opportunistic (Pietersen et al., 2020).

Within Kenya, the research primarily took place in the Masai Mara National Reserve (MMNR; Chapter 3; Figure 2.1), and a wider area of Narok County in the Rift Valley region of Kenya with a small subset of data collected in West Pokot County (Chapter 4; Figure 2.2). The MMNR is a state-owned reserve located on the border with Tanzania (Birdlife International, 2023). The wider ecosystem, known as the Masai Mara Ecosystem, is approximately 6500 km² (Ojwang, 2015) and is linked with the northern Serengeti ecosystem with about 5560 km² of land. 1500 km² of this is the MMNR (-1.593574, 35.134277) and the remainder is comprised of community conservation areas and conservancies just outside of MMNR (Protected Planet, 2018). The land to the north, east and west is now pastoralist and agricultural schemes, which are increasing in density (Dublin, 1996; Ghosh, Arvind and Dobbie, 2019). The Mara ecosystem was chosen as the primary study site for data collection because there is a known presence and suspected high population density of pangolins in this area. However, the true population size was unknown at the time of data collection for this study. Pangolins were known to be consistently sighted within MMNR and the surrounding conservancies by local communities, guides, and tourists. Pangolins in this region feed on ant and termite species, and water is primarily consumed through feeding (Pietersen et al., 2020) so they do not rely on the Mara River as a water source. As these conditions are entirely natural this population may be representative of wild pangolins in East African habitat.

MMNR was established in 1961 and was only ~520 km^2 at the time. It has expanded over the years to cover 1500 km^2 and in 1974 it received National Reserve designation, and it is now one of the main tourist attractions in Kenya (Masai Mara, 2023). Since its establishment a portion of the land has been returned to the surrounding Masai communities, which are now known as conservancies (Masai Mara, 2023). These areas are outside of the national reserve and are managed by local communities to benefit both wildlife and the local people. These conservancies are assisted by the Maasai Mara Wildlife Conservancies Association and aim to improve the overall local ecosystem while boosting tourism. There are 12 conservancies in the Mara area, each with their own regulations (Masai Mara, 2023).

A small subset of data was collected in West Pokot opportunistically (Figure 2.2), as there is also known pangolin presence here but little research has focused on this region (C.Okell, personal communication, 2022). West Pokot County is located on Kenya's western border with Uganda (1.671258, 35.234725) and is approximately 9169 km^2. It is within the Rift Valley and is primarily agricultural and livestock land (Westpokot, 2023). The northern regions of the county are low-altitude dry plains and the southeastern area encompasses Cherangai Hills, with an altitude of 3370 m (Westpokot, 2023).

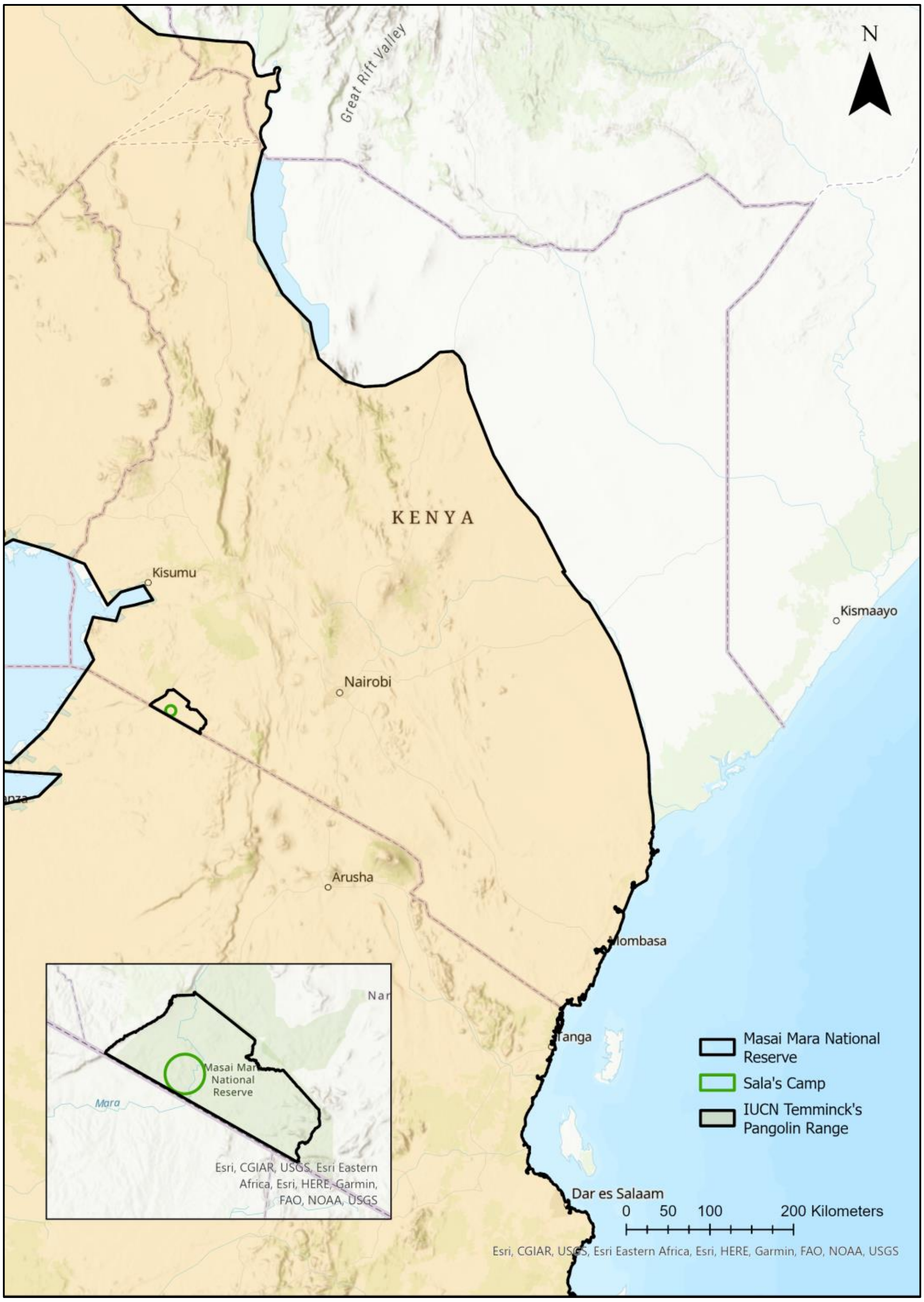


Figure 2.1 Map of Kenya showing the study site for Chapter 3. The site area, Sala's Camp, is shown in a green circle. The inset map shows an enlarged study area for Sala's Camp. The map shows Temminck's pangolin range in Kenya as predicted by the IUCN (Pietersen, Jansen and Connelly, 2019). Masai Mara National Reserve is shown in black (United Nations Environment Programme - World Conservation Monitoring Centre [UNEP-WCMC and IUCN], 2022).

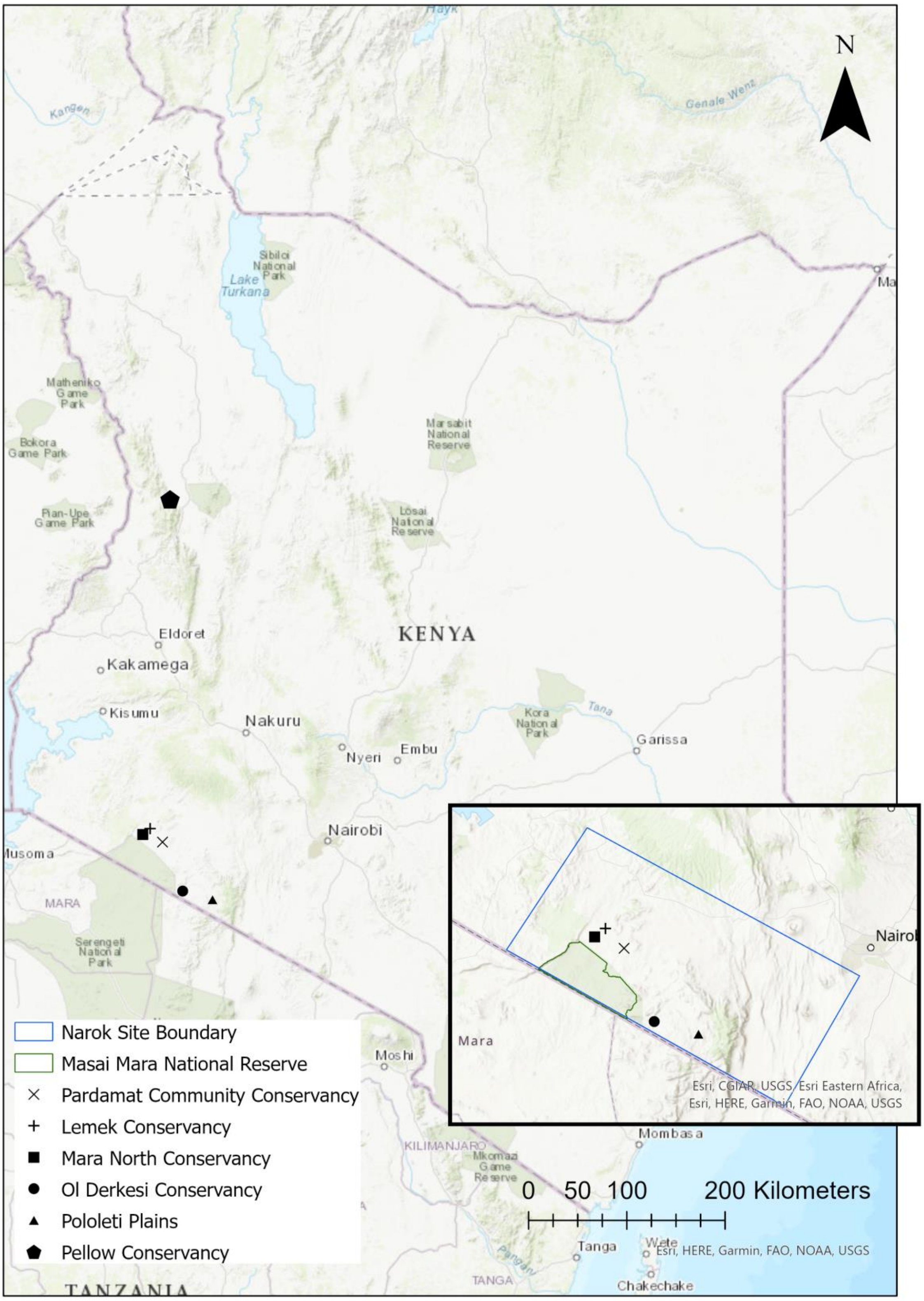


Figure 2.2 Map of Kenya showing the six community study sites for Chapter 4. The inset map shows an enlarged area within Narok County which is the Narok County study site. Masai Mara National Reserve is shown in green (UNEP-WCMC and IUCN, 2022).

2.1.1.1. Region and climate of Kenya

Kenya is located in eastern Africa on the horn of Africa. The equator runs through Kenya thus temperatures are relatively stable throughout the year with annual mean temperature of 15.5 °C – 25.5 °C throughout the country (Fick and Hijmans, 2017; Figure 2.3), and a range of 14.8 °C – 28.1 °C in the Mara ecosystem (Dublin, 1996). Mean annual rainfall across the country ranges from 155 – 1997 mm per year (Fick and Hijmans, 2017; Figure 2.4). The country has two wet seasons, between March and May, and November to December, whilst there are two dry seasons, in June to October and January to March (Ottichilo, 2000). Annual rainfall is between 600 – 1000 mm and over 80% of this occurs in the wet seasons. The primary threats to wildlife throughout Kenya are habitat loss, human-wildlife conflict, and poaching, which have led to a decline in many species over recent years (Kiringe and Okello, 2007; ZSL, 2023).

The Masai Mara altitude ranges from 1500 – 1900 m above sea level (Birdlife International, 2023). The climate within the reserve varies between semi-arid and sub-humid (Ottichilo, 2000). The highest amount of rainfall occurs in the western regions of the reserve and the lowest are easternly (Lamprey and Reid, 2004). The habitat types here predominantly consist of savannah, grassland, and scrubland, with sporadic riparian areas including along the Mara River, although the primary habitat is considered to be open grassland (Ghosh et al., 2019). The Mara River is the largest perennial river in the Mara ecosystem (Dublin, 1996). Soils are considered highly fertile as they are derived from volcanic ash, and they are able to maintain the widespread grasslands that support a range of grazing wildlife (Ottichilo, 2000). As well as pangolins, this ecosystem is famous for the biodiversity it supports and the high density of species there (Green et al., 2019), including a variety of antelope species, rhinoceroses (*Diceros bicornis*, *Ceratotherium simum*), giraffes (*Giraffa camelopardalis tippelskirchi*), lions (*Panthera leo*), leopards (*Panthera pardus pardus*), elephants (*Loxodonta africana*), and numerous other species (Ghosh et al., 2019). There are few fences or boundaries within the Mara ecosystem apart from a fence around MMNR and local fences around pastoral land, thus wildlife can move freely for the most part.

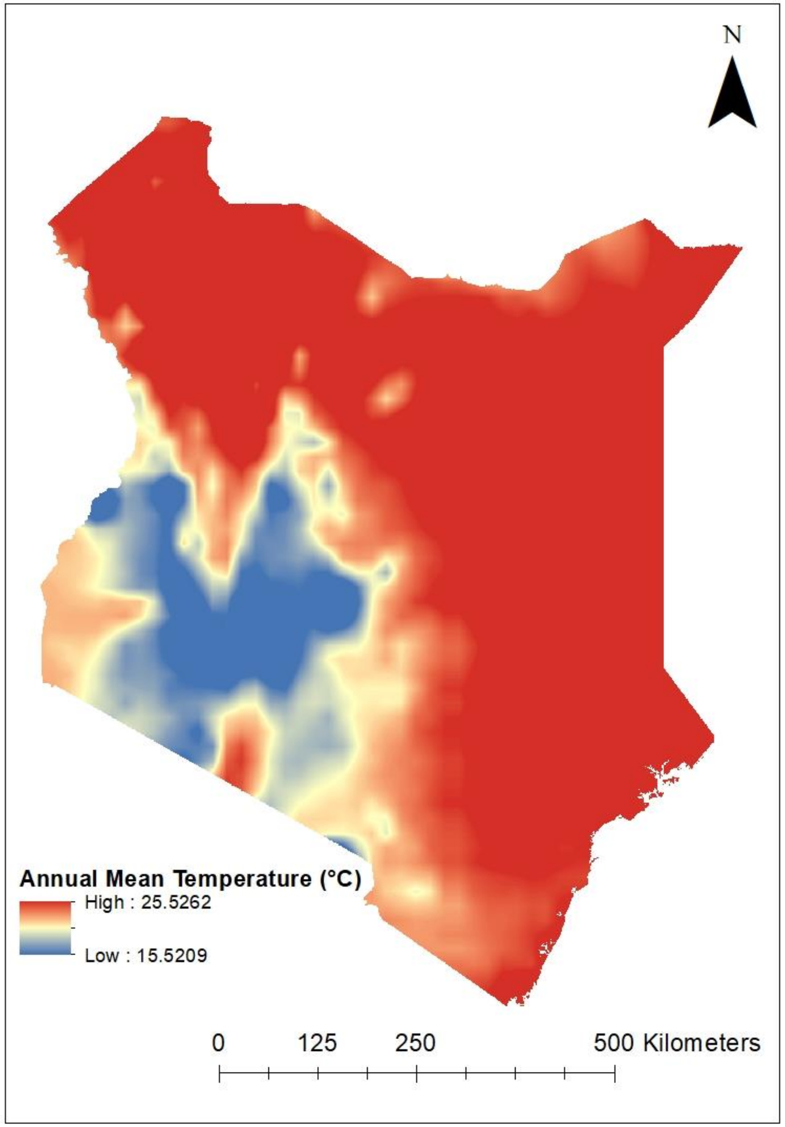


Figure 2.3 Annual mean temperature within Kenya (°C) from BioClim data (Fick and Hijmans, 2017).

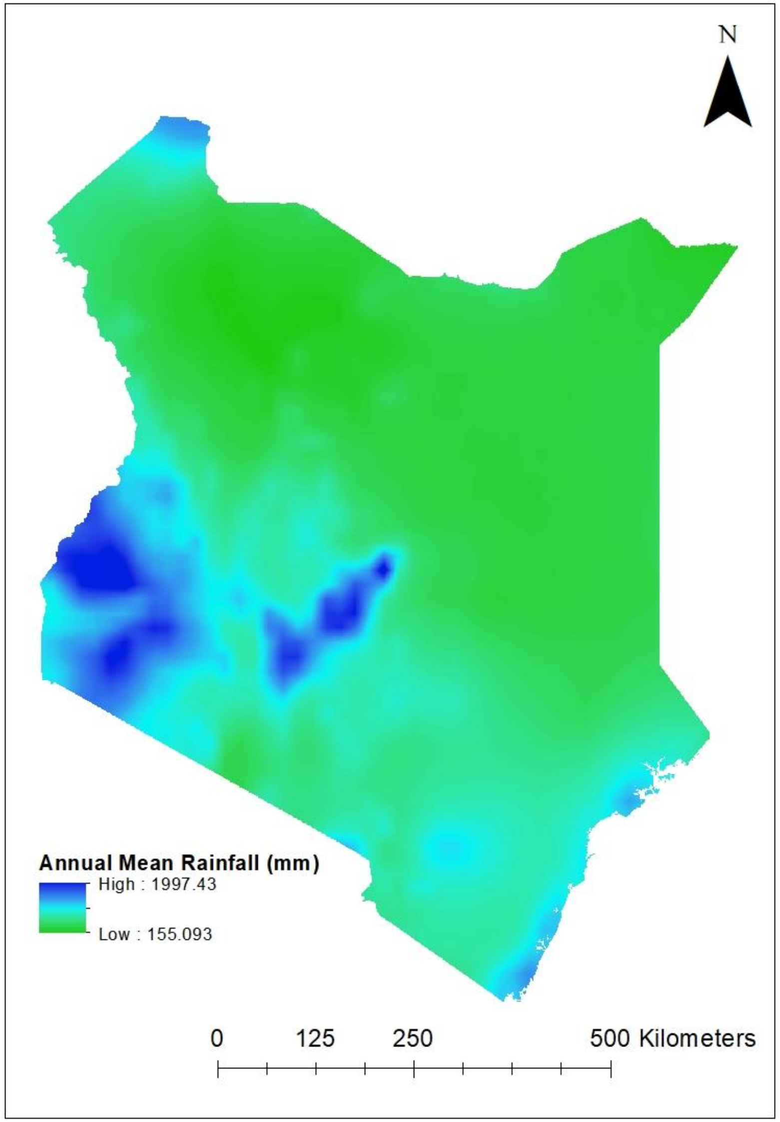


Figure 2.4 Annual mean rainfall within Kenya (mm) from BioClim data (Fick and Hijmans, 2017).

2.1.1.2. Site: Sala's Camp (Chapter 3)

Pangolin burrow use (Chapter 3) was studied in Sala's Camp (-1.599905, 35.131882) within the Masai Mara National Reserve. The Masai Mara is government owned, and Sala's Camp is a privately owned tourism lodge where the research team was based. The immediate surrounding reserve area was the study area. This site is an approximately 16 km² area located in the southern region of MMNR, directly on the border of Tanzania and is situated along the Sand River (Figures 2.1 and 2.2). The river acts as a natural barrier that may limit some wildlife from moving into Tanzania. This habitat here is entirely open grassland with interspersed riparian habitat along the river. This site was selected due to the known presence of pangolins in the immediate vicinity which were reported by guides and lodge staff to PP.

2.1.1.3. Site: Narok and West Pokot communities (Chapter 4)

For Chapter 4, pangolin habitat suitability and risk modelling were studied in Narok County, throughout five local communities across 5600 km² in the Narok County. All communities bordered MMNR and were: Lemek Conservancy (-1.162033, 35.182599), Mara North Conservancy (-1.229395, 35.119892), Pardamat Conservation Area (-1.292469, 35.250489), Pololeti Plains (-1.798277, 35.595282), and Ol Derkesi Conservancy (-1.731305, 35.417577; Figure 2.2). These communities are located within protected areas and habitat consisted of savannah, grassland, agricultural, and rural settlements. This study area was selected due to the known presence of pangolins throughout Narok County. A sixth community, Pellow Conservancy (1.834826, 35.364868) in West Pokot, was the only community involved in this study outside of Narok County.

Each of these communities are located within protected areas for wildlife conservation and are managed by the local community. They aim to establish wildlife subsistence and provide income for local people via tourism safaris so that both benefit from this arrangement (Masai Mara, 2023). Within Narok, in the northern regions above MMNR three communities were involved in this study. Lemek Conservancy was the northern most community involved in the study and is located near the northern boundary of MMNR. It is 77 km^2 and consists of 480 community members (Mara Conservancies, 2023). To the southwest of Lemek Conservancy is Mara North Conservancy. It is approximately 730 km^2 and is owned by 768 Maasai landowners (Mara North, 2023). To the east, just outside of MMNR, is Pardamat Conservation Area. It is approximately 260 km^2 and has 850 landowners (Mara Conservancies, 2023).

Directly to the east of MMNR near the border with Tanzania is Ol Derkesi Conservancy, this land is 80 km^2 and is managed differently to the aforementioned conservancies (CWCT, 2023). While the other conservancies are managed by local community members, Ol Derkesi is owned by a community of Maasai people who lease the conservancy for conservation purposes to Cottas Wildlife Conservation Trust (CWCT), and it is managed by CWCT and the Ol Derkesi Wildlife Community Trust (CWCT, 2023). Pololeti Plains is a pastoral community further east of MMNR and does not have any specific conservancy land. In West Pokot, Pellow Community Conservancy is located between the Ugandan border and Turkana County border in Kenya. It is a community managed conservancy and has approximately 29,184 residents (Pellow Community Conservancy, 2023).

2.1.2. South Africa (Chapter 5)

Chapter 5 of this thesis was an online questionnaire that targeted participants throughout the pangolin's range, with a specific focus on South Africa. Within South Africa, pangolin range is primarily in the northern provinces (Figure 2.8) including, the Northern Cape, North West Province, Limpopo, Mpumalanga, and KwaZulu-Natal, although they are locally extinct in most of KwaZulu-Natal (Pietersen et al., 2020). South Africa was targeted due to the widespread extent of fences presumed in the country as a result of high levels of land management. South Africa has a widely varied climate and a range of habitats, including Succulent karoo, Nama karoo, Kalahari Desert, Albany thicket, forests, mopane shrub, and semi-arid savannah (Department of Agriculture, Fisheries and Forestry [DAFF], 2015; Figure 2.5). Annual mean rainfall and temperature vary between the western provinces like the Northern Cape, with 50 – 400 mm per year and a temperature range of 4 – 37 °C (SA Venues, 2023), and the more eastern provinces such as Mpumalanga, with up to 1000 mm of rain per year and a 3 – 26 °C temperature range (SouthAfrica.com, 2023; Figures 2.6 and 2.7).

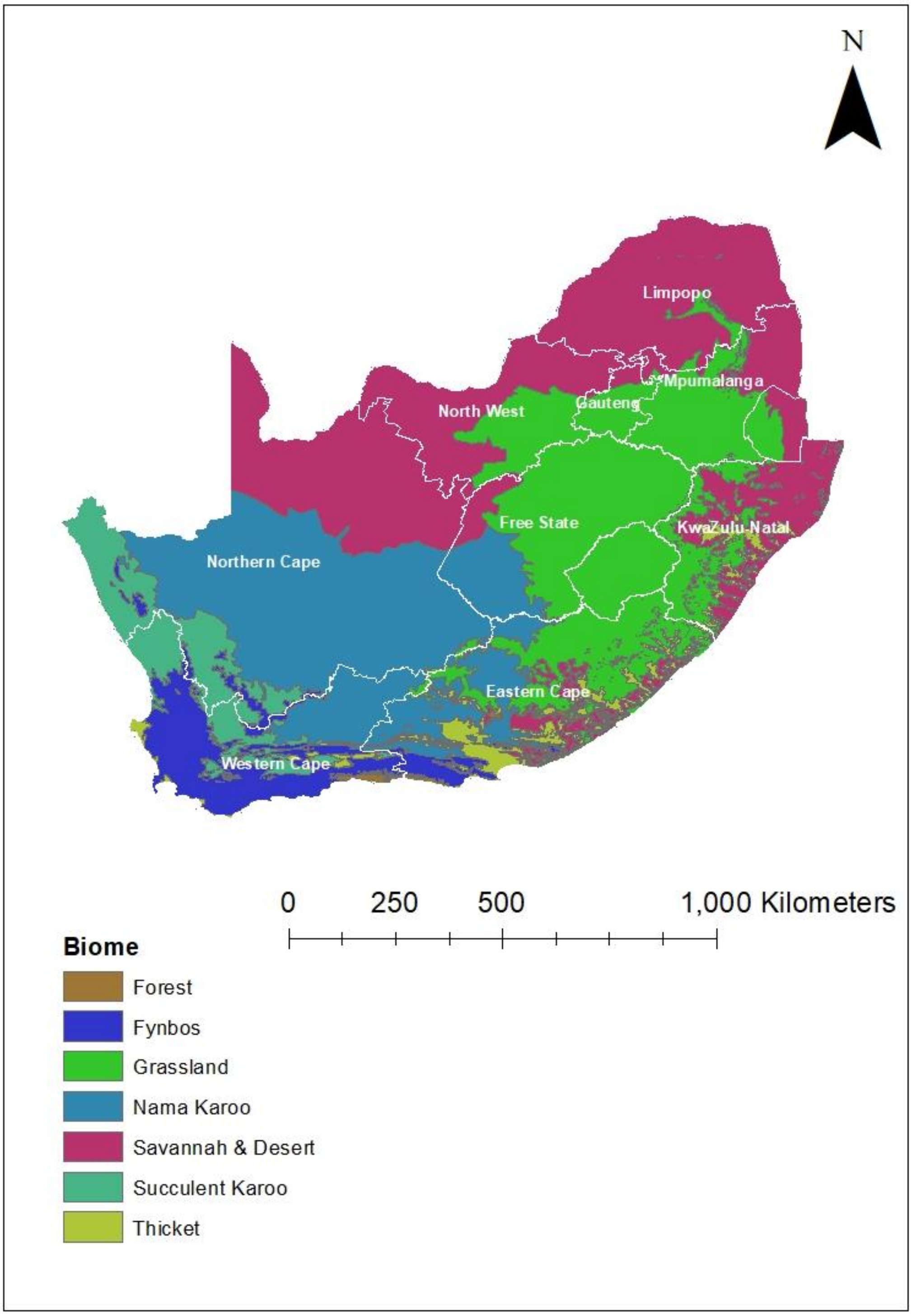


Figure 2.5 Biome distribution within South Africa. Provincial boundaries and labels are shown in white (South African Environmental Observation Network [SAEON], 2011). Biome data from DAFF (2015).

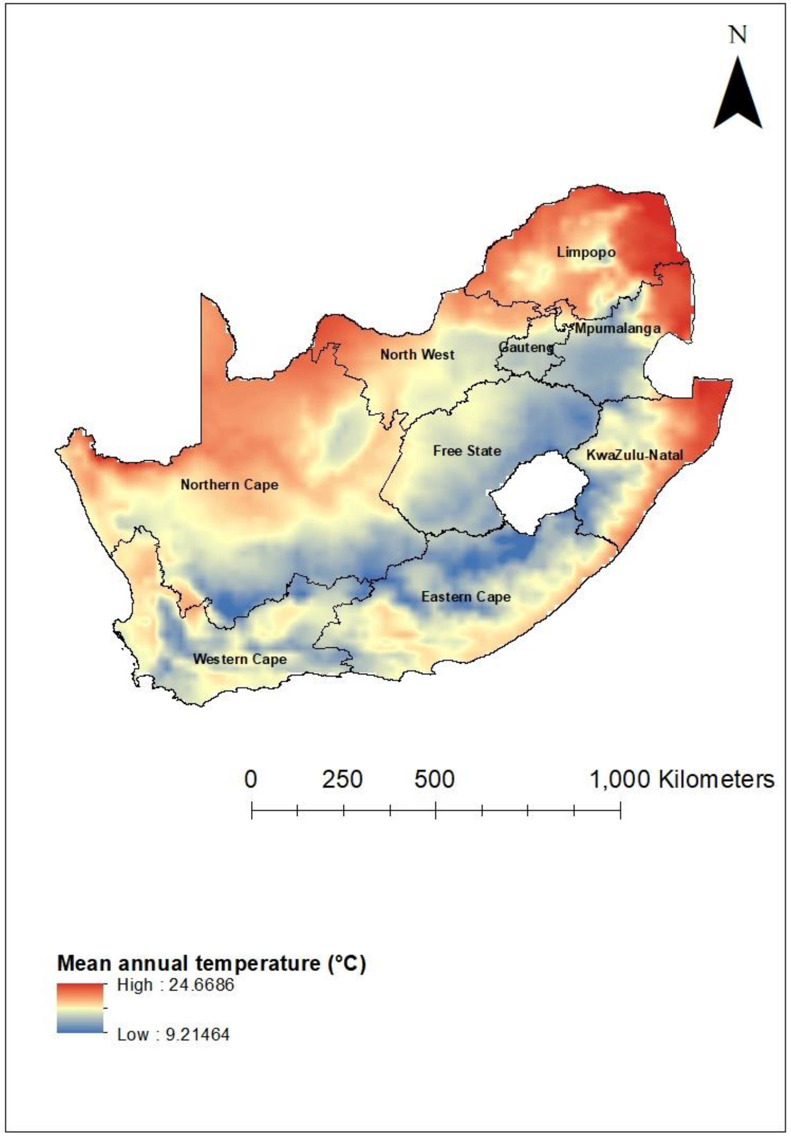


Figure 2.6 Annual mean temperature in South Africa. Data from Bioclim (Fick and Hijmans, 2017). Provinces of South Africa shown (SAEON, 2011).

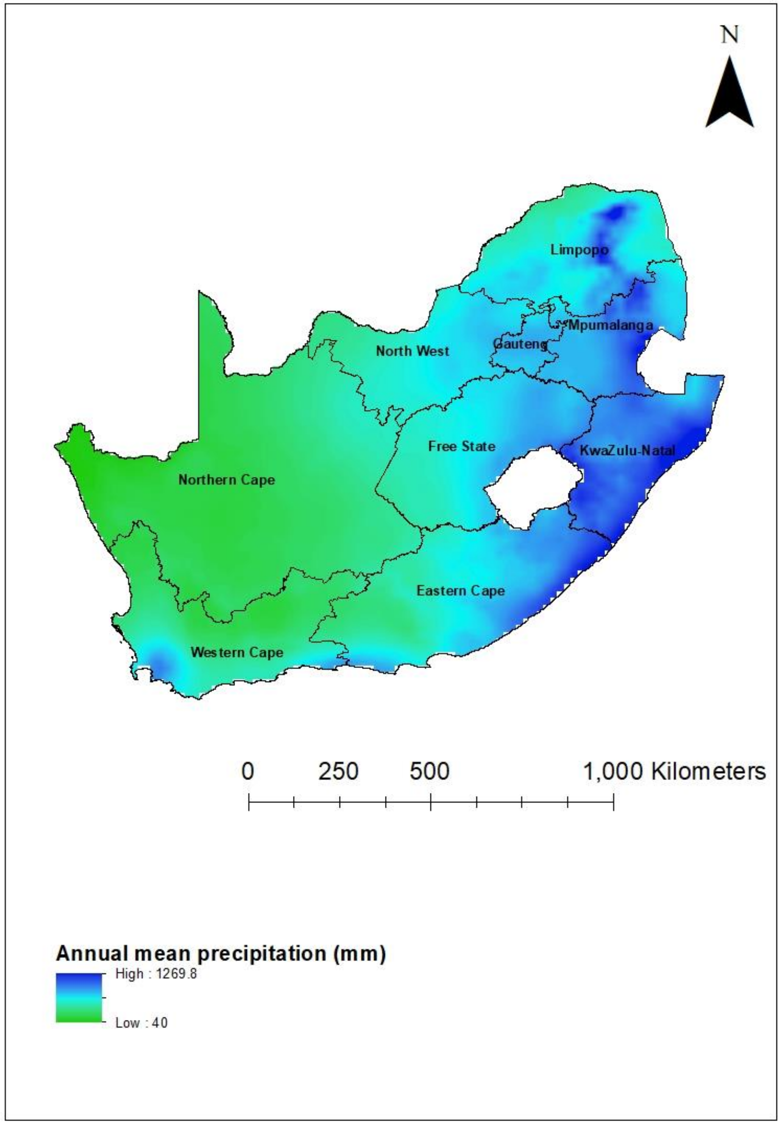


Figure 2.7 Annual mean rainfall South Africa. Data from Bioclim (Fick and Hijmans, 2017). Provinces of South Africa shown (SAEON, 2011).

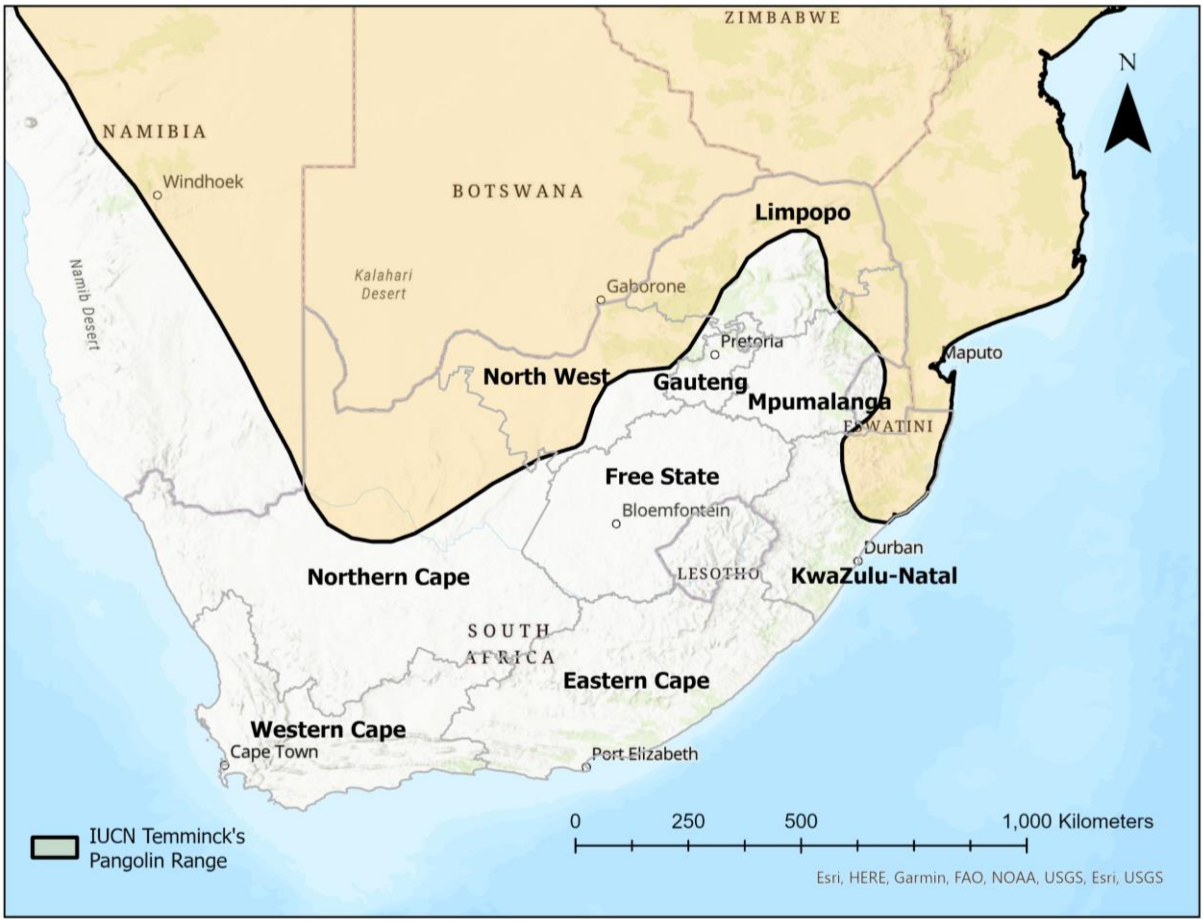


Figure 2.8 Map of Temminck's pangolin range in South Africa as predicted by the IUCN (Pietersen, Jansen and Connelly, 2019). Provinces of South Africa shown with grey boarders and black labels (SAEON, 2011).

2.2. Collaboration

The Kenya-based research was in collaboration with The Pangolin Project, a Kenyan non-profit organisation. The Pangolin Project collected pangolin ecology data in MMNR between 2019 – 2022. Data for Chapters 3 and 4 were collected by The Pangolin Project. Author contribution statements are located on page 13.

2.3. Ethics and permissions

Kenya: Ethical approval was obtained through the University of Brighton Research and Ethics Committee (Reference number: 2022-9600-Stracquadanio). A Memorandum of Understanding was generated between Leandra Stracquadanio, University of Brighton, and The Pangolin Project, to ensure fair data sharing and usage (Appendix 1).

South Africa: This research received approval from the University of Brighton Tier 1 Ethics Review Process on 19 May 2021 (2021-8212-Stracquadanio). All data were anonymised and stored according to European GDPR regulations on the university OneDrive system. These protocols also address and cover South Africa's Protection of Personal Information Act (POPIA) data protection regulations. All responses were stored within the University of Brighton OneDrive and each response was coded with a random number, with all identifying information, such as name and contact information, removed.

2.4. Data collection and analyses

2.4.1. Kenya: Pangolin Project data (Chapters 3 and 4)

The Pangolin Project collected several datasets in the Mara ecosystem over a three-year period (Figure 2.9). These datasets were utilised in Chapters 3 and 4 to answer research questions on pangolin habitat use, distribution, and threats.

2.4.1.1. Chapter 3: Burrow use and characteristics sampling

- Maps of burrow locations within Sala's Camp

To investigate burrow density and characteristics within the Sala's camp site, the research team generated a total count of all aardvark burrows within a 16 km² area in 2019. This was done by using a map of the study site and overlaying 1 km parallel transect lines, spaced approximately 20 m apart. These were walked by The Pangolin Project Team over the course of ten weeks. This took place in the dry season when grass was short and burrows were easily visible. All burrows within eyeline (10 m) of either side of the transect line were recorded. Burrow characteristics, including aspect, termite mound presence, entrance size, and soil grain size were also collected when each burrow was recorded. The full details of these methods are available in Chapter 3.

- Burrow use data in Sala's Camp

Over the three-year data collection period (2019 – 2022) the total burrow count map at Sala's Camp was used to monitor pangolin burrow utilisation. This was done by utilising satellite and very high frequency (VHF) data, as well as camera trap data. Three pangolins were satellite and VHF tracked almost daily to their current burrow and this burrow use was recorded. The Pangolin Project placed camera traps outside of randomly selected burrows from the burrow list, and also targeted burrows known to be used by pangolins. This generated data on the duration of use, how often burrows changed, and recorded pangolins sharing burrows with other species. Throughout the study, if a new burrow without previously recorded characteristics was found then this was noted and characteristics were collected. The full details of these methods are available in Chapter 3.

- Satellite telemetry data

Both satellite and VHF tags were attached using the same protocol as Pietersen et al (2014b) and Sun et al (2019). Pangolin morphology means traditional collars are not practical thus tags are attached directly to the dorsal scales. This is done by drilling two small holes into the non-vascularised section of one of the scales and attaching the tag to these holes using bolts and epoxy resin. This is the standardised and commonly used method for attaching tags to pangolins. It is a relatively quick and non-invasive procedure that ensures the welfare of the animal and requires no veterinary care.

Three female pangolins were tagged with satellite tags and tracked for three months each. These pangolins were found opportunistically by The Pangolin Project team during a previous study. Data was collected between 2019 – 2020 and was recorded remotely via the satellite tag system. Tags were set to collect each pangolin's location (fixes) once a day, on average. The pangolins were given a unique identification code: FM001, FM002, and FM003. FM indicated the sex of the pangolin and the subsequent number indicated the order in which individuals were tagged. Tracking periods did not overlap for any of the individuals, with FM001 tracked from August to November 2019; FM002 from January to April 2020; and FM003 tracked from April to June 2020. Satellite tracking was limited to three months each due to battery life constraints. This data contributed to establishing burrow use by pangolins.

- VHF tracking data

The same three pangolins were also fitted with VHF tags and were tracked almost daily between 2020 – 2022. VHF tag battery life lasts much longer than satellite tags thus this was done to supplement the satellite tag data and preserve satellite tag battery by minimising the number of fixes that were collected. Additionally, once the satellite tag batteries ran out it was still possible to manually track each pangolin. The research team used an aerial antenna to locate the VHF signal and track the live location of each pangolin. A GPS location was taken when the pangolin was located. Data such as behaviour and burrow use were noted during this research.

2.4.2. Citizen Science

Citizen Science was used in both Chapters 4 and 5 by collecting local ecological knowledge reports. These chapters involved survey/questionnaire reporting systems to record pangolin sightings, and wildlife fence mortalities, respectively.

2.4.2.1. Chapter 4: Citizen science pangolin reports

Citizen science reports were utilised to analyse pangolin distribution and habitat use. Between 2020 – 2022, The Pangolin Project collected citizen science sightings of pangolins in Narok and West Pokot County using a survey. The Pangolin Project team, along with local volunteers known as "Pangolin Ambassadors", visited each of the five communities in Narok County for a minimum of 3 – 5 times per month, and recorded all reported sightings from members of the public and their corresponding locations. West Pokot was visited opportunistically throughout the study. Historic sightings were also collected, as was the behaviour of the pangolin when possible. The data recorder noted the location of each survey therefore survey effort was also collected. The full details of these methods are available in Chapter 4.

2.4.2.2. Chapter 5: Online questionnaire sampling

This study aimed to assess the types of fencing and the extent of fencing within pangolin range, and determine how often mortalities occur on these fences. In 2021, an online questionnaire built using the Jisc Online Surveys (2020) platform was distributed to landowners and managers across Temminck's pangolin range in Africa. This was developed and distributed by the PhD candidate. This study focused on pangolins but as many species are known to be killed on fences, data on all species was collected. Participants were asked to record each species they witnessed killed on a communal map using Canvis.app (McGill, 2020). All questions were voluntary because fences are a main proponent of security therefore this data was considered potentially sensitive. As an incentive to participate, a prize draw was offered to participants. Further details are in the Methods section of Chapter 5.

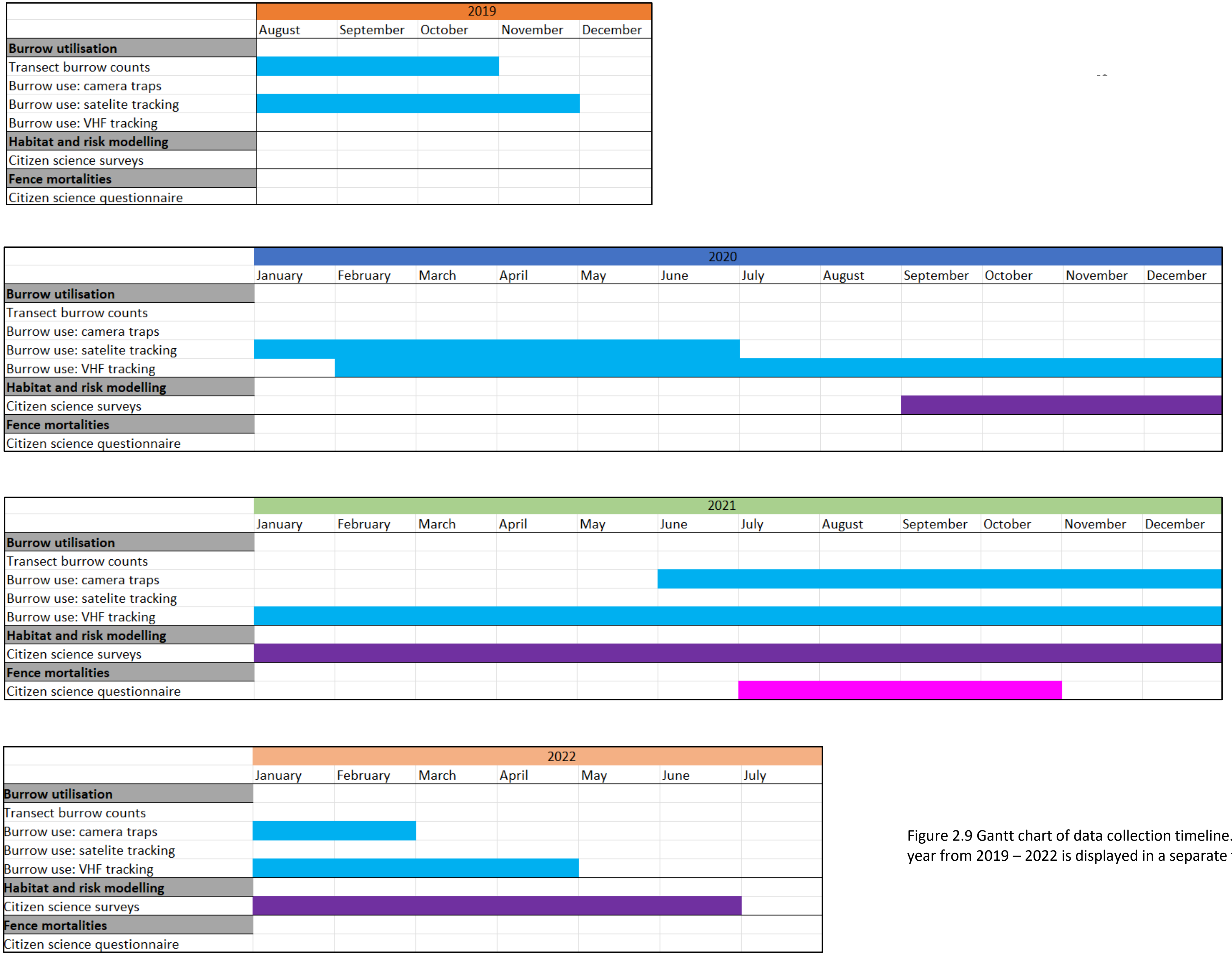


Figure 2.9 Gantt chart of data collection timeline. Each year from 2019 – 2022 is displayed in a separate table.

2.5. Data analyses

Descriptive and statistical data were analysed for all chapters using RStudio version 2023.03.0 (The RStudio Team, 2023), SPSS version 28.0.1.1 (IBM, 2019) and Jamovi version 2.2.5 (The jamovi project, 2021). Data was visualised using: the ‘ggplot2’ package in RStudio (Wickham, 2016); the chart builder in Jamovi; SPSS; and Microsoft Excel version 2308 (Microsoft Corporation, 2023). ArcMap 10.8.1 (Environmental Systems Research Institute [Esri], 2020) and ArcGIS Pro 3.1.41833 (Esri, 2023) was utilised to generate maps throughout all chapters.

SaTScan version 10.1 was utilised to analyse patterns of burrow use in Chapter 3 (Kulldorff, 2009). Maximum Entropy Modeling of Species Geographic Distributions (MaxEnt) 3.4.4 (Phillips, Dudík and Schapire, 2020) was used to generate habitat suitability and risk models for Chapter 4. Canvis.app was used to record mortality locations in Chapter 5 (McGill, 2020). Environmental and climate data layers sources are detailed in the relevant chapters. Further details of data analyses are available in each individual chapter.

Chapter 3 - The influence of environmental factors of aardvark-generated burrows in pangolin burrow utilization

3.1. Introduction

Burrows are a common form of shelter created by various different species, including arthropods, mammals, birds, and fish, across numerous habitats (Whittington-Jones, Bernard and Parker, 2011; Hofstede and Dziminski., 2017). They are holes or tunnels excavated from the ground that animals use for refuge. Burrows are an important landscape feature that not only benefits the species that creates them but often many other species within that habitat (Hansell, 1993). Burrows are typically used either for dwellings, foraging, or both (Sun et al., 2021). Moreover, burrows act as refuge from environmental conditions like extreme temperatures and offer shelter, stable temperatures, and protection from predators (Louw, Haussmann and le Roux, 2019; Sun et al., 2021). More broadly in the landscape, burrows contribute to habitat heterogeneity and are thought to improve species diversity (Hansell, 1993; Yoshihara et al., 2010). The presence of burrows in a landscape aerates and mixes soils, improves vegetation cover, and enhances drainage, although these impacts are seen more in scrubland and grassland than semi-arid savanna (Louw, Haussmann and le Roux, 2019; Sun et al., 2021). By doing all this, they also can facilitate climate change adaptation by enhancing thermoregulation for a wide range of species (Pike and Mitchell, 2013). Burrows often exist long after an animal has died so their impact on a habitat can be long lasting (Sun et al., 2021). Additionally, in fire-prone landscapes burrows can act as areas of safety for certain species, such as wombats in Australia (Friend, 1993).

Burrows are used by four pangolin species Temminck's (*Smutsia temminckii*), giant pangolins (*Smutsia gigantea*), Chinese (*Manis pentadactyla*), and Indian (*Manis crassicaudata*). Some, such as Chinese pangolins, excavate their own burrows, while others utilise the excavations of other species (Sun et al., 2021). The focal species of this study – Temminck's pangolin (hereafter "pangolin") fits into the latter category, predominantly using other species' excavations (89.8% of observations versus 11.2% in "natural" refuges e.g. vegetation, rocks and caves [Pietersen et al., 2014b]). Pangolins rarely dig their own burrows, Pietersen (2013) witnessed only one burrow excavation by a pangolin over a three-year period of radio tracking (N = 12). Up to 69.7% of the burrows used by pangolins in South Africa are reported to be excavated by aardvark (*Orycteropus afer*), with the remainder excavated by Cape porcupines (*Hystrix africaeaustralis*) and Spring hares (*Pedetes capensis*; Pietersen, 2013; Pietersen et al., 2014b). Pangolins use burrows both as dwellings and for feeding on ants and termites (Pietersen et al., 2020; Sun et al., 2021). They are reported to move between burrows frequently, occupying one for 1 – 2 weeks at a time thus numerous burrows are required within their habitat (Bräutigam et al., 1994). They will utilise a burrow for a mean of 16 – 17 days before moving on, and will revisit burrows approximately 18 – 23% of the time (Pietersen et al., 2020). Further research is needed to evaluate why many burrows are only utilised for short periods of time. There has been little documentation of pangolin burrow use outside of southern Africa.

Aardvarks are considered ecosystem engineers because they can create a high density of burrows within a small area increasing the spatial heterogeneity of habitats (Haussmann et al., 2018). They have highly developed forelimbs that enable them to easily construct complex burrow systems with numerous entrances (Taylor, 1998). Aardvarks are thought to gradually alter entire habitats and can create unique microhabitats by generating patches of disturbance, which can increase abiotic heterogeneity of the landscape (Hansell, 1993; Sun et al., 2021). There can be a high turnover of burrows due to collapses of old burrows and frequent creation of new burrows (Haussmann et al., 2018). Whittington-Jones et al (2011) recorded densities of aardvark burrows across sites in South Africa from 122/km^2 to 795/km^2. In 1948, Hediger and Verschuren recorded 27 burrows in a 400 m^2 area (Melton, 1976). These burrows are easily utilised by small and medium sized mammals and reptiles, particularly because aardvarks themselves only use the burrows for 4.9 – 8.6 days on average, however the reasons for such temporary usage are unknown (Taylor, 1998; Taylor and Skinner, 2003).

Since pangolins appear to be consistent users of aardvark burrows, the presence of these burrows should provide information on pangolin presence and distribution, although, aardvark burrowing behaviour is itself little known. It is possible aardvark burrow use and locations are chosen due to proximity to foraging opportunities (Smithers, 1971; Haussmann et al., 2018). Aardvark burrows are known to offer refuges from climatic changes and adverse weather conditions for many species, and may additionally present foraging opportunities for insects such as termites and ants (Whittington-Jones et al., 2011). Aardvark burrows have their own microclimates, with temperatures generally stable inside and humidity typically high (Bulova, 2002; Whittington-Jones et al., 2011; Haussmann et al., 2018). Soil type or grain size may contribute to burrow temperature regulation (Kay and

Whitford, 1978) and could act as a proxy for burrow climate. Soil temperature fluctuates the most near the surface because soil retains heat from the sun long after sunset (Burda, Šumbera and Begall, 2007). Temperature stabilises with burrow depth and is relatively consistent below depths of 30 – 60 cm but this may vary between soil types (Bennett, Jarvis and Davies, 1988; Burda et al., 2007). For instance, dry soils have a lower capacity for retaining heat (Burda et al., 2007). Additionally, the permeability of a soil may influence where a burrow is created. For example, European badgers (*Meles meles*) prefer dry and well-draining soils such as loam over sand (Revilla, Palomares and Fernández, 2001; Mickevičius, 2002). These climate regulation aspects may be important to pangolin survival in climates with very high and low temperatures. Burrow use allows them to either warm up or cool down, as necessary depending on the climate. Inside Chinese pangolin burrows, temperatures vary on average between 17.8 – 21 °C while outside temperatures range from 4.6 – 38.3 °C (Bao et al., 2013), although this species creates their own burrows. Many species, including snakes, use burrows for thermoregulation (Johnson, Poulin and Somers, 2022), especially in variable seasonal climates (Milling et al., 2018). Aspect of burrow entrance can also have an impact on the microclimate within a burrow. Burrows that face north or south tend to avoid direct sunlight so these burrows may experience more consistent temperatures than those that face east or west (Cunningham, 2001). External environments may influence burrow use or placement because species, such as badgers, may seek a burrow that is sheltered or hidden by vegetation (Revilla et al., 2001).

Three studies have investigated the environmental characteristics in relation to aardvark burrows (Whittington-Jones et al., 2011; Epps et al, 2021; Mapuru, Hansen and Haussmann, 2021). Epps et al (2021) found that aardvark presence in Kruger National Park, South Africa, was positively correlated with elevation and vegetation productivity (as measured through a normalised difference vegetation index [NDVI]) and was negatively correlated with distance to water sources. Rainfall and termite activity were both weakly correlated with aardvark presence, while soil type was not a predictor. Conversely, Whittington-Jones (2021) report that aardvark presence is influenced by prey availability in South Africa at three arid and semi-arid sites. This study found that slope did not influence the presence of a burrow, with an equal number of burrows appearing on flat and sloped land. The primary aspect of these burrows was different at each site and varied between north, northeast, and bimodal north/south axis (Whittington-Jones et al., 2011). However, Mapuru et al (2021) found that no environmental variables (including soil type, geology, vegetation, and distance to waterways) influenced burrow placement in Rietvlei Natura Reserve, South Africa.

There has been little research into pangolin burrow physical characteristics, hence a knowledge gap exists regarding what makes a burrow suitable for pangolin use. Additionally, it is common for pangolins to share their burrows with other species such as bats, snakes, and rodents, and it is unknown how this influences burrow use (Lehmann et al., 2020). Social interactions between pangolins may also influence burrow use as Temminck's pangolins are solitary, and home range overlap varies by location, season, and sex of the individuals (Swart, 2013; Pietersen et al., 2020; Prediger 2020). This is likely influenced by mating systems, for example, in the Kalahari of South Africa, males and females are known to have closely overlapping home ranges, whereas in the Kruger National Park region of South Africa, male home ranges overlapped with several female ranges (Swart, 2013; Pietersen et al., 2014b). Prediger (2020) recorded seasonality of home range overlaps, with less overlaps in the non-growing season in Namibia compared to the growing season. The overlap of home ranges may influence burrow choice, which may also vary seasonally. However, the majority of studies into home range overlap come from southern Africa and may not be applicable to Kenyan pangolin populations.

Identification of potentially influencing factors will enable us to better understand pangolin distribution and habitat suitability. Entrance and burrow dimensions have been suggested to be influential as smaller entrances may impede access by larger predators, such as spotted hyaena (*Crocuta crocuta*), leopard (*Panthera pardus pardus*) or lion (*Panthera leo*; Harper and Batzli, 1996). Adult pangolins are much smaller than adult aardvarks (mean animal body weight: Temminck's pangolin: 9 – 10 kg; aardvark: 45 – 65 kg (Hutchins et al., 2003; Pietersen et al., 2020). Aardvark burrows are typically 40 x 40 cm height and width, and up to 80 cm diameter (Melton, 1976). Heath (1992) recorded one Temminck's pangolin burrow with a diameter of 20 – 25 cm and Pietersen (2013) reported burrow entrances in South Africa to vary greatly i.e., between 20 – 100 cm in diameter, for both aardvark and porcupine burrows. Prediger (2020) monitored pangolin burrow use in Namibia and found the mean height and width of burrows used were 33.79 cm and 34.19 cm, respectively.

Pangolins have also been reported to preferentially use burrows within termite mounds (Prediger, 2020) indicating the importance of proximity to a food source. Whittington-Jones et al (2011) found the mean height of aardvark burrows ranged between 32.2 – 41.9 cm, depending on the site. This variation is suspected to be attributed to different sized aardvarks creating the burrow openings. When burrows have been used by pangolins often the burrow is modified and the chambers widened (Pietersen, 2013). These studies involving pangolin burrow choice took place in southern Africa and thus there might be behavioural differences between populations found outside of this region.

Not all pangolin species use burrows created by other species and there are likely differences in refuge site utilisation and habitat characteristic preference. Indian pangolins were found to prefer high elevations (75-100 m) with steep slopes and preferred to be located away from human activity (Karawita et al., 2018). Chinese pangolins were found to show a slight preference for red soil over brown in Nepal (Sharma et al., 2020b). Chinese pangolins are known to dig burrows solely for foraging, and prefer sites with a moderate slope, moderate canopy cover, and locations near agricultural areas (Tamang, Sharma and Belant, 2022). Many of these burrows are also found near termite and ant mounds. These studies show that burrow preference varies between the pangolin species, particularly between those that dig their own burrows and those that use pre-existing ones.

The comparison of burrow use characterises has not been previously conducted for many mammal species but has been studied in other taxa, including burrowing owls (*Athene cunicularia*) in North America, pygmy blue tongue lizards (*Tiliqua adelaidensis*) and fiddler crabs (*Uca mjoebergi*) in Australia, and desert tortoises (*Gopherus agassizii*) in Nevada (Bulova, 1997; Milne and Bull, 2000; Belthoff and King, 2002; Reaney and Backwell, 2007). These include *in situ* and *ex situ* studies, the latter including construction of artificial burrow enclosures to monitor use with greater ease. All compared known used burrow characteristics with unused burrows and each revealed preferential burrow use for each study species. Characteristics that were found to be associated with use included entrance width, soil geochemical composition, temperature factors, or a combination of these variables. All species in the studies excavated their own burrows apart from the pygmy blue tongue lizard, which utilised the burrows of lycosid and mygalomorph spiders (Milne and Bull, 2000). Burrow use is likely to be species-specific, and may not be easily predicted, especially where one species uses a burrow created by another (Bulova, 1997; Milne and Bull, 2000; Belthoff and King, 2002; Reaney and Backwell, 2007). The factors that influence burrow use may therefore differ between pangolins and aardvark, and between Temminck's pangolin and other burrowing pangolin species.

To investigate burrow selection, it is essential to know the number of burrows in an area and which are being utilised by pangolins. The use of distance sampling or transects might be beneficial for detecting the total number of burrows present, however difficulties lie with determining if one is being used by a pangolin (Ingram, Willcox and Challender, 2019). A combination of methods including camera trap recordings and researcher observations can be used to achieve this, especially since Temminck's pangolins are an elusive, seldom seen species. Once this information is collected for several pangolin individuals or populations, the characteristics of used and unused burrows can be compared to assess if certain burrows are preferentially utilised by pangolins.

3.1.1. Aims

This study sought to examine how and why Temminck's pangolins utilise some burrows over others within their home range and explore the characteristics that affect the choice of these burrows in Masai Mara National Reserve, Kenya. As burrows are the primary shelter source used by pangolins, burrow characteristics may influence pangolin distribution and habitat use. The findings have the potential to inform on pangolin ecology, habitat use, and behaviour, within Kenya.

Objective 1 was to determine if the characteristics of aardvark burrows, including aspect, termite presence, soil type, soil grain size, and entrance area dimensions, affect burrow use by pangolins. Pangolins were predicted to choose burrows based on a combination of these characteristics, which may be influenced by prey availability, thermoregulation, or predator avoidance. Objective 2 was to investigate the distribution pattern of burrows within the broader landscape. The presence and distribution of burrows created by aardvarks throughout the landscape was predicted to influence burrow choice and habitat use of pangolins within their home ranges.

3.2. Methods

3.2.1. Study area

See General Methodology sections 2.1.1. for descriptions of Masai Mara National Reserve, and 2.1.1.2 for descriptions of the Sala's Camp study site. A map of the site location is found on page 50, Chapter 2: Figure 2.1.

3.2.2. Burrow data collection

This study aimed to record all aardvark burrows within the Sala's Camp 16 km² study area and collect data on the physical characteristics of these burrows. It was presumed that all burrows were created by aardvark due to the known presence of this species in the region and the high proportion of aardvark burrows utilised by pangolins reported in other studies (Pietersen, 2013; Pietersen et al., 2016b).

A total burrow count was conducted across the study area. Transects of 1 km length were spaced parallel 20 m apart, in a north to south direction. These were overlayed on a map of the study area to provide comprehensive sampling across the site. There was a total of approximately 800 transects. A team of six observers walked parallel transects at the same time, alternating between north to south and south to north (Appendix 2: Figure A1). The team spent 31 days over ten weeks in August – October of 2019 undertaking the transects. This took place in the dry season to ensure burrows would be easily visible to the research team. The same six observers collected the data throughout the study. Each person walked a mean of 4.3 transects per day. Each observer used a GPS (Garmin eTrex 10, < 15 m accuracy) to record all burrows they encountered within a 10 m line of sight on either side of the transect line. A burrow was defined as an excavated area that was big enough to fit a pangolin, deemed to be at least 14 cm by 14 cm. If a burrow had more than one entrance, each was counted as a separate burrow. When recording a burrow location, each burrow was given a random number as a unique identification method. If a previously unrecorded burrow was found throughout the pangolin use monitoring period, then this was noted down and characteristics were recorded.

When a burrow was found five variables measuring physical burrow characteristics were recorded (Table 3.1). The variables were: 1) aspect of burrow entrance; 2) whether the burrow was located directly within a termite mound (“yes” or “no”; Figure 3.1); 3) soil type; 4) soil grain size; and 5) burrow dimensions in the form of burrow height multiplied by width and termed cross-sectional area (hereafter “CSA”). Aspect was collected using a compass and divided into 8 categories, and was collected to determine if sun movement influenced burrow microclimates thus burrow selection. The team was unable to identify termite species in the field as there are several in the region, thus all species were collected as presence/absence data. Soil type was collected by remote sensing from the Soil and Terrain Database for Kenya (ISRIC, 2014) and soil grain size was collected in the field and comprised mean grain size in millimetres and was assessed visually from 4 categories (Table 3.1). Grain size categories were selected based on the feasibility of the team to visually identify and measure different sizes in the field. These were selected as variables to determine if soil composition influenced aardvark burrow creation, and to investigate if pangolins had a preference for soil type which may relate to habitat type or thermoregulation abilities. A tape measure was used to record height and width in centimetres. Height was measured from the centre of the floor at the burrow mouth, to the tallest point of the entrance hole, and width was measured from the widest horizontal part of the burrow entrance. Measures of CSA under 200 cm^2 with either height or width measuring less than 12 cm were excluded from the analyses because these were considered too small for a pangolin to access, due to pangolin burrows ranging from 20 – 25 cm entrance diameter (314 – 490 cm^2; Heath, 1992). CSA was selected as a variable because it may influence predator interactions and thermoregulation abilities.

Table 3.1 The burrow characteristics collected to evaluate pangolin burrow use. The subcategories used for data collection for each categorical variable are listed.

Characteristic	**Subcategories**
Aspect	North, South, East, West, Northwest, Northeast, Southwest, Southeast
Termite presence	Presence, Absence
Soil type	Eutric planosols, Luvic phaeozems[1]
Soil grain size	< 1mm, Some > 2mm, All 2 – 5mm, 5mm
CSA (cm^2)	N/A

[1] Eutric planosols: Common in semi-arid environments. A dark soil with volcanic material. Poorly draining with a varied texture from silty loam to clay (Britannica, 2000; ISRIC, 2023a).
Luvic phaeozems: A highly arable and humus-rich soil with little clay presence. Typically with grass present. (Britannica, 2019; ISRIC, 2023f).

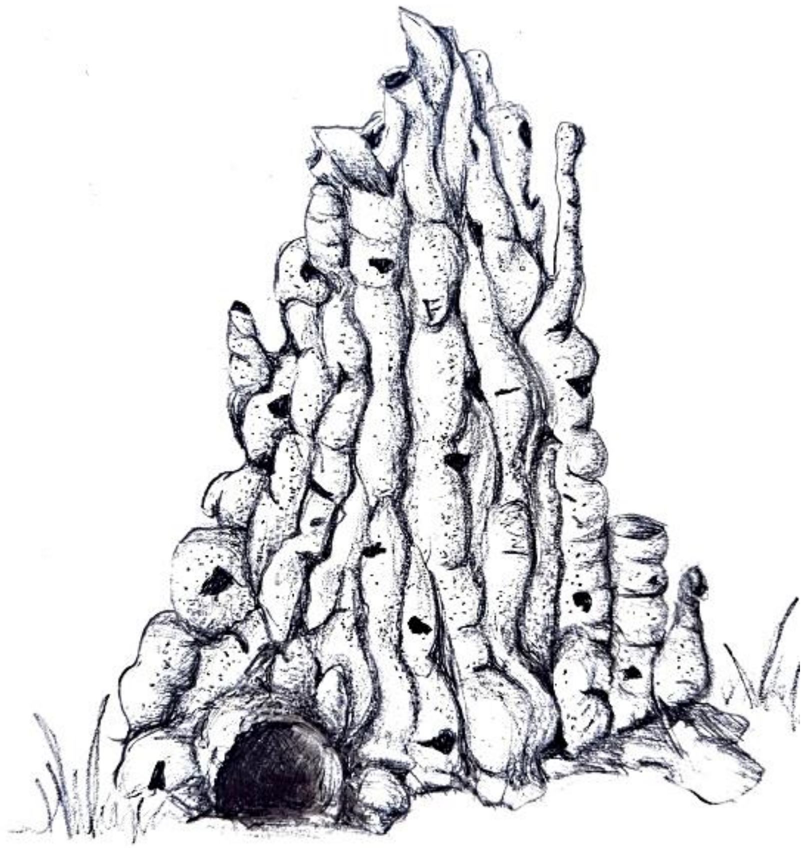


Figure 3.1 Diagram of a termite mound with an aardvark burrow present at the base. Illustration by Maryellen Stracquadanio.

3.2.3. Pangolin burrow use sampling design

All burrows were considered unused by pangolins unless there was observed pangolin occurrence either by: using Very High Frequency (VHF) or satellite tracking to track a pangolin to a burrow, or by capturing pangolins on camera traps (Chapter 2: section 2.4.1.1.). VHF and satellite tracking took place as part of a parallel study undertaken by the Pangolin Project between 2019 and 2022 (N = 3) where these pangolins were tracked to burrows and cameras were placed outside the closest burrows to establish pangolin burrow use. VHF and satellite monitoring were used to record which burrows were used by tracked pangolins and how frequently they moved between different burrows.

Data were also collected on the duration of burrow use by each pangolin. Every time a pangolin was tracked to a burrow this was noted and the number of days that the pangolin spent in that burrow were recorded, by tracking the pangolin on each subsequent day until it moved from that burrow. If a pangolin moved location, it was tracked to the next burrow and the process was repeated. A remote camera ("camera trap") network was additionally deployed from June 2021 – February 2022 to monitor the activities of both the tagged pangolins and any other individuals within the study area. Ten cameras were placed at a total of 61 burrows throughout the study period. Camera traps were deployed for unstandardised periods of time (1 – 365 nights, mean = 39) hence true absences could not be established, and camera images/video footage were collected as presence-only data points. These videos were grouped by burrow identification number. Burrows used by both pangolins and any other species within 12 hours were recorded. All burrows were considered unused by pangolins (absent) unless there was observed pangolin presence from a) images or video footage or b) using VHF or satellite tracking. This presence-only approach means that there were potentially false absences as not all burrows could be monitored simultaneously due to logistical constraints.

3.2.4. Data analyses

Maps were created using ESRI ArcMap Desktop (Esri, 2020) and ArcGIS Pro (Esri, 2023). Figure 3.2 shows the minimum convex polygon home ranges of each tracked pangolin and the distribution of used and unused burrows. A kernel density heat map was generated to show the distribution of occupied burrows (Figure 3.3). This was done using the Spatial Analyst 'Kernel Density' tool in ArcMap with default settings; and the planar distance method was used given the small size of the study area. The default search radius was 600.25 m.

Due to the pangolin burrow use dataset containing presences but not absences, a series of Chi^2 Goodness of Fit tests were used to assess whether counts of aardvark burrows in different categories deviated from uniform (observed versus expected) for each of the four categorical variables. To determine how variation in the five burrow characteristics influenced pangolin burrow occurrence, a binomial logistic regression (GLM) with a logit link function was computed to model how variation in burrow characteristics influences pangolin burrow occurrence in RStudio, using the 'lme4' package (Bates et al., 2015). The response variable (pangolin presence) was modelled as 0,1 (presence/absence) and the full (global) model included all five burrow characteristics as explanatory variables. Reference levels for each parameter were chosen by selecting the most frequent category from each: Aspect - Southwest; Termite - yes; Soil type - eutric planosols; and Soil grain size - < 1 mm. If a categorical level had a count of less than 5 and had no presence in the response variable, the level was removed from the analyses but retained in the descriptive statistics.

The R package 'car' (Fox et al., 2012) was used to test for multicollinearity amongst the explanatory variables included in the best-fit top model, and none was found (all produced a VIF score of < 3); hence all were retained. Subsequently, the variables were scaled using the 'arm' package to ensure they were all comparable and to standardise coefficients (mean = 0, and standard deviation = 0.5; Gelman et al., 2020). The 'dredge' function within the 'MuMin' package was used to create an *a priori* candidate model (Barton, 2016). 'Dredge' was used for convenience to compare all possible models as all variable combinations were considered valid. Model averaging was then conducted using the 'MuMin' package, by utilising the Akaike information criterion to rank models and identify the most parsimonious ones. Any models with AICc < 2 were considered comparable best fit models (Burnham and Anderson, 2002). AICc was used because it is most appropriate for small sample sizes, and model averaging was generated from the best-fit models along with 95% confidence intervals. Confidence intervals were assessed for the predictor variables, which were only considered to influence burrow choice if their averaged coefficients did not overlap zero. Marginal and conditional R^2 values were computed for the best-fit models using 'MuMin', and these represented the variance from the fixed effects and entire model, respectively. This approach was based on similar methods applied by Ellis et al (2017) and Nomani, Carthy and Oil (2008).

The 'Average Nearest Neighbor' tool in ArcMap was utilised to investigate the distribution of aardvark burrows and those used by pangolins across the study site and determine if distribution was statistically clustered, random or, dispersed. To investigate broader patterns of burrow distribution in the landscape, SaTScan version 8.0 (Kulldorf, 2009) was used to generate predictive clusters of burrow use for high and low use areas. This provides a direct comparison between the observed distance between points and the expected distance in a simulated random configuration. SaTScan creates a circular window over the study area and imposes this on each burrow coordinate location. Circles of different sizes for each location are produced and tested multiple times. For each circular window, a likelihood ratio statistic ("scan statistic") is calculated based on the observed and expected number of used burrows. It compares this output to a likelihood of 0 and computes a probability (p)-value for each cluster. The visual size of each cluster represents the geographic coverage of the cluster and does not indicate likelihood value. This p-value is calculated by Monte Carlo hypotheses testing by randomly redistributing the locations and recalculating the scan statistics multiple times until some divergence measure is achieved. In this study, a Bernoulli model was used with spatial-only data for each burrow location. Bernoulli modelling compares the number of used burrows to the controls in each cluster to determine if there is significant clustering of either based on the spacing of the burrows. Controls in this study were the unused burrows. Once clusters were calculated, the difference in burrow characteristics between the significant clusters were calculated using the Chi squared and GLM approaches as above. Identical procedures to the original GLM were subsequently used to compare all burrows within one significantly low cluster of use, with all burrows outside of this cluster. Mann-Whitney U tests were conducted to investigate the difference in CSA between significantly clustered burrows and all other burrows. The original GLM analyses compared the pangolin used and non-used burrow characteristics, whereas the SaTScan analysis calculated the likelihood of each burrow being in a cluster based on pangolin occurrence and grouped the burrows accordingly.

Two differing statistical approaches were thus used in this study; an information theoretic approach for the original GLMs and null-hypothesis-significant testing (NHST) for the SaTScan analysis. This disparity was necessary due the in-built NHST method that SaTScan uses, and this software was deemed the most appropriate technique to explore broader burrow distribution.

The camera trap and burrow movement data were summarised descriptively rather than analysed inferentially because both were collected opportunistically and with *ad hoc* presence sampling. They are included to provide context for the main dataset and statistical results.

3.3. Results

A total of 281 burrows were recorded along with their characteristics during the study (Figures 3.2 and 3.3). For 18 of these burrows, only four variables were collected as grain size was not included due to observer difficulties in the field, hence five variables were recorded for 263 burrows (Tables 3.2 and 3.3). Burrow density at Sala’s camp ranged from 6 – 81 burrows per km^2.

A total of 50 burrows (17.7%) were recorded to have pangolin presence, i.e., they were used by pangolins at some time during the study. VHF tracking and camera trapping respectively revealed 43 and 34 events (total = 77) where pangolins used burrows, hereafter termed “burrow occurrences”. Of these, 27 were repeat measures i.e., recorded using both methods, hence a total of 50 independent burrow occurrences were recorded.

The majority of pangolin burrows were used by the tagged pangolins (96%; N = 48) and 2 (4%) were observations of non-tagged pangolins. Of these, 3 (6%) burrows were used by both a tagged and non-tagged pangolin.

Minimum convex polygon (MCP) home ranges were calculated for each of the tracked pangolins (Figure 3.2). These were: FM001 - 1.27 km^2; FM002 - 4.06 km^2; and FM003 - 0.52 km^2.

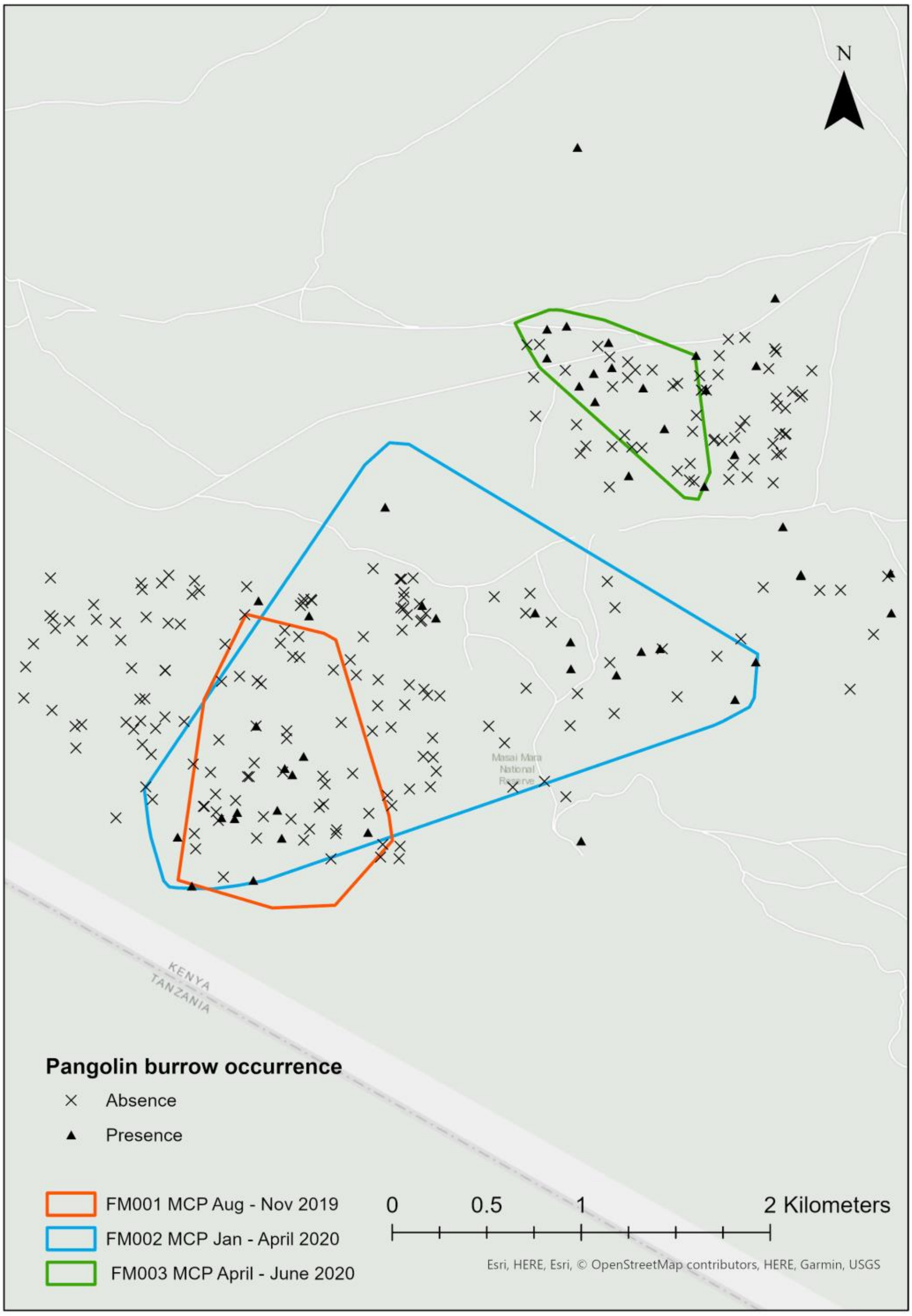


Figure 3.2 Map of the burrows (N = 281) for which burrow characteristics were measured within the study area. Pangolin burrow presence is represented by black triangles and absences are represented by black crosses. Minimum convex polygon home ranges for each pangolin's satellite telemetry data are shown: FM001 in orange, FM002 in blue, and FM003 in green.

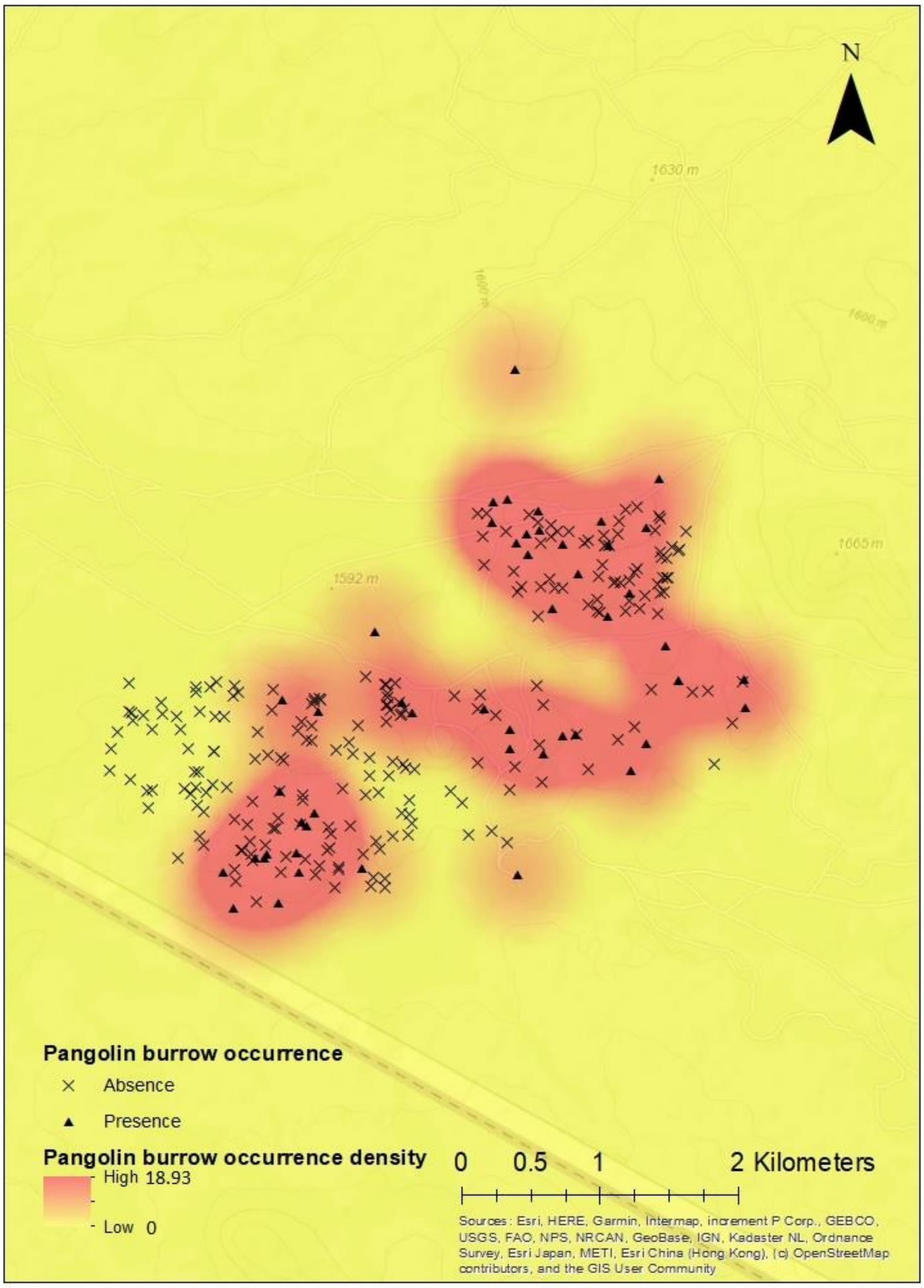
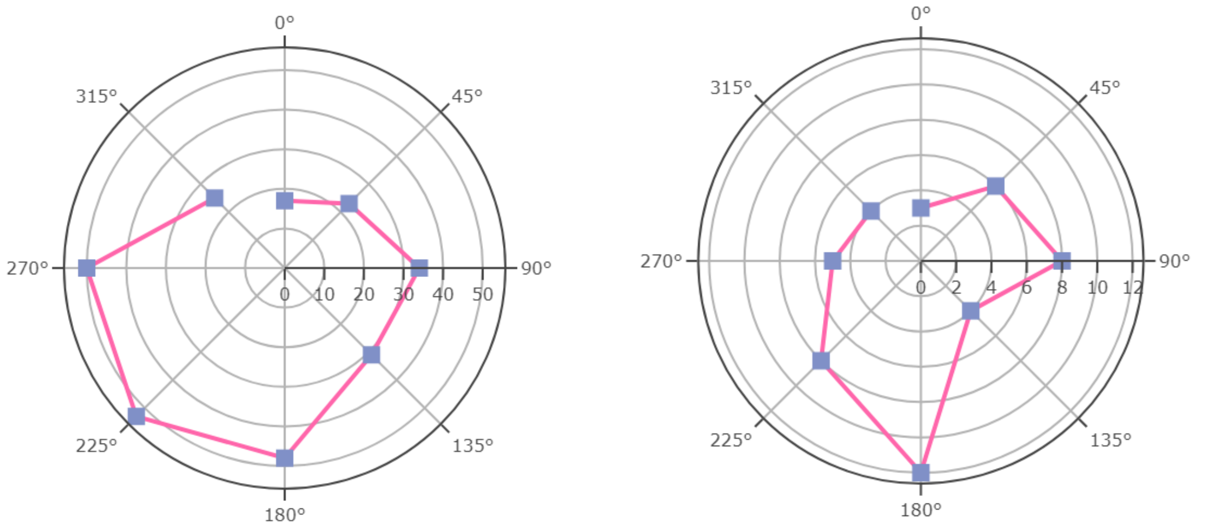


Figure 3.3 Kernel density estimate heat map of the burrows where pangolin occurrence was confirmed (N = 50) to show predicted high density areas of burrow use. There are 281 total burrows. High indicates up to 18.93 and low indicates 0, per square kilometre. Default search radius was 600.25 m. Method: Planar. Pangolin burrow presence is represented by black triangles and absences are represented by black crosses.

3.3.1. Burrow characteristics: descriptive statistics

Aardvark burrow characteristics

Raw data are summarised in Appendix 2: Table A1. Overall, southwest, west, and south were the most common directions for burrow entrances to face, making up a combined 53.6% of aspects (Figure 3.4). There were higher than expected rates of these 3 directions whilst, all other directions had lower than expected frequencies (Appendix 2: Figure A2). Most burrows (61.9%) were found within active or old termite mounds and the rate of these was higher than those without (Appendix 2: Figure A3). The most common soil type was eutric planosols (85.6%), followed by luvic phaeozems (14.4%; Appendix 2: Figure A4). There was a difference between these categories, with eutric planosols present more often than expected. Soil grain size was primarily < 1mm (89.73%; Appendix 2: Figure A5).



A **B**

Figure 3.4 Polar compass of burrow aspect frequencies for aardvark burrows (A) and burrows used by pangolins (B). North = 0°, Northeast = 45°, East = 90°, Southeast = 135°, South = 180°, Southwest = 225°, West = 270°, and Northwest = 315°.

Pangolin burrow characteristics

Pangolin burrow occurrences appeared to show a uniform representation of aardvark burrows, i.e., similar patterns emerged for pangolin and aardvark burrow characteristics. The most common burrow aspects were south (24%), followed by southwest (16%), and east (16%; Figure 3.5). All other aspects made up less than 12% each. Most burrows were found within termite mounds (64%). The most common soil type in which burrows used by pangolins were excavated was eutric planosols (75%) followed by luvic phaeozems (25%). Soil grain size was similar to aardvark burrows, with 84.4% being < 1 mm. Summary figures available in Appendix 2: Figures A2 – A5.

Mean height and width of burrow entrance was similar when comparing aardvark burrows overall and those in the pangolin presence subset, (overall mean ± SEM = 38.2 cm and 42.4 for height and width, respectively; pangolin subset mean = 35.8 cm for height and 42 cm for width [Appendix 2: Table A2 and Figure A6]). Mean CSA for all burrows was 1690 cm² and for pangolin burrows was 1550 cm². Figure 3.5 displays the mean burrow CSA of each soil type.

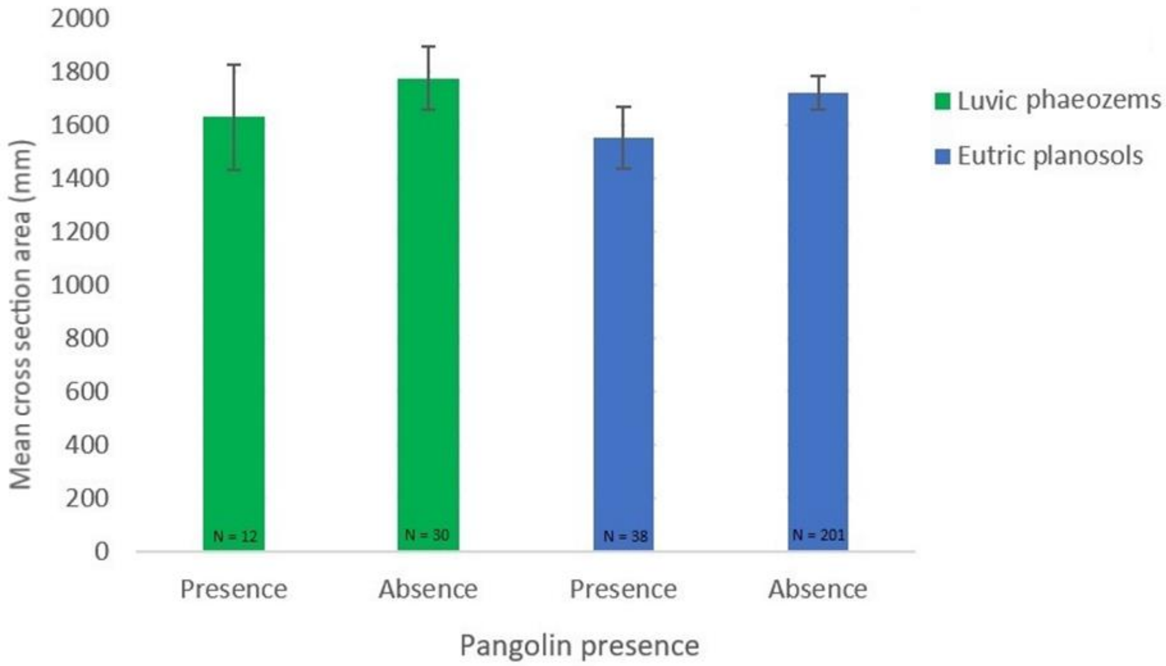


Figure 3.5 The mean cross section size (cm) for each soil type of luvic phaeozems or eutric planosols, for pangolin and non-pangolin burrows. N = the number above each bar. Standard error of mean bars are displayed.

3.3.2. Characteristics of pangolin burrow use

None of the explanatory variables affected pangolin burrow occurrence i.e., pangolins did not disproportionately use particular aardvark burrows according to the five burrow characteristics (Table 3.2). No variables were collinear (all VIF scores < 3; Appendix 2: Table A3) but the level '5 mm' for soil grain size was removed from the analysis due to counts of less than 5. Model averaging and selection revealed four models with ΔAICc of < 2 (Table 3.3). These were: 1) soil type only, 2) no variables (null), 3) soil type, termite presence and soil type, and 4) soil type, termite presence and soil grain size. All confidence intervals overlapped zero showing that these differences were unreliable and therefore not influential (Table 3.4; Appendix 2: Figure A7). N = 262 for this model. A subsequent model averaging analysis with a slightly larger dataset (N = 281) and only four characteristics (aspect, CSA, soil type, and termite presence) was run, and results were also non-significant (Appendix 3: Tables A1 – A4 and Figure A1).

Table 3.2 Binomial logistic regression of burrow use characteristics broken down by variable. Residual deviance: 185.12 on 249 degrees of freedom. AIC: 211.12. Number of Fisher Scoring iterations: 5. N = 262. Note. Estimates represent the log odds of "Pangolin = Presence" vs. "Pangolin = Absence".

Model Coefficients – Pangolin			
Predictor	**Estimate**	**SE**	**Z**
Intercept	-2.140	0.649	-3.295
CSA	-4.18e-05	2.46e-04	-0.170
Aspect: (Southwest versus)			
South	-0.0396	0.650	-0.061
Southeast	-0.4.00	0.758	-0.527
West	-0.969	0.743	-1.303
Northeast	-0.215e	0.870	-0.247
East	0.182	0.654	0.279
North	0.412	0.779	0.528
Northwest	0.0172	0.710	0.024
Termite: (Yes versus)			
No	0.241	0.408	0.590
Soil type: (Eutric planosols versus)			
Luvic phaeozems	0.879	0.489	1.797
Soil grain size: (< 1 mm versus)			
Some > 2 mm	1.03	0.749	1.38
2 – 5 mm	0.783	0.706	1.109

Table 3.3 Generalized linear models (GLMs) in AICc < 2 (top models) used for model averaging to describe the relationship between pangolin burrow use and burrow characteristics. logL = log-likelihood values; k = number of parameters per model; AICc = Akaike information criteria corrected value for the sample size between a model and the best fitting model; ΔAICc = the delta change in AICc; w = Akaike weight; R^2m = marginal R^2 (variance explained by the fixed factors); R^2c = conditional R^2 (variance explained by the fixed factors).

Model	**logL**	**k**	**AICc**	**ΔAICc**	**w**	**R^2m**	**R^2c**
Soil type	-95.83	2	195.7	0.00	0.4	0.02355681	0.02355681
Null	-97.24	1	196.5	0.80	0.27	0	0

Soil type + termite presence	-94.63	4	197.42	1.72	0.17	0.026247250	0.026247250
Soil type + soil grain size	-95.71	3	197.51	1.80	0.16	0.04072854	0.04072854

Table 3.4 Confidence intervals of each burrow characteristic for the average top models identified during model averaging.

Parameter	Estimate	Lower	Upper
Intercept	-2.01406	-2.408829	-1.61929
Soil (luvic phaeozems)	0.58058	-0.107820	1.694389
Soil 2 – 5 mm	0.11110	-0.403750	2.003881
Soil > 2 mm	0.17115	-0.403750	2.425599
Termite No	0.03182	-0.580822	0.972448

3.3.3. Spatial patterns in pangolin burrow occurrence

Aardvark burrow distribution (N = 281) was found to be statistically clustered (Nearest Neighbor Ratio = 0.733, z = -8.42, p = < 0.001), with less than a 1% chance of the distribution being considered random. Observed and expected mean distances were 82.85 m and 113 m respectively. For burrows used by pangolins (N = 50), distribution was also statistically clustered (Nearest Neighbor Ratio = 0.858, z = -1.9, p = 0.05), with less than a 10% chance of the distribution being considered random chance.

Eight spatial clusters of pangolin burrow use were identified during the SaTScan analyses. Cluster C1 had 53 burrows and no pangolin occurrence (p = 0.004, Table 3.5). One other cluster with non-significant low occurrence was identified, as well as 6 non-significant high occurrence burrows (Figure 3.6). Subsequently, a GLM was run to compare the burrow characteristics in the significant no-occurrence cluster (C1) with all burrows outside of this cluster.

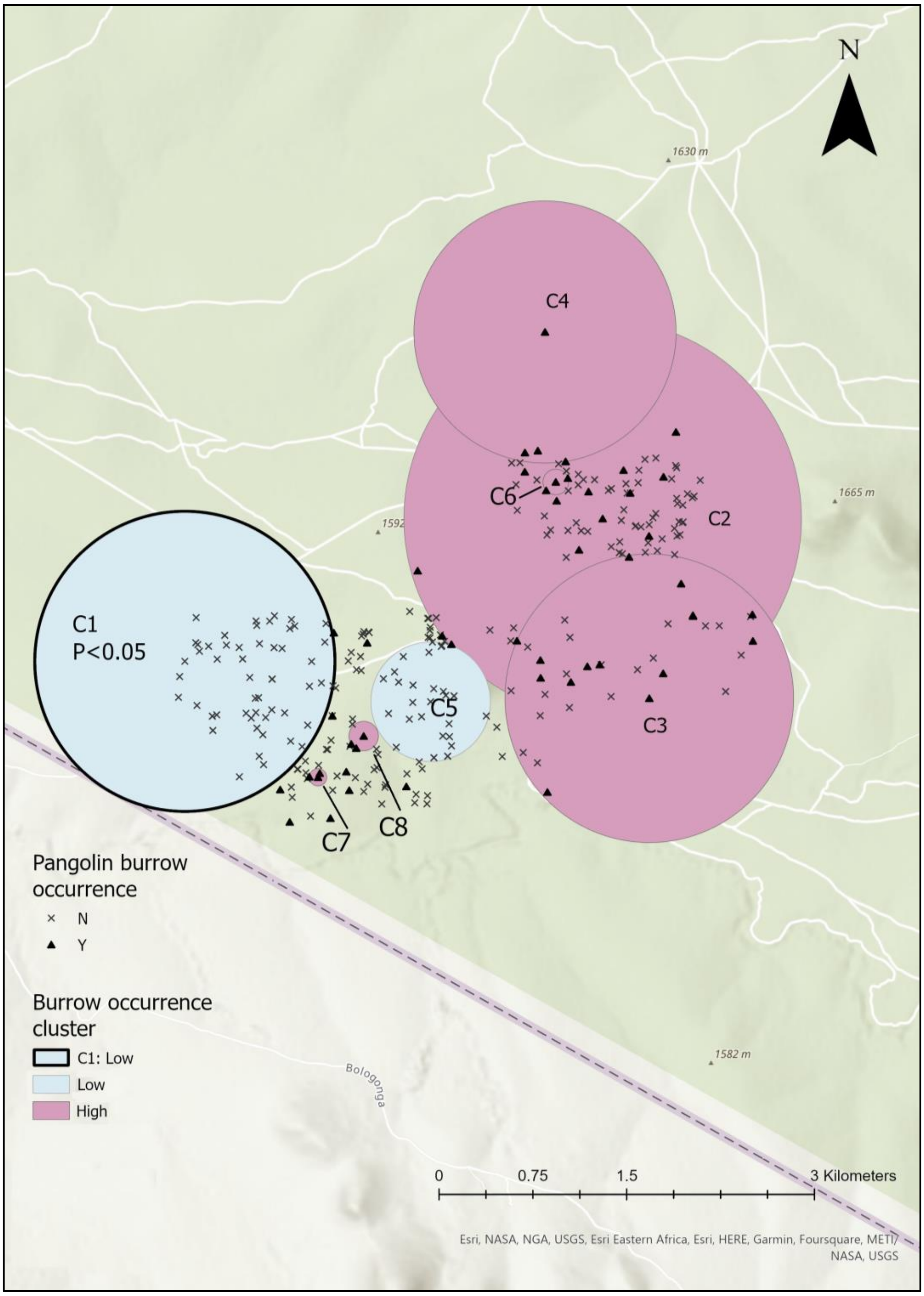


Figure 3.6 Burrow use predictive clusters identified by SaTScan. Low occurrence clusters are blue and high occurrence clusters are pink. P-values 0.05 or lower are indicated on the map, as with C1. The green represents Masai Mara National Reserve in Kenya and the grey represents Tanzania. Pangolin presence is shown with black triangles and absences with black crosses.

Table 3.5 Clusters of high or low pangolin presence identified by SaTScan and the scan statistics associated with each. Significant p-values are in bold.

Cluster	Number of total burrows	Observed used burrows	Expected used burrows	Observed/expected	Log likelihood ratio	p-value
C1	52	0	9.25	0	11.398891	**0.0040**
C2	117	34	20.82	1.63	8.634441	0.063
C3	35	15	6.23	2.41	7.043927	0.171
C4	4	4	0.71	5.62	7.041167	0.261
C5	26	0	4.63	0	5.374013	0.566
C6	3	3	0.53	5.62	5.254779	0.791
C7	3	3	0.53	5.62	5.254779	0.791
C8	3	3	0.53	5.62	5.254779	0.791

C1 cluster descriptive characteristics

South (22.64%) was the most common direction for C1 cluster burrows (Figure 3.7). Most burrows within C1 had termite mound presence (62.26%; Appendix 2: Table A4). Most burrows were excavated in eutric planosols soil (85%) and in soil of small grain size (84.91% with < 1 mm). 15% were in luvic phaeozems. Summary figures available in Appendix 2: Figures A8 – A11.

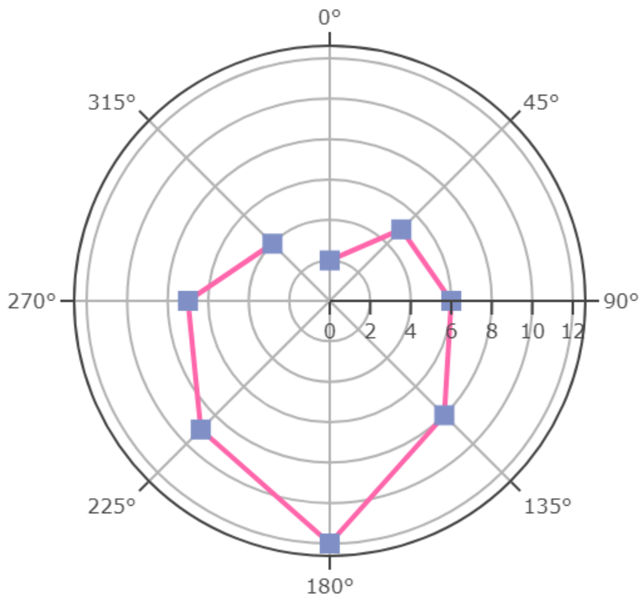


Figure 3.7 Polar compass of C1 burrow aspect frequencies. North = 0°, Northeast = 45°, East = 90°, Southeast = 135°, South = 180°, Southwest = 225°, West = 270°, and Northwest = 315°.

Burrow CSA was significantly greater for burrows within C1 compared to all other burrows (U = 2697, p = < 0.001). Mean C1 burrow CSA overall was 2213cm (mean height = 44.2 cm, width = 49.2 cm), while all other burrows were 1594 on average (mean height 37.2 cm, mean width 40.8 cm; Appendix 2: Figure A12). Mean CSA was lower for all soil types in Cluster 1 than outside of Cluster 1 (Table 3.6).

Table 3.6 Count of each soil type and mean cross section size located inside Cluster 1, compared to all other burrows.

		Eutric planosols	**Luvic Phaeozems**
Inside Cluster 1	Count	44	8
	Mean ± SEM CSA	2208.54 (± 104.2)	2093.55 (± 163.5)
Outside Cluster 1 (all other burrows)	Count	181	30
	Mean ± SEM CSA	1639.5 (± 63.3)	1571.5 (± 118.3)

3.3.4. Cluster C1 burrow characteristics

CSA was the only influential variable affecting presence or absence in the C1 cluster (Table 3.7). No variables were considered collinear because all VIF scores were < 3 (Appendix 2: Table A5). Model averaging and selection revealed three models within AICc < 2 of each other. These were: 1) CSA only, 2) soil grain size and area, and 3) soil type and area (Table 3.8). 95% confidence intervals for CSA did not overlap with zero indicating that an was the influential variable (Table 3.9; Appendix 2: Figure A13). CSA had a positive association with C1 presence. The categorical level '5 mm' soil grain size was removed from the analysis due to counts less than 5. N = 253 for this model.

Table 3.7 Binomial logistic regression of C1 burrow use characteristics broken down by variable. Residual deviance: 231.97 on 249 degrees of freedom. AIC: 257.97. Number of Fisher Scoring iterations: 5. N = 253. Note. Estimates represent the log odds of "Group = Inside cluster 1" vs. "Group = Outside cluster 1".

Model Coefficients – Group			
Predictor	**Estimate**	**SE**	**Z**
Intercept	-3.645	0.625	-5.834
CSA	9.295e-04	2.012e-04	4.619
Soil Type (Eutric planosols)			
Luvic phaeozems	1.889	0.469	0.402

Soil grain size (< 1mm versus)			
Some > 2mm	1.435	0.707	2.030
2 – 5mm	0.070	0.663	0.107
Termite (Yes versus)			
No	0.047	0.348	0.135
Aspect (Southwest versus)			
South	1.017	0.544	1.870
Southeast	0.870	0.594	1.463
West	0.076	0.590	0.129
Northeast	0.723	0.691	1.046
East	0.449	0.624	0.720
North	-0.226	0.873	-0.260
Northwest	-0.151	0.730	-0.207

Table 3.8 Generalized linear models in AICc < 2 (top models) used for model averaging to describe the relationship between pangolin burrow use and C1 burrow characteristics. logL = log-likelihood values; k = number of parameters per model; AICc = Akaike information criteria corrected value for the sample size between a model and the best fitting model; w = Akaike weight; R^2m = marginal R^2 (variance explained by the fixed factors); R^2c = conditional R^2 (variance explained by the fixed factors).

Model	logL	k	AICc	ΔAICc	w	R^2m	R^2c
CSA only	-121.22	2	246.49	0.00	0.5	0.12927606	0.12927606
Soil grain size + CSA	-119.66	4	247.48	0.98	0.31	0.14809134	0.14809134
Soil type + CSA	-121.14	3	248.37	1.88	0.2	0.1309746	0.1309746

Table 3.9 Confidence intervals of each C1 burrow characteristic for the average top models identified during model averaging. Confidence intervals which do not overlap zero indicate and influential variable and are in bold.

Parameter	Estimate	Lower	Upper
Intercept	-1.52843	-1.88039	-1.17645
Soil (luvic phaeozems)	0.03622	-0.69176	1.062706
Soil 2 – 5 mm	0.08467	-0.97227	1.526752
Soil > 2 mm	0.37931	-0.09057	2.574549
CSA	**1.41573**	**0.787056**	**2.044408**

3.3.5. Burrow sharing

Pangolins were recorded at burrows with other species on the same night 10 times at 5 different burrows. These included shrews (*Soricidae spp.*) and bats (*Chiroptera spp.*) three times each, and once each for crested porcupine (*Hystrix cristata*), African hare (*Lepus victoriae*), spotted hyaena (*Crocuta crocuta*) and African lion (*Panthera leo*). Pangolins and other species were not always present in the same video, but they were recorded at each burrow on the same night. The instances with spotted hyaena and lion did not include either utilising the burrow. One of these recordings included two other species at the same burrow, which were bats and shrews. 14.7% (5 out of 34) of burrows with camera traps included some form of burrow sharing with another species.

3.3.6. Movement between burrows

The telemetry tracked pangolins were found to spend a mean of 7 – 12 days in a burrow before moving on to a different burrow. They each revisited between 22 – 56% of the burrows they used. When reusing a burrow, they spent between 2 weeks and 3 months away (Table 3.10). Minimum convex polygon home ranges of each pangolin in relation to Cluster 1 are available in Appendix 2: Figure A14, A15 and A16.

Table 3.10 The number of burrows used by each tagged pangolin. The mean use per month is displayed. Each pangolin had several gaps in data collection timeframes, up to several months. Standard error of means displayed.

Pangolin ID	**Timeframe**	**Number of days recorded at burrows**	**Number of burrows used**	**Mean time spent in burrows**	**Mean number per week**	**Per 14 days**	**Per month**	**Number revisited**	**Gap between revisit**
FM001	Feb 2020 – Feb 2022	217	32	7.15 days (±1.2)	1.77 (±0.16)	2.95 (±0.29)	3.67 (±0.44)	18	15.4 days – 2.8 months
FM002	April – July 2020	47	9	12.1 days (±4.95)	1.80 (±0.32)	3(±0.92)	3.67(±1.45)	2	15 days
FM003	Aug 2020 – Nov 2021	79	16	8.8 days (±2.56)	1.75(±0.19)	2.33 (±0.33)	3.67 (±0.42)	5	16 days – 1 month

3.4. Discussion

This study is the first in East Africa to 1) describe physical characteristics of aardvark burrows; 2) quantify use of aardvark burrows by pangolins relating to these physical characteristics; and 3) document patterns in spatial distribution of pangolin burrows across a savannah/grassland landscape. None of the burrow characteristics studied were found to influence pangolin burrow use in standard statistical analysis, indicating that pangolins are burrow generalists. However, whilst the study site had a high density of burrows available, pangolins were observed to utilise only a small proportion of these, suggesting that there may be unstudied variables determining burrow selection. Further, spatial cluster analyses found that pangolins avoided an area with larger than average burrow entrances. It is well known that pangolins utilise burrows created by other species, primarily aardvarks (Pietersen et al., 2014b). Therefore, pangolin presence may be based on the overall presence of aardvarks, rather than the presence of specific burrow traits. Aardvarks are important ecosystem engineers, and their presence likely influences numerous burrow-using species (Whittington-Jones et al., 2011). Pangolins exhibit commensalism with aardvarks where they gain shelter and food sources, and aardvarks neither gain nor lose any resources from this relationship (Delaney, Cates and Warner, 2014).

Average Nearest Neighbor analysis revealed aardvark burrow distribution to be clustered non-randomly, indicating selection. Any preferential choice by aardvarks subsequently impacts the distribution of pangolin burrows by influencing what is available for use, which may partially explain why pangolins do not show strong selection for particular burrow characteristics. Aardvark burrow density was low compared to other studies with an average density of 28/km² compared to 122/km² to 795/km² (Whittington-Jones et al., 2011), and pangolins used a small proportion (12%) of aardvark burrows with an average density of 4.5/km².

Aardvark burrows exhibited patterns in their physical characteristics, in that they were more likely to face south, southwest or westerly directions, were mostly found within termite mounds, and primarily within eutric planosol soils of < 1 mm grain size. These results contrast with those of Epps et al (2021), who found that soil type and termite presence did not influence aardvark burrow locations in South Africa, and while aspect was influential, this was in an opposing direction, i.e. most burrows were north facing or north-south facing with bimodal entrances. The contrasting results may arise from geographical variation in termite presence and/or preference by termites for different soil types between South Africa and Kenya. Aardvark distribution is thought to be dependent on prey availability (Taylor and Skinner, 2004), which may in turn be influenced by termite soil preference as termites are reported to prefer fine grained soils (Jouquet, Lepage and Velde, 2002; Kanyi et al., 2021). This likely impacts both aardvark and pangolin distribution because they are known to share a moderate dietary niche overlap (Pietersen and Robertson, 2023). The variation in entrance aspect may be different due to geographic variation, as Kenya is on the equator thus sun movement likely differs here compared to other regions and may depend on season. It is likely that entrance aspect primarily influences how fast burrow entrances warm up or cool down, rather than the temperature of internal chambers (Wu et al., 2003; Wu et al., 2020), depending on the depth of the burrow. Aardvark preference for these burrow aspects may thus arise from a need to avoid intense light during warmer periods, or to warm up during colder periods, which correspondingly influences temperature and humidity (Bulova, 2002). North and south burrow entrances do not experience much direct sunlight at certain times of year (Torres et al., 2003). For example, from October to March, the MMNR experiences sun from a southerly direction and from April to September, a northerly direction (SunCalc, 2022). Therefore, MMNR experiences slightly more sunlight from a northernly direction throughout the year, meaning southern-facing burrows may experience marginally less direct sunlight overall than northern-facing ones. However, other factors may influence sunlight level, such as seasonal rainfall levels and associated cloud levels. Additionally, if the land is sloped then this may mean some entrance aspects could be prone to flooding during rainfall, thus certain aspect orientations may be selected to prevent flooding. The effect of aspect on burrow temperature may vary according to latitude, explaining the difference between South Africa and Kenya. Further research is needed to confirm if aspect does influence aardvark burrow positioning.

Since there were greater patterns in aardvark burrow distribution than those in pangolin burrow distribution (the distribution of aardvark burrows used by pangolins) shown in the Average Nearest Neighbor analyses, we can conclude that pangolins appear to be less selective when choosing burrows than aardvarks. In other words, pangolin appear to use whatever is most available to them, using aardvark burrows in a random manner with respect to the measured burrow characteristics variables, with the exception of their potential selection for smaller burrow entrances. This is consistent with most pangolin species, which are known to be habitat generalists (Morin et al., 2020). Pangolins move burrows frequently, approximately every 1 – 30 days according to previous studies, but the reason for this is unknown (Pietersen et al., 2014b; Bruce et al., 2018). Thus, they likely require the presence of many burrows and may need to be indiscriminate with their burrow utilisation to meet this need. Nonetheless, the non-random clustering in pangolin burrows revealed by average nearest neighbour analysis suggests that additional, unmeasured factors may affect burrow use, which may include burrow climate variables such as temperature and humidity (Prediger, 2020). Additionally, include intrinsic factors such as social and other biological factors relating to pangolin populations may influence burrow use.

Although data from three tagged pangolins tracked for three-months each were used in the current study, these periods were not simultaneous so determining seasonality of use, and social interactions between individuals was not possible. Temminck's pangolins are solitary and not thought to be strongly territorial (Swart, 2013; Pietersen et al., 2020), however males are known to attack other intruding males in their home ranges, and juveniles will disperse from their mother's home range to establish their own territories (Pietersen et al., 2014b; Pietersen et al., 2020). Spacing of burrow occurrences in this study may therefore have been influenced by home range boundaries for at least some of the individuals recorded. This may have varied seasonally or based on mating behaviour (Pietersen et al., 2020; Prediger, 2020), and further research is required to establish this.

What can be inferred from the MCP home range analysis is that the tagged pangolins were absent from the cluster of low pangolin burrow occurrence in general (Cluster 1), suggesting avoidance of the entire area. Kernel density burrow use analyses correspondingly confirmed pangolin absence in Cluster 1 and revealed areas of high burrow use density in much of the surrounding area, including to the north and eastern regions of the study site. All methods used thus point to pangolin avoidance of areas containing larger than average burrow entrances. However, this may also be influenced by the population density of pangolins in the study area. Since few occurrence records were from non-tagged individuals this may indicate a low density in general. In the current study, pangolins utilised burrows with a mean CSA of 1550 cm^2, which was slightly smaller than the mean CSA of all aardvark burrows (1690 cm^2). These findings were consistent with, but slightly larger, than Prediger's (2020) findings of pangolin burrow diameter range of 33.79 – 34.19 cm (approximately 1142 – 1169 cm^2, if using the diameter as both the height and width, e.g. 33.79 x 33.79), and with

Whittington-Jones et al (2011) who report aardvark burrow diameter to range between 32.1 and 41.9 cm (1030 – 1755 cm²). The similarities found across these studies indicate consistent burrow sizes for aardvarks and suggest that pangolin burrow use is a function of what burrows are accessible to them, unless the burrow entrances exceed approximately a CSA of 2000. In comparison, Indian pangolins in India dig their own burrows and the mean entrance width of these is 25.65 cm (approximately 657.9 cm²), while pangolins in Bangladesh create a diameter of 15 – 20 cm (approximately 225 – 400 cm²; Mahmood et al., 2013; Trageser et al., 2017). Giant pangolins, which also utilise aardvark burrows, have been found to have a burrow diameter of 30 – 60 cm (approximately 900 – 3600 cm²; Bruce et al., 2018; Hoffmann et al., 2020).

Burrow depth, entrance size (cross section) and the number of entrances may be influential when choosing a burrow for shelter purposes. Burrows can vary greatly in depth and the number of chambers; those with numerous chambers can offer more shelter and hiding places than smaller or shorter burrows (Pietersen et al., 2014b). Entrance size additionally contributes to the level of security offered by a burrow. If an entrance is large enough to allow a predator in, risk of using that burrow increases (Harper and Batzli, 1996). This is commonly seen in marine species that utilise pre-existing burrows, including spiny lobsters (*Panulirus argus*) and many reef fish (Hixon and Beets, 1989; Eggleston and Lipcius, 1992). Pangolins likely use burrows that fit their own body size and are not large enough to allow predators access. Adult aardvarks are typically at least 4x larger than Temminck's pangolins, at 45 – 65 kg and 45 – 65 cm at shoulder height, compared to 9 – 10 kg and 30 – 40 cm shoulder height (Hutchins et al., 2003; Knöthig, 2005; McWilliam, 2019), thus they can create large burrow entrances. Pangolins in this study chose burrows slightly smaller than the mean aardvark burrow size and avoided those with consistently larger entrances. Mean adult leopard weight is substantially larger than adult pangolins, at 45.9 kg and 70 – 80 cm shoulder height for males (Stuart and Wilson, 1988; Dickman and Marker, 2005), while the mean for adult lions is even larger at 187 kg and 120 cm shoulder height for males (Smuts, Robinson and Whyte, 1980; Stuart and Wilson, 1988), and the mean weight for spotted hyaena males is 41 – 55 kg with a shoulder height of ~85 cm (Johnson-Ulrich et al., 2018; Mhlanga, 2018). The burrow sizes utilised by pangolins on average are small enough to protect them from predators thus size is likely to be a factor that influences burrow choice. This is particularly important for females and juveniles because they have smaller body sizes (Pietersen et al., 2020) and are more vulnerable to predation and thus require smaller shelters. It is plausible that pangolins did not use burrows within Cluster 1, because entrances in this area were larger and would allow predators to enter more easily. This was consistent across both soil types in this cluster and thus does not indicate a relationship between soil type and cross section. The reason for the existence of larger burrows in this area was unexplained by factors measured during this study. Adult aardvarks can vary in size substantially (Hutchins et al., 2003), thus it is possible that these burrows were created by a larger individual(s) in this area. However, the avoidance of this area may be unrelated to entrance size and may have been caused by unstudied environmental or habitat factors.

As stated previously, thermoregulation is an additional primary reason that pangolins are believed to utilise burrows. Burrows generally offer consistent climate conditions and insulation abilities that do not vary to the extent that the open air, above ground climate does (Wu et al., 2003; Wu et al., 2020). Temperatures and humidity levels do not change greatly, even if there are extreme weather conditions on the ground surface. Pangolins cannot regulate their body temperature by sweating or panting, as other mammals can, and their scales provide little insulation, so they rely on shelters to do this (Pietersen et al., 2014b). By utilising burrows, especially during the hottest or coldest times of day, they can better regulate their body temperatures. This may be an important factor for burrow choice because they may use the burrows with the most stable temperature or humidity conditions. Utilisation based on thermoregulation may change throughout the year as seasonal temperatures vary and different requirements are needed (Edelman, 2011). Aspect may influence burrow climate due to where the sun faces, impacting how fast burrow entrances warm up or cool down. The south-facing aspect of most of the burrows in this study may relate to avoidance of direct sunlight to reduce heat levels (Cunningham, 2001), depending on the burrow depth. Future studies into burrow use should consider collecting burrow temperature and humidity data to evaluate this. Soil characteristics can differ greatly, with varying levels of water retention, grain size, or drying abilities, all of which may potentially impact internal burrow climates (Rawls and Brakensiek, 1982) and this is linked to soil type. As only two soil types were present in the study and no preferential use was found between them, burrow use was likely a metric of availability in terms of soil type. In other regions this may differ where more soil types are available.

When active, pangolins spend much of their time feeding (Swart, 1996; Pietersen et al., 2020). For example, Indian pangolins have been known to feed on termites and ants burrow walls while within their burrows (Mahmood et al., 2013). Others, including the Chinese pangolin, utilise specific burrows solely for feeding (Wu et al., 2020; Tamang et al., 2022). This suggests that distance to food impacts pangolin distribution and burrow use, but the current study found no evidence for this. Although most pangolin burrows were recorded within termite mounds, pangolins did not preferentially select burrows within termite mounds. This may be explained by a surplus of food in the immediate area that makes food easily available and thus not a limiting factor. However, pangolin dietary choices are not always straightforward, with pangolins from different areas or regions preferentially feed on different ant or termite prey species. Some are known to prefer termites and others, ants (Coulson, 1989; Swart et al., 1999; Pietersen et al., 2020), and further work is needed to determine if this influences burrow use. In Sabi Sand Wildtuin, South Africa, Swart, Richardson and Ferguson (1998) recorded 55 ant and termite species yet only five termite and 15 ant species were predated by pangolins, suggesting that prey species richness does not impact the number of species consumed (Swart et al., 1998). Aardvarks also predate ants and termite species, with a typical preference for ants (Willis, Skinner and Robertson, 1992; Taylor, Lindsey and Skinner, 2002), although they are generalist predators of ants. Termite mounds may be influential for aardvark burrow site choice due to ease of prey access. Swart et al (1999) reported that 99% of feeding observations took place underground. The use of termite burrows by pangolins could simply be a result of where aardvarks have created them. To understand how food sources influence burrow choice for Temminck's pangolin further it would be necessary to study what species are being consumed by these pangolins.

Further investigation should consider the presence of other species in burrows. Numerous species utilise aardvark burrows, including rodents, birds, hares, and snakes (Whittington-Jones et al., 2011), and pangolins may actively avoid these burrows depending on the species. Of the species found to be sharing burrow space with pangolins, African hare and porcupine are predicted to be avoided by pangolin due to small burrow size limits. The frequency at which pangolins move burrows means they may not preferentially choose unused burrows if the burrow is large enough to host them alongside another species. To investigate this, it would be necessary to consider the size and number of chambers in a burrow, and the frequency at which burrows are shared along with the size of the species sharing the burrow. The sighting of a spotted hyaena and lion at the same burrow as a pangolin in this study may reflect predator-prey interactions (Pietersen et al., 2020) rather than burrow sharing.

It is possible that burrow use depends on individual pangolin preference. Sex and age may play a role in this choice, for example, females might prefer a burrow with more shelter, such as deeper chambers, than a male when she is pregnant or has a pup, and juveniles may also prefer shelter if they have recently dispersed from their mothers. Of the 34 camera trap nights with pangolins recorded during the study, one showed burrow sharing between two adults, potentially indicating a mating pair, and two burrows involved a mother and juvenile sharing. Females who have newly given birth are known to move burrows with their pups shortly after, and pups share burrows with their mothers until dispersal, which occurs between 3 – 12 months (Smithers, 1983; Pietersen et al., 2020). Utilisation may change seasonally based on thermoregulation needs and breeding routines, and males may choose burrows that are close to females. One male was observed to share a burrow with a newly dispersed offspring in a previous study, which may influence their use if this is a common behaviour (Pietersen et al., 2020). Sex and age information was available for the tagged pangolins (all adult females), however were not feasible to gather for wild pangolins during this study but would be an interesting factor to consider in the future. Camera traps or satellite tags (Morin et al., 2020) may make it possible to determine individual burrow preference or preference by sex.

3.4.1. Limitations

The primary limitation of this study was the inability to monitor all burrows for pangolin use simultaneously due to a limited number of camera traps and telemetry tags. Burrows were either considered ‘detected or ‘undetected’, which may have caused some false absences. To combat this issue in the future, it may be better to select a smaller study area and attempt to monitor all the burrows in this area at one time, e.g., by using camera traps at every burrow. Matthews et al (2022) indicate that targeted camera traps are effective for monitoring giant pangolins and thus may be a useful method for Temminck’s pangolin burrow monitoring. Increased monitoring would improve precision and the accuracy of estimates regarding burrow use. The use of endoscopes or detection dogs may be useful to increase monitoring accuracy, however the effort needed for these methods is high and may not be logistically feasible for a small research team.

Almost all of the pangolin burrow occurrences were from the three tagged pangolins. These individuals were monitored consistently throughout the study period, meaning the majority of their used burrows should have been detected, limiting false absences. However, this also means that the inferences from this study are applicable to these three individuals but not necessarily all pangolin populations. This likewise limits the ability to draw conclusions about the absence of pangolins in Cluster 1. Unrecorded factors, such as the presence of other non-tagged pangolins, may be influencing this absence. The VHF and satellite tracking of the three tagged pangolins did not take place simultaneously or for standardised periods of time, thus it is not possible to infer how social interactions or seasonality may influence burrow choice.

Burrows may have varied in size between 2019 and 2022, affecting overall inference. Furthermore, the number of burrows in the study site changed throughout the study period. Some burrows were known to have collapsed over the study period, hence monitoring for pangolin use throughout the study was not always possible (Pietersen et al., 2014b), and likewise new, un-recorded burrows were likely to have been excavated during this period. Further studies should therefore quantify burrow dynamics over time and incorporate this into statistical models.

Many variables that may influence pangolin burrow choice were collected, however, several variables that would have enhanced the findings were not recorded. For instance, inclusion of burrow temperature and humidity and demographic variables as covariates would have been beneficial in evaluating burrow microclimates. These variables would have helped bridge the knowledge gap in pangolin biology necessary to fully understand burrow utilisation, however, there are inherent difficulties and challenges with collecting this data and they require specialised equipment and training. Soil moisture content, prey species abundance, and predator abundance would be interesting variables to consider, however at the time of this study, they were not feasible to collect and hopefully in the future it will be possible.

3.5. Conclusion

This study found that pangolins are generalists when utilising aardvark burrows and appear to choose whatever is readily and easily available to them, with the caveat that they avoid burrows with large entrances. Pangolins only chose a small number of burrows even when there were many to choose from, indicating selection on some level, but predictors of such variation are currently unknown. The aardvark burrows recorded in this study were predominantly south and west facing, within termite mounds and excavated in eutric planosol soils with small particle size, although the latter may simply reflect the predominant soil type available. Pangolin burrow occurrence did not conform to any patterns of physical burrow characteristics, except that pangolins avoided a part of the study site where cross-sectional area of burrow entrances was large. Several burrow characteristics, particularly those involved with burrow microclimate regulation, need to be assessed further to fully understand why the utilisation of certain burrows occurs and to determine if burrow selection is taking place. Shelter and thermoregulation are certainly important considerations for pangolin persistence and are likely influential factors when considering pangolin distribution. Investigating these characteristics further is a key next step to understanding pangolin burrow use which will in turn aid in developing conservation plans. Additionally, it is likely that intrinsic variables such as social factors influence pangolin burrow use and further study investigating pangolin space use overlap and dynamics where multiple individuals are tagged simultaneously is necessary to confirm this. The combination of SaTScan analysis and Average Nearest Neighbor estimates are an informative analysis combination for studies where identifying areas of high and low burrow use are important research goals.

Chapter 4 - Using citizen science sightings to assess pangolin habitat suitability and predict potential threats

4.1. Introduction

Monitoring elusive species such as Temminck's pangolin can be challenging due to their low-density nature. Traditional tracking methods, like detecting field signs, are not typically viable for this species, thus alternative methods must be sought (Willcox et al., 2019). Citizen science offers the opportunity to gather distribution data by utilising local knowledge from those who reside within pangolin range and may opportunistically witness them (Sompud et al., 2023). This data can be collected on a wide scale and can result in a large amount of data with relatively low effort needed to collect it, however, data quality may vary depending on the participant and the data collection methods (White et al., 2005). Citizen science can be collected either throughout scientific study, community interviews, or by examining social media posts from tourists including ecotourists, all of which may be useful for pangolin spatial and ecological monitoring (Di Minin and Hausmann, 2020).

Citizen science has been utilised to collect pangolin data to a limited extent thus far and it is indicated as a promising method for the future (Willcox et al., 2019). Community interviews have been suggested as an efficient and cost-effective method to evaluate pangolin distribution at a broad scale (Willcox et al., 2019). These can be opportunistic, semi-structured, or structured (Ingram et al., 2019). As pangolins are an easily identifiable set of taxa they may be recognised by members of the public, which could be particularly useful in areas were population status is unknown (Willcox et al., 2019). This form of data may also provide behavioural and ecological knowledge, and may be used to plan surveys and identify conservation priority areas (Willcox et al., 2019). This is known as local ecological knowledge (LEK) and is very useful for providing preliminary data on pangolin ecology. This could even be applicable for estimating occupancy if sampling is structured appropriately and consistently (Morin et al., 2020). Even if data is not collected in a structured manner, it can provide confirmation of pangolin presence for regions where this is unknown and may be applicable to all pangolin species (IUCN SSC Pangolin Specialist Group, 2018).

Few studies have employed citizen science as a method to monitor pangolin distribution and typically this data has been used in combination with other data sources. LEK was utilised by Simo et al (2020) to assess the distribution of the white-bellied pangolin in Cameroon, alongside camera trap data. Newton et al (2008) conducted semi-structured interviews with hunters to collect pangolin presence records and evaluate hunting practices in Vietnam. Further, Tenorio and Baril (2019) used social media interviews to investigate public knowledge of the Philippine pangolin across its range. Whilst, Sompud et al (2023) used an informal questionnaire from local residents, combined with camera trap data, to gather sighting reports for the Sunda pangolin, and investigate their distribution in University Malaysia Sabah Hill, Malaysian Borneo. For Temminck's pangolin, only one study by Pietersen et al (2021) utilised citizen science alongside other historic records and literature to generate a habitat suitability model for South Africa. These studies all indicate that using citizen science in the form of LEK is valuable method for gathering pangolin ecological data, particularly in remote regions where data is lacking. In particular, habitat suitability models generated with citizen science presence data can provide predictive insight into pangolin distribution and environmental requirements.

4.1.1. Habitat suitability models

The rarity and nocturnal behaviour of pangolins means that evaluating their distribution and habitat use can be difficult (Sharma et al., 2020b). Habitat suitability models (HSMs) are becoming an increasingly common tool for estimating the predicted distribution and habitat use of a species by extrapolating presence data based on environmental data. These models evaluate environmental features such as terrain, habitat type, aspect, slope, and available resources, like prey presence, to assess where a particular species is most likely to be present and ascertain how much of this habitat exists (Doswald, Zimmermann and Breitenmoser, 2007; Bradter et al., 2018). HSMs extract important variables linked to species' presence at known sites and predict the probability of occurrence where the species has not yet been recorded (Phillips and Dudík, 2008; Elith and Leathwick, 2009; Pietersen et al., 2021). These models infer the relationship between the target species, habitat features, and environmental conditions (Zhang et al., 2019). Results from HSMs can inform conservation practice and policy by additionally assessing how habitat loss and human presence might impact a species' distribution. Distribution is often prerequisite knowledge for conservation initiatives and is important for species protection (Sharma et al., 2020a). Habitat suitability models rely on presence data for the target species, which can come from radio or GPS telemetry, direct observation, camera traps, or a combination of methods (Watts et al., 2019; Pietersen et al., 2021). This means citizen science data is ideal for conducting habitat suitability models because a large quantity of species presence data can be collected for a wide area (Dissanayake et al., 2019; Crawford et al., 2020). Henckel et al (2020) compared the use of opportunistic citizen science data and inferred absences with systemically collected ecological survey data, and assessed the accuracy of habitat suitability models for several bird species. The study found that both methods provided comparable predictions, for all species, indicating that simple citizen science studies are able to generate reasonable habitat suitability predictions. However, the effectiveness of this approach may depend on the rarity and ecological traits of the focal species. Bradter et al (2018) utilised a similar approach by collecting opportunistic observations from volunteers for an uncommon species, the Siberian jay (*Perisoreus infaustus*). The HSMs from this agreed with systemically collected data, showing that this method is appropriate for less common species. Using citizen science for HSMs is applicable to numerous taxa and has been done for several mammal species. For example, Turner, Freeman and Carbone (2021) implemented citizen science to create habitat suitability predictions for hedgehogs (*Erinaceus europaeus*) in London, UK. Whereas, Sequeira et al (2014) utilised data from a one-day citizen science initiative to model koala (*Phascolarctos cinereus*) distribution in southern Australia. Habitat suitability models can also be used to monitor invasive species. Serniak, Chan and Lajtha (2023) used citizen science reports from iNaturalist to predict the potential distribution of jumping worms (Genus *Amynthas*) in North America (iNaturalist, 2023). The majority of these studies either included inferred absences, pseudo-absences, or bias predictions, to limit the inherent spatial bias of citizen science points.

Habitat suitability models require habitat variables, for example, climate, habitat type, soil type, and water source locations, which can be remote sensed to be analysed with citizen science presence data (Dickinson et al., 2012). These models can be used to assess how wildlife is impacted by human landscape features. For example, Wall et al (2021) used habitat suitability models to evaluate how human presence impacted the availability of suitable African elephant habitat and if the human landscape footprint influenced elephant home ranges. Maximum entropy modelling is the most common methodology for these models and utilises presence-only data to make ecological pattern predictions based on richness or abundance from presence points (Xiao, McGlinn and White, 2015). This approach can be very informative for elusive species because it does not depend on large datasets to make predictions (Sharma et al., 2020b). Habitat suitability models have been conducted for four of the eight pangolin species: Temminck's pangolins (Pietersen et al., 2021), giant pangolins (*Smutsia gigantea*; Mouafo et al., 2023), Chinese pangolins (*Manis pantadactyla*; Dorji, Chong and Dorji., 2020; Sharma et al., 2020a; Suwal et al., 2020) and Indian pangolins (Suwal et al., 2020; Waseem et al., 2020). Mahakata et al (2021) examined environmental characteristics that correlated with Temminck's pangolin distribution, however this was done by testing for correlations between environmental data at each presence location, rather than producing habitat suitability predictions using maximum entropy modelling.

In Kenya, pangolins are found throughout much of the country, but no studies here have investigated their preferred microhabitats within their home ranges (i.e., 4th order habitat selection) or why they select particular areas as home ranges (i.e., 2^{nd} or 3rd order selection; Montgomery and Roloff, 2017). They have not been recorded in some areas that appear to have suitable habitat, so it is likely their distribution is greater than currently known. Their distribution is thought to be influenced by habitat loss, such as that created by agriculture (Pietersen et al., 2020). Temminck's pangolin have a wide elevation range, from sea level to 1700 m above sea level and are found where annual rainfall ranges from 250 – 1400 mm (Coulson, 1989; Pietersen et al., 2020). A habitat suitability model for Temminck's ground pangolin has been conducted for South Africa using climate and habitat variables but this did not include anthropogenic variables, such as poaching, as a threat evaluation component (Pietersen et al., 2021). Pietersen et al (2021) modelled both current and past distribution of Temminck's pangolins in South Africa. Presence records were compiled through literature reviews, databases, and citizen science efforts. These were split into two groups, prior and post 2011, to form historic and current records. This study included five bioclimate variables: annual mean temperature, mean diurnal range of temperature, maximum temperature of warmest month, minimum temperature of coldest month, and annual rainfall, based on known ecology of the species. Soil type, vegetation, vegetation type, and bioregion were also included. The study found that grassland type, followed by soil and vegetation type, contributed most to pangolin distribution, while annual rainfall contributed the least. This was consistent between the historic and current data groups. Mahakata et al (2021) utilised historical sightings data for Temminck's pangolin in Zimbabwe to evaluate important environmental characteristics. This study did not generate a habitat suitability model but did assess the spatial correlation between sightings data and environmental characteristics. This found that pangolins in Zimbabwe are primarily found in Zambezian and Mopane woodlands, and that rainfall varied across region but did not correlate with pangolin sightings. Mouafo et al (2023), conducted a HSM study on giant pangolins in Cameroon. Seventeen variables including, NDVI, elevation, distance to waterways, soil type, and lithology were included to analyse giant pangolin burrow distribution. One anthropogenic variable, distance to national park borders, was also included. Results showed that the distance to national park borders and NDVI were the main predictors of giant pangolin habitat suitability. Burrows were located primarily between 2400 – 23000 m away from park boundaries indicating some form of human pressure. Meanwhile, elevation, distance to waterways, and soil influenced prediction to a lesser extent (Mouafo et al., 2023).

Sharma et al (2020a) used presence data from an 11-year period across Nepal to predict Chinese pangolin distribution by recording field signs whenever they were encountered. They found that a low variation in temperature was ideal for Chinese pangolins because they have a limited ability to regulate body temperature (Sharma et al., 2020a). The most suitable habitat for this species was in cultivated areas that are rich in ant and termite populations, typically close to forest areas for refuge. Suwal et al (2020) studied the distribution of both the Chinese and Indian pangolin in Nepal and found that pangolin distribution was primarily influenced by ground and canopy cover of 50-75%, litter depth, and distance to termite mounds. Pangolins were mostly found in human-dominated landscapes, and distance to roads was an influential variable (Suwal et al., 2020). In a similar study, Indian pangolins (*Manis crassicaudata*) habitat suitability was assessed using habitat and bioclimate variables. It found that elevation was the most important variable, followed by temperature, settlement presence, land class, slope and then aspect. Cultivated land was the most important habitat type and grassland was the least used (Waseem et al., 2020). Both studies revealed that agricultural land was very important for pangolin use, likely due to the presence of food sources. A study by Mahmood, Andleeb and Akrim (2021) found that most Indian pangolin signs occur in wild areas, followed by areas near human activity, and lastly, agricultural areas, although the study utilised field signs only and did not conduct habitat modelling. These findings contrast somewhat with those of Pietersen et al 2021, who report that a high level of farmland and habitat conversion in some regions of South Africa may cause Temminck’s pangolin to use protected areas and small areas of natural vegetation (Pietersen et al., 2016a; Pietersen et al., 2021). Prey requirements differ between pangolin species, which therefore use habitat types in different ways (Mahmood et al., 2020; Pietersen et al., 2020; Wu et al., 2020). Human-derived habitat fragmentation was found to be a common feature in Chinese pangolin habitats and potentially those of Indian pangolins also. Fragmentation can have numerous impacts on a species, including increased predation pressure, resource competition, and increased disease outbreaks, which all can be caused by the reduced area that a species can inhabit (Teckentrup, Kramer-Schadt and Jeltsch, 2019; Bozzuto, Canessa and Koella, 2021). Additionally, fragmentation may indicate a close proximity to humans if the habitat is fragmented by human structures or activity, thus there may be a high threat due to poaching activities (Sharma et al., 2020a). It is probable that anthropogenic impacts are equally impactful for Temminck's pangolin given the significance of poaching for traditional uses and bushmeat consumption for their populations.

4.1.2. Threat risk modelling

Typically, habitat suitability models aim to assess primarily environmental variables such as climate and habitat, however several recent studies have included anthropogenic factors like settlements or roads (Pérez-García et al., 2017; Fabrizio et al., 2019; Wall et al., 2021). This has led to the development of models that predict human-wildlife interactions and impacts, known as risk modelling. These models can incorporate human population density or other indices such as, human activity, buildings, roads, or fence lines, to assess if there is an impact on wildlife. They can be used to examine poaching threats, habitat loss, or barrier effects created by roads and fences. For example, Wadey et al (2018) used mechanistic modelling frameworks to assess elephant behavioural responses to roads as barriers in Malaysia. This approach used a habitat selection and movement model to determine if there was an ongoing barrier effect caused by roads. Whittington et al., (2005) used a similar approach when evaluating wolf road-related behaviour to create a spatial map of wolf habitat to identify areas of enhanced roadkill risk. While human activity likely influences the distribution of many species, risk models can also be used to determine what habitat is lowest risk for a species. Since pangolins are under severe threat from humans due to poaching, proximity to humans is a main consideration for this due to the increased likelihood of both planned and opportunistic poaching (Pietersen et al., 2016a). By including anthropogenic activities in a habitat suitability model, it is possible to generate a model that predicts the most at-risk areas for human-related threats. In particular, including population and proximity to human settlements can be used to infer the level of anthropogenic impact, which may include poaching risk.

In addition, there are lesser-known threats that pangolins face. Numerous taxa including pangolins, primates, and small mammals, are electrocuted on powerlines or fences, but birds are one of the most commonly electrocuted taxa, which has led to the majority of studies focussing on them (Bevanger, 1994; Dwyer, Harness and Donohue, 2014; Pérez-García et al., 2017). Although morphologically very different, the modelling and risk prediction methods used for bird electrocutions can be applied to pangolins and other species. Pérez-García et al (2017) created a risk prediction map for the electrocution of numerous protected bird species in Spain. This was conducted using historic electrocution records alongside species presence records to evaluate the risk level of each grid area. Habitat suitability models were created to assess electrocution rates in different areas with different environmental variables. From this, low, medium, and high priority areas for electrocutions were identified and the results were used to inform future species protection. A similar approach was used by Crespo-Luengo et al (2020) to study raptor electrocutions. This study created species distribution models using historic data to evaluate raptor spatio-temporal data in relation to electric wires. The study evaluated electrocution risk based on the number of power poles present compared to known raptor presence. Study sites were then classified as low, medium, or high risk for electrocutions. A similar method could be used to investigate threats to pangolins, encompassing fences, roads, and proximity to human settlements.

Studies that assess the impact of manmade landscape features such as roads, powerlines, fences, and railroads on wildlife have become increasingly popular over the last decade. Researchers have only recently begun to investigate the impacts of barriers such as fences, or anthropogenic risk factors such as road collisions or powerline electrocutions, on wildlife. These barriers can be impermeable and cause the loss of movement corridors, while increasing habitat fragmentation (Gregory et al., 2021). Mortalities caused by vehicle collisions are known to impact numerous species globally, including pangolins, with up to 280 pangolins killed per year in South Africa (Pietersen et al., 2014a; Pietersen et al., 2016b). In a 24-month study in Pakistan, 131 carcasses and 18 species (including two Indian pangolins) from seven orders were recorded as killed by vehicle collisions, the majority of which were on paved roads and immediately adjacent to protected areas (Akrim et al., 2019).

Barriers such as roads and fences can filter or prohibit animal movement by causing habitat fragmentation, which often occurs alongside habitat loss (Robinson et al., 1992; McDonald and Clair, 2004). Interacting with barriers like fences means that animals need to navigate their habitats in a more complicated way (McDonald and Clair, 2004) and barriers often cause edge or barrier effects. Barriers have the potential to limit access to food, shelters, and overall space. This has a potential knock-on which will inevitably have impacts effects on population fitness and reproduction rates (Fahrig and Rytwinski, 2009; Grilo et al., 2012). It is likely that habitat preference plays a major role in a species' behaviour towards barriers, those that are habitat specialists may be restricted to areas that incorporate barriers whereas generalists might ignore these areas (Grilo et al., 2012). Understanding spatial behaviour in relation to barriers is vital for the conservation biology of many species, and knowledge of how animals move through a fragmented system is an important indicator of landscape connectivity (Poessel et al., 2014). The effects of this fragmentation can influence species over large time scales and impact entire communities, and may put increased pressure on migratory species (Brum et al., 2020; Robson, 2011). Roads in particular may not represent a major barrier if unfenced, as individuals may be able to cross them easily (Porto Peter et al., 2013), yet roads still have the potential the impact home ranging behaviour, particularly if there are other forms of disturbance, such as noise. Busy roads may produce a high level of noise during their use, as well as both their operational and construction phases when they are constructed, which can disturb and displace wildlife (Gaughran et al., 2021).

The versatile uses of citizen science data mean it is possible to generate habitat suitability models for pangolins, and subsequently, risk models can be created that assess anthropogenic threats to pangolins and evaluate poaching risk. Additionally, if contextual data is collected during citizen science observations this can provide interesting insights into pangolin behaviour and distribution. The combination of these approaches will allow us to evaluate regions where pangolins are most threatened and plan conservation action accordingly.

4.1.3. Aims

This study aimed to utilise citizen science to examine the wider-scale habitat and climate variables that influence Temminck's pangolin distribution throughout Kenya, and assess anthropogenic risk factors. Since little is known about pangolin ecology and habitat use in East Africa, a range of variables were necessary, selected because they provide a comprehensive dataset that informs in detail on the Kenyan ecosystem and environment. This included examining how: annual mean rainfall, annual mean temperature, vegetation greenness, topography, distance to waterways, and soil type, are predicted to influence pangolin distribution. Then the study aimed to evaluate the level of threat caused by distance to roads, distance to buildings (as a proxy for human activity), distance to fences, and human population density, all of which are known to pose threats to pangolins.

Objective 1 was to create a habitat suitability model for pangolins using climate, habitat, vegetation, and soil data. This aimed to assess how much suitable habitat exists in southern Kenya and the distribution of this habitat. It was predicted that a combination of these variables would influence pangolin distribution and that this would vary between the Narok County study site and Kenya overall. Objective 2 then aimed to use anthropogenic datasets to generate species risk models and assess human impact on pangolin distribution. It was predicted that proximity to humans and roads would be the largest risks, as poaching is a well-known threat to pangolins and road presence is widespread (Pietersen et al., 2014a). Risk level was expected to decrease with increased distance from roads, human populations, and areas of human activity. Fences were predicted to be a lesser threat due to their relatively low presence throughout the study area.

4.2. Methods

Citizen science data were collected in Kenya, over 21 months between September 2020 and June 2022. Five communities and conservancies from the Narok region were surveyed: Lemek Conservancy, Pardamat Conservation Area, Mara North Conservancy, Pololeti Plains, and Ol Derkesi Conservancy and one in West Pokot, Western Kenya. Narok County was chosen due to known pangolin presence and West Pokot was included as a result of consistent public reports to The Pangolin Project (PP) of pangolins in the region. The main study site was defined as an ~5600 km^2 portion of Narok County in southern Kenya that included all Narok target communities, as well as

Masai Mara National Reserve (Figure 4.4). This site boundary did not include all of Narok County in order to reduce the spatial extrapolation of the results to obtain the most accurate predictions. This is referred to as the 'Narok County site'. A map of the site location is found on page 51, Chapter 2: Figure 2.2.

PP staff and volunteer 'Pangolin Ambassadors' collected the data. Ten volunteers from the five Narok communities with an interest in pangolin conservation were appointed as Pangolin Ambassadors to coordinate the research and were selected using two methods: 1) conservancies and communities within Narok selected candidates amongst themselves; 2) roles were advertised within the conservancies and communities by word of mouth from PP staff. Project staff also acted as recorders and collected data alongside the Pangolin Ambassadors. PP staff conducted all surveys in West Pokot. Data in all locations were collected in the same format but by different personnel. Pangolin Ambassadors conducted several different activities during their role. They recorded details of pangolin sightings and locations of pangolins on a form (Appendix 4) during the following activities: delivering key messages to interested village members about pangolin conservation during organised in-person village visits; answering questions the public had about pangolins in the same forum as key messages; recording pangolin sightings, both historic and current; attending The Pangolin Project team meetings; and conducting first responder activity if a pangolin needed rescuing or medical attention. This study utilised pangolin presence-only sightings data and this was recorded throughout all of the above roles.

4.2.1. Citizen science data collection

The ambassadors collected citizen sightings of pangolins throughout their communities. They went into their communities for a minimum of 3 – 5 days per month to collect sightings data. During all visits, data was conducted in two ways, by recording historic sightings and by asking members of the public to report new sightings, with the use of a survey form (Appendix 4, and Appendix 6: Table A1 – A4). Firstly, whenever an ambassador undertook activities they recorded historic and previous pangolin sightings from the community. They approached interested members of the public and asked them to report any sightings. This had no time restriction so sightings could be reported from previous years or decades, although the target for this study were sightings within the last 10 years thus older sightings were removed from the analyses. If a participant could remember the year but not the date this was recorded as 1st of January for that year. The goal of this was to collect sightings data from as many people as possible living within each community.

At the end of each visit, the ambassador gave out their mobile contact number to anyone who participated so that they could report any further sightings. It was requested that the community members report sightings as soon as they occurred. Once notified of a sighting, the ambassador travelled to the community to record the sighting. Every ambassador activity and pangolin sighting recorded was used as a metric of effort for pangolin monitoring. Participants were asked to estimate the location of the sighting and the number of pangolins present, as well as select from categories regarding: the behaviour of the animal, the vegetation present, and the time of day (Appendix 4). Reporters could not always recall this information, so this data is unbalanced. These data points were summarised descriptively and not included in the habitat suitability analyses.

4.2.2. Habitat and risk variable remote sensing

To conduct habitat modelling, climate and environmental variables potentially influencing pangolin distribution and habitat selection were remotely sensed (Table 4.1). Habitat was modelled through Normalised Difference Vegetation Index (NDVI), which shows the level of green vegetation. This was selected as a modelling layer because it is directly related to vegetation cover (Borowik et al., 2013), and savannah and grassland areas are the predominant habitat types in the study site (Li et al., 2020). NDVI data from May 2022 was utilised as green vegetation is most prevalent during this time of year in southern Kenya due to it being the rainy season (Ottichilo, 2000). Soil type was included in the model because this abiotic factor may influence habitat choice (Shrestha et al., 2021), prey distribution, or burrow distribution. Topography was modelled through including Shuttle Radar Topography Mission (SRTM) because it may impact how land is used by pangolins. Climate data comprised annual temperature (°C) and rainfall (mm). Distance to waterways was also included. Pangolins are thought to typically be water independent (Pietersen et al., 2020), but waterways data was included to determine if this is the case for pangolins in Kenya. The remaining variables included in the models were all anthropogenic and included: roads, buildings, and human population layers. Pangolins are known to die on roads and fences (Pietersen et al., 2014a) so this was an important consideration for the model. All road types were merged and treated homogenously. The other human variables represent general human activity (buildings) and proximity (human population) so were included to assess the level of poaching risk that pangolins may face.

Table 4.1 All remote sensed variables used in the habitat and risk models. These were remote sensed raster and shapefiles and all are open access. All sources are listed.

Variable	Description	Data type	Source
Soil	Soil type distribution data.	Categorical	RCMRD Geoportal, 2015
Waterways	All waterways and water sources.	Continuous	HOT, 2021
NDVI	Normalised difference vegetation index.	Continuous	USGS, 2022
Roads	All roads, including paved and unpaved.	Continuous	ROSEA, 2018
Fences	All fences, including electric and non-electric. Covers Narok site only, does not cover full Kenya extent.	Continuous	Tyrrell et al., 2022
Buildings	All buildings.	Continuous	HOT, 2022
Human population density per km²	Population data from the 2020 national census.	Continuous	WorldPop, 2018
SRTM (topography)	High radar shuttle resolution topography map.	Continuous	Macharia, 2004
Climate	Temperature and rainfall data.	Continuous	Fick and Hijmans, 2017

4.2.3. Data formatting and analyses

Both sighting and ambassador data were filtered to include only georeferenced records and data were cleaned by removing erroneous GPS locations (e.g., locations outside of Kenya). Participants could report sightings as far back as memory allowed, however only data from within the last ten years were included (2012 – 2022). Sightings for which there was no date or year were excluded from analyses. The analyses included two sites: the Narok County site, and all of Kenya. A total of 140 pangolin occurrences were recorded, with 137 within Narok and three additional in West Pokot, the latter only included in the full Kenya analysis.

Pangolin spatial points were mapped in ESRI ArcMap Desktop 10.8.1 (ArcGIS, 2020). Habitat suitability and risk modelling was conducted in Maximum Entropy Modeling of Species Geographic Distributions (MaxEnt) 3.4.3 (Phillips et al., 2020) and statistical tests were run in RStudio 1.4.1106 (2021) and SPSS (IBM, 2019). Descriptive maps of Pangolin Ambassador effort and pangolin density were generated using default settings of the 'Kernel Density' tool. Default search radii were used for each, these were 5156.98 m and 13055.16 m, respectively. The 'Near' tool in ArcMap was utilised to calculate the mean distance and distance ranges of pangolins within the Narok site to waterways, roads, and fences (Table 4.2).

MaxEnt is generally considered robust to issues of variable collinearity because correlations between the predictor variables are stable across the area for which models are generated. It does this by controlling model complexity through downplaying the importance of redundant variables (Phillips and Dudík, 2008; Elith and Leathwick, 2009; Elith et al., 2011; Shcheglovitova and Anderson, 2013; Feng et al., 2019). However, it is still important to take potential collinearity into account when interpreting results (Kornejady, Ownegh and Bahremand, 2017). To assess collinearity of the remotely sensed variables, SPSS was utilised to run Pearson correlation coefficient tests on both the environmental variables and the risk variables. Values of ≥ 0.7 were considered highly collinear (Dormann et al., 2013; Kornejady et al., 2017; Suwal et al., 2020).

<u>Data formatting for MaxEnt analyses</u>

Resolution and formatting varied between the remotely sensed data layers. To generate the roads datasets, two datasets were merged – one that encompassed all of Kenya and one that was fine-scale and focused on Narok County (ROSEA, 2018; Tyrrell et al., 2022). To standardise all data, all layers were reformatted to the same cell size and geospatial extent in ArcMap. All layers were in the WGS84 decimal degrees coordinate system. Firstly, each layer was clipped using the 'Clip' tool twice, once to the site size and once to Kenya's border outline. For raster datasets including climate data, human population, NDVI and topography, the 'Resample' tool was used to change the existing cell size. All original layers were examined for their cell size and the smallest size (0.000833333, 0.000833333) was selected to aid in producing the clearest visual maps. The 'Nearest Neighbor' resampling technique was used for raster layers except for the temperature and rainfall data. For these the 'Bilinear' format was used to ensure the layers were resampled smoothly. After resampling, the layer was clipped again to each desired site. Polygon shapefile datasets, including soil type and lithology were converted to rasters using the 'To Raster' tool. During this process the same cell size as above was inputted as the desired output extent and an identical rasterization process was repeated.

Several polyline shapefile datasets were utilised. These were roads, fences, buildings, and waterways. For these datasets, the desired output was the distance to each of these features, rather than the feature itself. To achieve this, the 'Euclidean Distance' tool was used. To provide a meaningful distance estimate in metres, each layer was first converted to UTM 37S projection using the 'Project' tool so that the Euclidean distance output would be in metres rather than decimal degrees. Once in UTM, the polyline files were inputted into the 'Euclidean Distance' tool that yielded outputs as raster files, before clipping each file to the desired site. Following this, the 'Project' tool was used to convert the files back to WGS coordinate system.

All files were checked to ensure the coordinate system, cell size, and geographic extents matched as this is a requirement for MaxEnt to operate. Lastly, all files were converted to ASCII format.

4.2.4. MaxEnt analyses

MaxEnt habitat suitability and risk models were generated for both the Narok County study site and for all of Kenya. Cross validation of MaxEnt settings was done for each to determine the most appropriate settings for the datasets. The variable files were input into MaxEnt and setting protocols were modified to match those used by Pietersen et al (2021) on Temminck's pangolin in South Africa, and those of Mouafo et al (2023) on giant pangolins (*Smutsia gigantea*) in Cameroon. These included determining the cross validation number, regularisation multiplier, and output format settings. Output format was set to logistic, and the maximum number of iterations was 1000. As the sample size was greater than 80 (N = 104), MaxEnt's Linear, Quadratic, Product, and Hinge, models were used in combination (Mouafo et al., 2023). Jackknife testing was used to assess the influence of individual variable predictors on the model. All other settings were kept at default.

<u>Dealing with sampling bias</u>

Spatial bias is often an unconsidered and unaccounted for issue in habitat suitability modelling and MaxEnt requires unbiased sampling of occurrence (Kramer-Schadt et al., 2013). MaxEnt assumes that all locations are equally likely to be sampled yet most sampling locations have some bias due to frequent sampling near human activity, like towns and roads (Merow, Smith and Silander Jr, 2013). As there were only five data collection sites in this study it is likely that the data were biased due to skewed sampling effort and distribution. It is especially important to consider bias for presence-only data as no absences exist to inform fully on which locations were searched (Merow et al., 2013). To combat this, bias files were created and used during all MaxEnt modelling. The Species Distribution Modelling (SDM) Toolbox extension (Brown, 2014) was added to ArcMap and the 'Gaussian kernel density of sampling localities' tool was utilised. This tool creates a bias grid across the study site and upweights the occurrence points with the fewest neighbours, which accounts for sampling bias (Kramer-Schadt et al., 2013; Brown, 2014; Zhao et al., 2022). Bias in each cell is ranked and scores of 1 equal no bias, and higher scores indicate higher levels of bias (Brown, 2014; Fourcade et al., 2014). All occurrence points are inputted along with a *Sampling bias distance* (SBD) value, which is a user-selected value based on the distance between sampling points. SDM toolbox recommends using between 30 – 100 km before adjusting as necessary based on the site size (Brown, 2014). For focal sites of differing sizes, different SBD values may be necessary to accurately reflect the sampling distance in relation to the site size.

For the Narok site, bias files with five SBD values were generated: 11 km, 30 km, 50 km, 90 km, and 112 km. Cross validation of 20 and 500 iterations were used to test these bias files. This was computed for the environmental variables and then for the anthropogenic risk variables. During cross validation the same parameters as above, and a regularisation multiplier of 1 (default), were used. This was repeated for the full extent of Kenya, with a cross validation of 10 and 100 iterations, to improve computational time as the dataset was very large. SBD values of 112 km, 350 km, 700 km, and 1000 km were tested to account for the much larger site size compared to the study site. SBD values below 100 km did not generate feasible bias files as these resulted in no bias variation, likely due to the occurrence points being too clustered.

The average Area Under the Curve (AUC) value was used to determine the most appropriate SBD value. AUC is utilised to interpret the predictive power of the models, with AUC values of > 0.9 considered excellent, 0.8 – 0.9 considered very good, 0.7 – 0.8 considered good, 0.6 – 0.7 considered fair, and < 0.6 considered poor. For the site environmental data only models, each SBD value yielded an average AUC above 0.8 thus a very good rating. 30 km was selected as the value to be used for all subsequent environmental models as this is within the recommended SDM range and accounts for the distribution of the sampling effort without overfitting the model or generating too much noise. For the anthropogenic variables, only the 11 km SBD yielded an average AUC value of ≥ 0.7 (good), while all other variations produced values of 0.6 – 0.7, thus 11 km was used for all subsequent risk models.

For the full extent of Kenya, all bias files for the environmental and risk variables produced AUC scores over 0.9 meaning all were excellent models. A value of 112 km was selected as this model did not produce noise or overfit, and because it was within SDM recommended range. This also maintained consistency between the datasets.

Regularisation multiplier selection

Cross validation was set to 20 and was used to determine the most appropriate regularisation multiplier (RM) and the bias file was included during these analyses. RM is used to reduce overfitting of the model. RMs of 0.5, 1, 1.5, 2, 2.5, and 3, were tested based on each average AUC value generated during cross validation, following Mouafo et al (2023). During cross validation the same parameters as above were used, except iterations were lowered to 100 to save computational time, which is common practice for exploratory analyses. This was done for both the Narok County site environmental variables, and again for the anthropogenic variables. For the Narok environmental data, each RM had an AUC of over 0.8, with 0.5 and 1 having the highest values. For the Narok anthropogenic models, each had an RM of 0.71 – 0.72. For the full extent of Kenya, cross validation was set to 10 and both the environmental models and risk models produced scores of > 0.9. An RM of 1 was selected for all subsequent models as this is the default MaxEnt RM value, which has previously been used for numerous taxonomic groups (Merow et al., 2013). 0.5 was not selected as lower RMs generally create more complex models with excess noise and potential overfitting, while higher RMs may generate clearer, more concise models and reveal similar dominant patterns to lower RM models (Merow et al., 2013; Phillips, 2017). However, if an RM is too large it may result in less localised predictions (Phillips, 2017).

MaxEnt Output

The values selected from cross validation for SBD and RM were applied to all habitat and risk models for the Narok County site and all of Kenya. Final models were run and the results and maps are reported below.

Figures displaying the influence of each environmental variable and their corresponding standard deviation were generated during the cross validation process. MaxEnt produces a map with the predicted level of suitable habitat, along with results for how each variable influences this model. The suitability map includes values from 0 – 1 that represents the overall probability of presence based on the environmental variables. Zero indicates the lowest probability and one indicates the highest (Phillips, 2017). For the risk models, this represented the probability of presence in relation to the anthropogenic variables.

Following each model, the levels of suitability or risk for each model were binned into range categories to assess the proportion of each classification type available within the study sites, for ease of interpretation. Habitat suitability was classified into: very unsuitable, unsuitable, somewhat suitable, suitable, and very suitable. Risk was classified into: very low risk, low risk, moderate risk, high risk, very high risk. This was done using '*natural breaks'* in ArcMap symbology as this classifies the data based on natural groups in the data distribution (Esri Technical Support, 2023). The proportion of each was calculated using the 'Zonal Histogram' tool, along with the amount of land covered by each category in kilometres. To achieve this, the 'Project' tool was used to convert each to UTM 37S so the result would be expressed in the metric system.

Once a habitat suitability and risk model were generated for each of the Narok County site and Kenya full extent, these were analysed together to determine regions with the most suitability and highest risk overlap. This was done to identify where the most suitable areas of habitat for pangolins overlaps with the areas of highest risk to them. The 'Raster Calculator' tool in ArcMap was utilised to multiply the habitat and risk rasters together, which generated a new raster with a pangolin distribution risk scale. From this, raster was split into categories of: very low, low, moderate, high, and very high risk, as above. The proportion of and amount of land in each category was calculated. This method was chosen over the method of inputting all ten variables into one MaxEnt model to avoid creating a 'black box model' in which it is difficult to interpret how the variables interact. By generating separate habitat and risk models it is possible to understand how the habitat variables influence pangolin distribution independently of risk factors, and subsequently analyse areas of risk. This provides a clear understanding of areas of high suitability and risk separately. Multiplying these output rasters together then provides a hotspot raster of overall risk by indicating where the most suitable habitat and highest risk areas overlap.

4.3. Results

4.3.1. Data summary

A total of 272 sighting points were collected through both historic and recent reports, and 193 of these sightings included a date or year. Any points dating back over 10 years (N = 22) were considered historic and thus discarded. The majority of sightings (53.3%, N = 132) took place between 2019 – 2022 (Appendix 5: Table A1 and Figure A1). Out of the total sightings points, 140 included exact GPS coordinates, and this was the subset used in subsequent analyses. Of these, 137 were from Narok County and 3 were from West Pokot, thus there were disproportionately more records from Narok.

There were 741 Pangolin Ambassador activity days recorded between September 2020 and June 2022. Most pangolin ambassadors operated in Narok (99.5%, N = 655), with three in West Pokot (Appendix 5: Table A2 and Table A3). The remainder did not record a location. Figure 4.1 and Figure 4.2 show the distribution of pangolin sightings and the distribution of Ambassador surveys. Pangolin sightings were recorded during 13.9% (N = 103) of activity visits.

The pangolin sightings were reported by 224 participants to ten Pangolin Ambassadors and three Pangolin Project staff members, hence most of the sighting were reported by unique individuals. The Pangolin Ambassadors collected 155 of these points and The Pangolin Project staff collected 117.

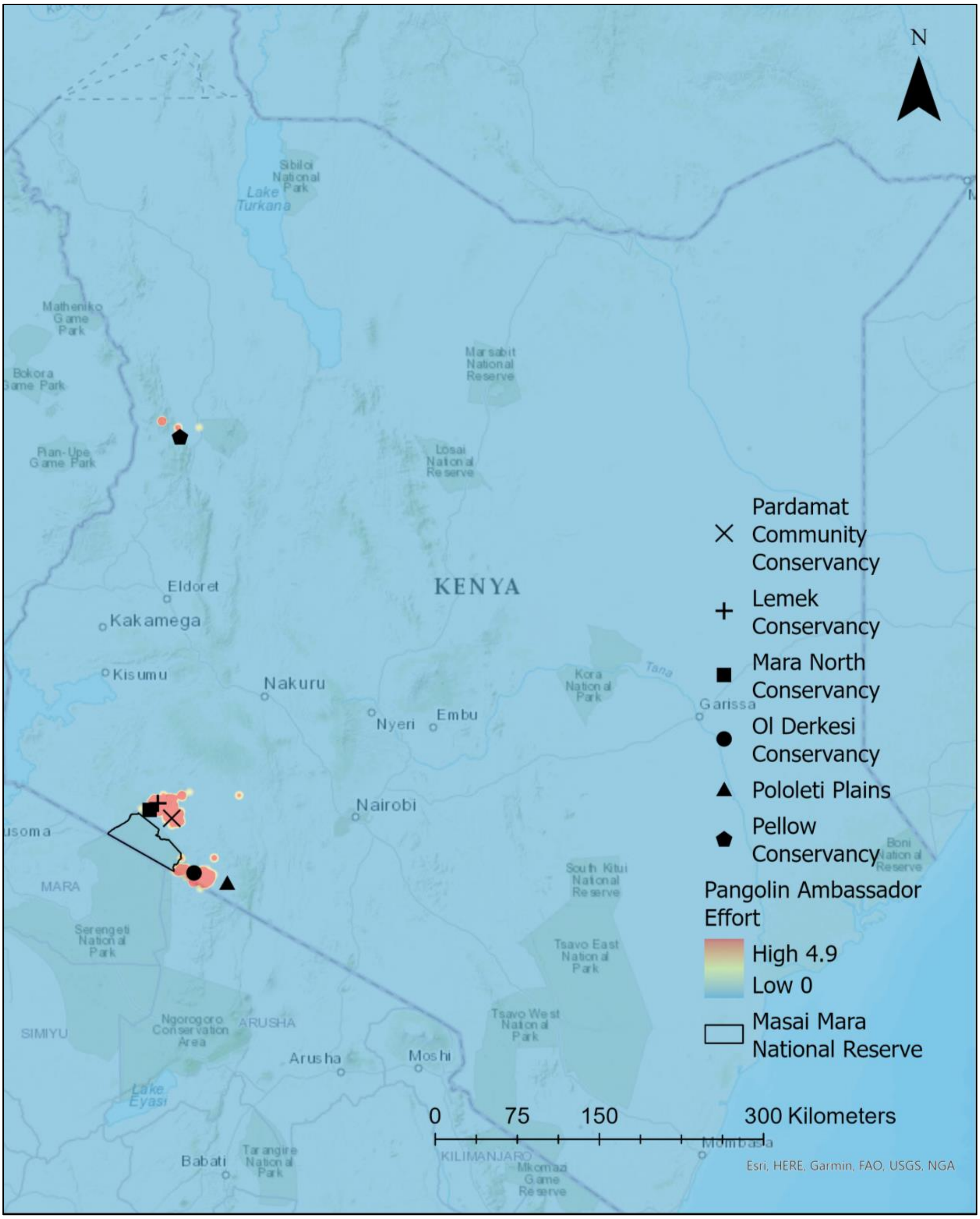


Figure 4.1 A map of Kenya with the distribution and estimated kernel density of the Pangolin Ambassador survey reports. High indicates up to 4.9 and low indicates 0 effort density, per squared kilometre. Method: Planar. Default search radius: 5156.98 m. Each participating community is shown. Masai Mara National Reserve is shown in black (UNEP-WCMC and IUCN, 2022).

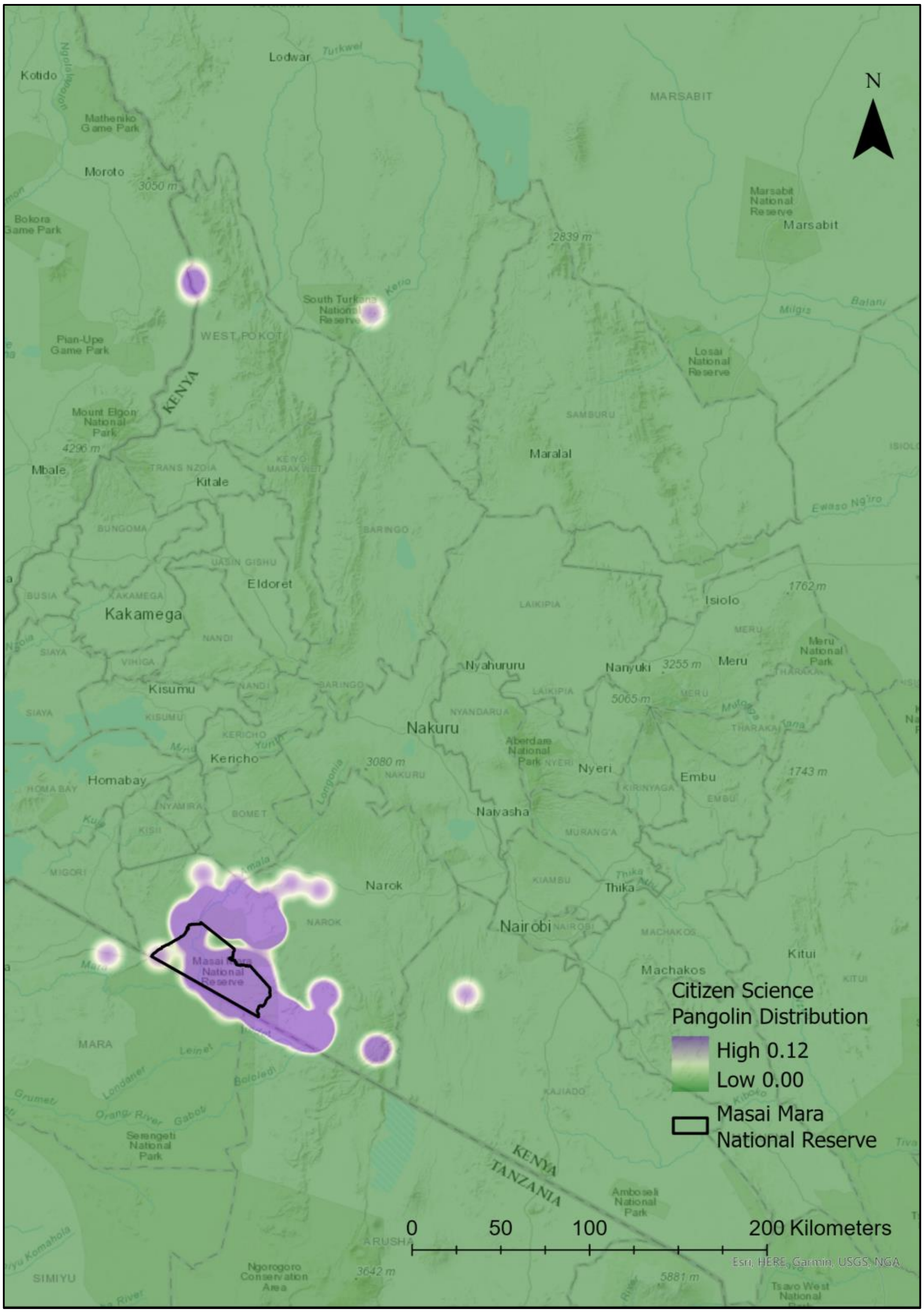


Figure 4.2 Distribution and estimated kernel density of all reported citizen science pangolin observations collected during Pangolin Ambassador surveys. High indicates up to 0.12 and low indicates 0, per squared kilometre. Method: Planar. Default search radius: 13055.16 m. Masai Mara National Reserve is shown in black (UNEP-WCMC and IUCN, 2022).

4.3.2. Descriptive variables

Most sightings took place in the evening or at night-time with 79.1% (N = 197; Appendix 5: Figure A2). Only 6% (N = 15) of sightings took place in the morning. The weather during sightings was primarily overcast (53.8%, N = 134), although 20% (N = 46) of participants could not recall the weather at the time (Appendix 5: Figure A3). Pangolins were predominantly reported in grassland, or 'bush' habitat, referred to by the participants (71.4%, N = 178) and only 10.4% (N = 26) were seen near human settlements or structures (Appendix 5: Figure A4). Most pangolins sighted were moving and feeding (64.3%, N = 147), while a combined 22.4% (N = 56) were in a ball or laying on the ground, which are both known defensive behaviours and may have been in response to the observer. Other behaviours were rarely seen (Appendix 5: Table A5 and Figure A5). Of all the sightings, only one reported a dead pangolin.

The mean distance of pangolin occurrence was over 3 km from roads or fences, over 1000 m from water (Table 4.2). Of the 137 points within the Narok County site, 90 of them were closer to fences and 47 were closer to roads. The total amount of fencing, roads, buildings, and waterways within MMNR, Narok County site, and all of Kenya are displayed in Table 4.3.

Table 4.2 The mean distance and distance range of pangolin occurrence points to waterways, fences, and roads within the Narok County site.

Variable	**Mean distance (km)**	**Distance Range (km)**
Waterways	1.22	0.00745 – 12.25
Fences	3.22	0.01 – 30.61
Roads	3.78	0.01 – 18.96

Table 4.3 The total amount in kilometres of fences, roads, and waterways in MMNR, the Narok County site, and all of Kenya. The total number of buildings in each of these is also displayed. The proportion of each variable in the Narok County site that is found within MMNR is displayed as a percentage in MMNR row, as is the proportion of each variable within Kenya that is found within the Narok County site.

Variable	**Roads (km)**	**Fences (km)**	**Buildings**	**Waterways (km)**
Masai Mara National Reserve	467 (11.98%)	272 (1.78%)	5,145 (1.16%)	1,217 (13.10%)
Narok County site	3,898 (24.55%)	15,740	440,956 (16.61%)	9,285 (13.09%)
Kenya	15,878		2,654,009	70,912

4.3.3. Collinearity

Pearson correlation coefficient analyses indicated several correlated variables amongst both the environmental and risk datasets (Table 4.4 and Table 4.5). Many environmental variables are inherently linked thus some collinearity is expected. Annual temperature was correlated with the most variables, including soil type, annual rainfall, NDVI, and topography. Followed by annual rainfall, which was correlated with NDVI, annual mean temperature, and topography. The risk variables exhibited no strong correlation amongst variables. These correlations are discussed in the discussion and limitations sections.

Table 4.4 Correlation matrix from Pearson correlation coefficient for environmental variables used for HSM. Determinant = 0.001. Correlation is scaled from -1 to 1, with 1 being perfectly colinear. Values above 0.7 are considered highly colinear and coloured orange.

		Species	**Soil**	**Annual rainfall**	**Distance to water**	**NDVI**	**Annual temp**	**SRTM**
Correlation	Pangolin	1.000	0.003	0.005	0.001	0.005	0.004	0.005
	Soil	0.003	1.000	0.549	0.449	0.700	0.838	0.563
	Annual rainfall	0.005	0.549	1.000	0.039	0.829	0.845	0.941
	Distance to water	0.001	0.449	0.396	1.000	0.444	0.519	0.437
	NDVI	0.005	0.700	0.829	0.444	1.000	0.891	0.833

	Annual temp	0.004	0.838	0.845	0.519	0.891	1.000	0.876
	SRTM	0.005	0.563	0.941	0.437	0.833	0.876	1.000

Table 4.5 Correlation matrix from Pearson correlation coefficient for risk variables used for the risk analysis modelling. Determinant = 0.395. Correlation is scaled from -1 to 1, with 1 being perfectly colinear. Values above 0.7 are considered highly colinear.

		Species	**Distance to roads**	**Human population**	**Distance to fences**	**Distance to buildings**
Correlation	Pangolin	1.000	0.001	0.000	0.000	0.003
	Distance to roads	0.001	1.000	-0.005	0.016	0.541
	Human population	0.000	-0.005	1.000	0.651	0.015
	Distance to fences	0.000	0.016	0.651	1.000	0.131
	Distance to buildings	0.003	0.541	0.015	0.131	1.000

4.3.4. Habitat suitability models

4.3.4.1. Narok County site

This model included annual rainfall, annual mean temperature, NDVI levels, soil type, topography, and the distance to waterways (Figure 4.3). Soil type was the highest contributor to the model (Table 4.6), with three of the 25 soil types considered highly suitable and two considered unsuitable. These were haplic acrisols, humic cambisols, and eutric regosols; and haplic phaeozems and haplic greyzems, respectively. The remaining 20 soil types were somewhat suitable. Soil type had a moderate permutation importance, meaning it was important for the model's performance. Soil type code key available in Appendix 5: Tables A6 and A7. Annual mean rainfall contributed the second most to the model and had a very high permutation importance, with between 600 – 1600 mm/year indicating the highest level of suitability (Figure 4.4). Following this, each variable contributed less than 6% to the model and had relatively low permutation importance (Table 4.4). Distance to waterways of over 14 km away this indicated low suitability (Figure 4.4). Suitability increased as NDVI increased (4.8%), meaning pangolins prefer greener areas. The ideal mean temperature range for pangolins was 16 – 22°C, with 17°C being the most suitable mean temperature. Temperatures above this decreased in suitability. Topography above 600 m indicated more suitable areas. Overall, half of the Narok County site land was found to have somewhat suitable, suitable, or very suitable land for pangolins (Table 4.7).

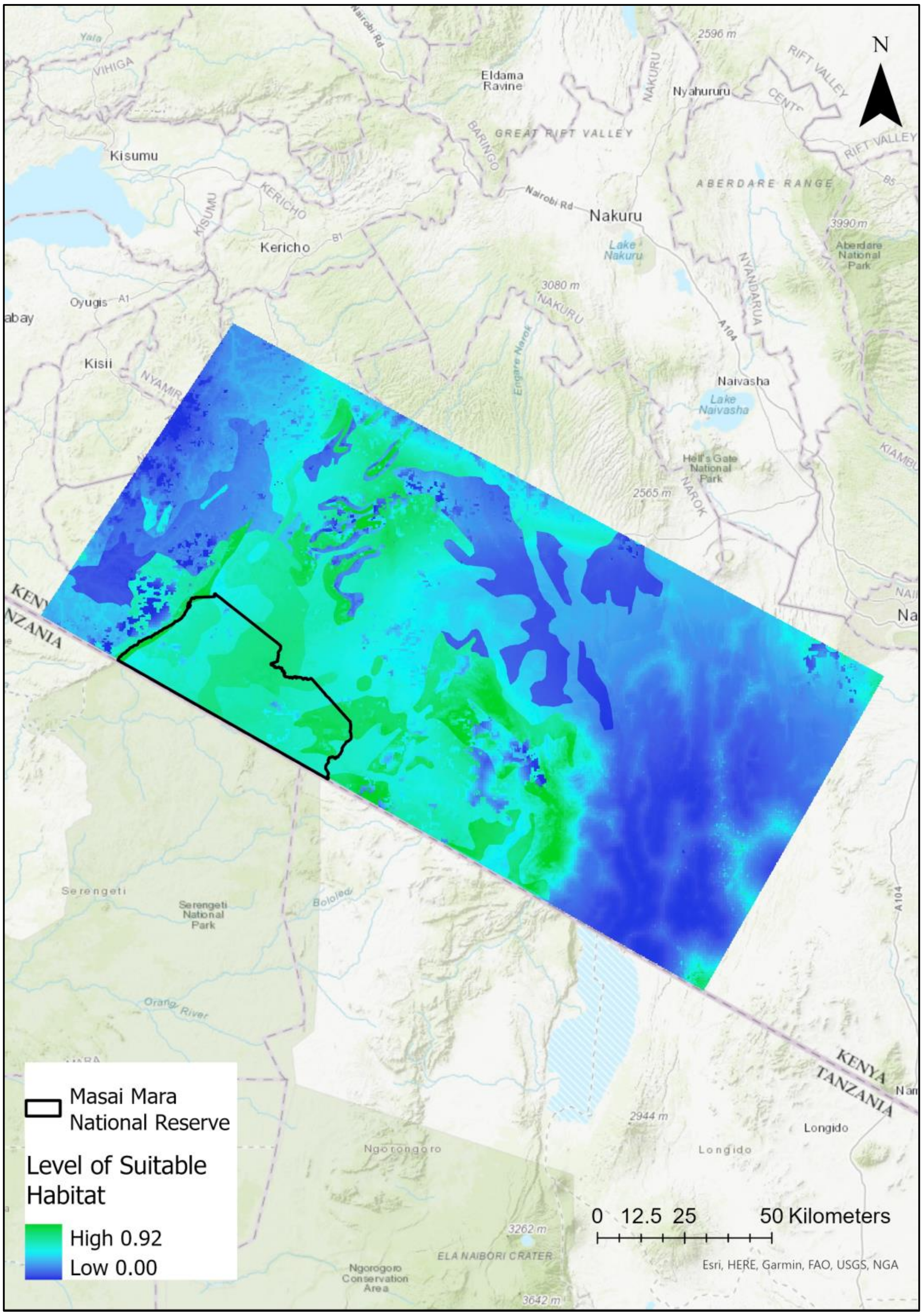
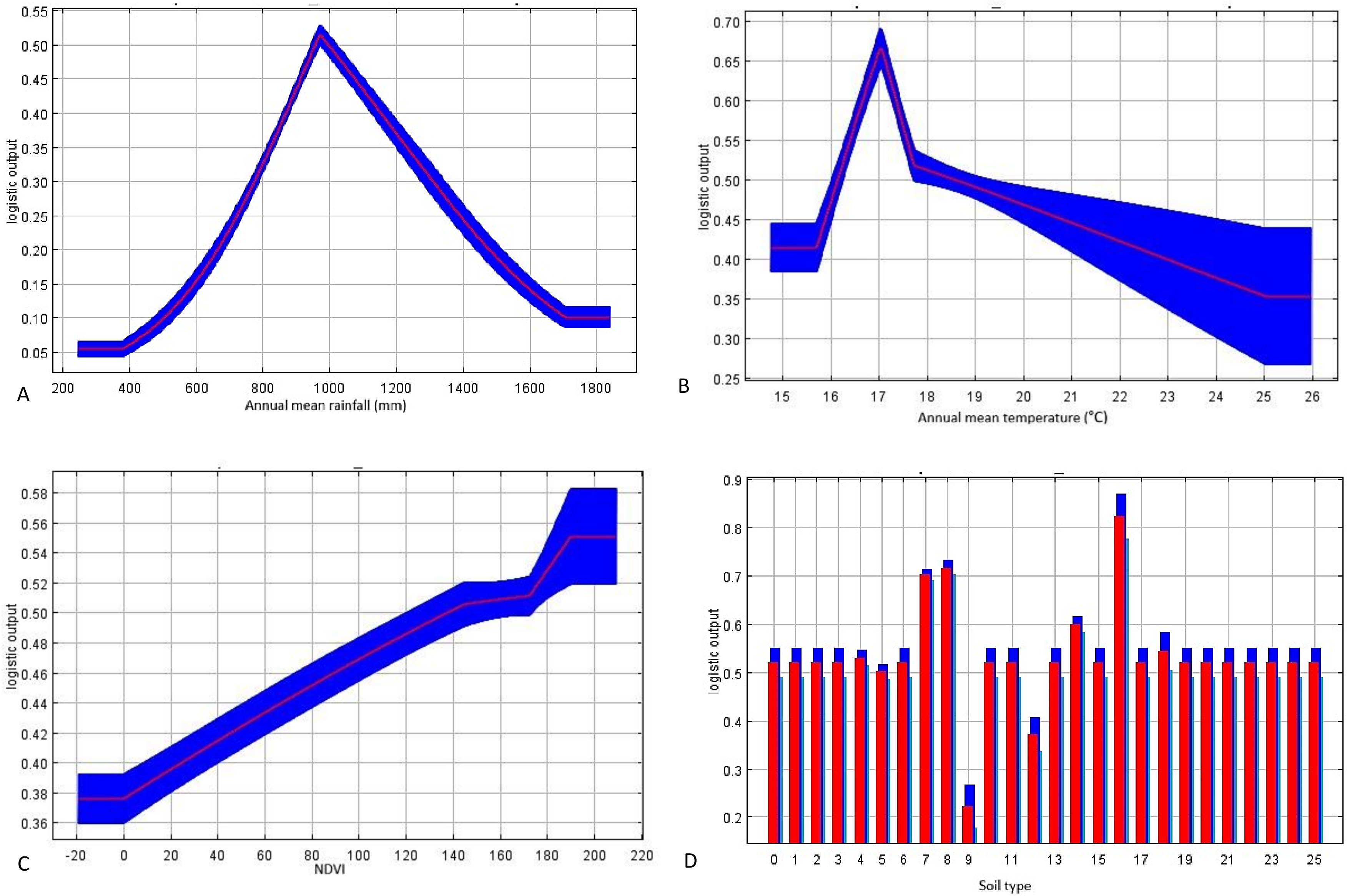
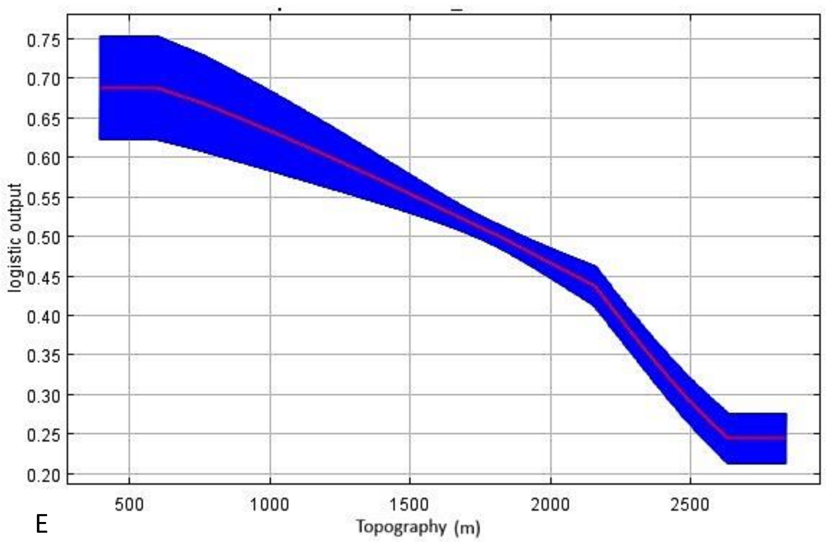


Figure 4.3 Narok County habitat suitability map indicating areas of high and low suitability for pangolins based on annual rainfall levels, soil type, annual mean temperature, NDVI, topography, and distance to waterways. Green indicates high suitability and dark blue indicates low suitability. Masai Mara National Reserve is shown in black (UNEP-WCMC and IUCN, 2022).

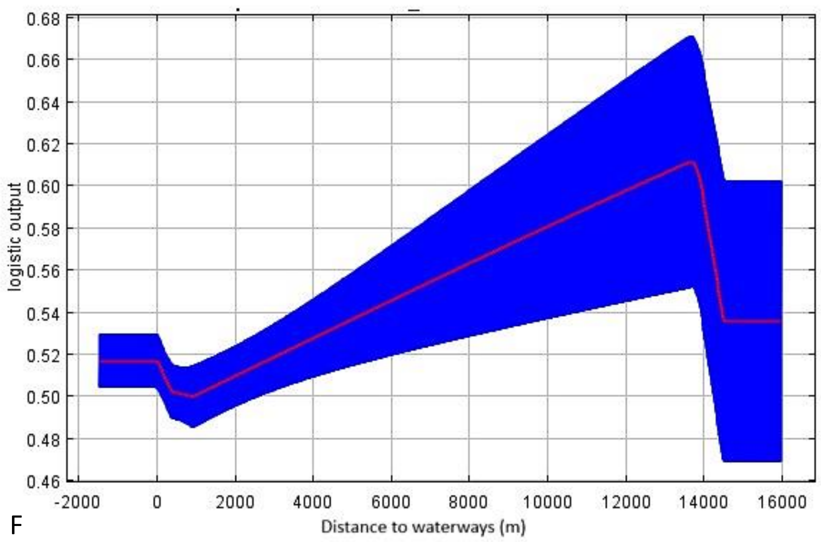
Table 4.6 Narok site habitat suitability variable contributions to the MaxEnt model and permutation importance for each. AUC = 0.861.

Variable	Percent contribution	Permutation importance
Soil type	55.5	22.4
Annual rainfall	31.9	57.7
Distance to waterways	5.4	1.4
NDVI	4.8	4.3
Annual temperature	2	8
Topography	0.4	6.1


A
logistic output
Annual mean rainfall (mm)
200 400 600 800 1000 1200 1400 1600 1800
0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55
B
logistic output
Annual mean temperature (°C)
15 16 17 18 19 20 21 22 23 24 25 26
0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70
C
logistic output
NDVI
-20 0 20 40 60 80 100 120 140 160 180 200 220
0.36 0.38 0.40 0.42 0.44 0.46 0.48 0.50 0.52 0.54 0.56 0.58
D
logistic output
Soil type
0 1 2 3 4 5 6 7 8 9 11 13 15 17 19 21 23 25
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9



E



F

Figure 4.4 A – F Output from 20 times cross validation showing how the predicted probability of suitability changes as each habitat variable is varied in the Narok County site, keeping all other environmental variables at their average sample value. Blue indicates standard deviation. A soil type key is available in Appendix 6: Table A6. Logistic output is the probability that the species is present assigned by MaxEnt. A = annual rainfall; B = annual temperature; C = NDVI; D = soil type; E = topography; F = distance to waterways.

Table 4.7 The proportion of each habitat suitability type available within the Narok site. Total area 21943.4 km². Land percentage is shown as well as the MaxEnt suitability value.

Habitat Level	Value	Total area (km²)	Land percentage
Very unsuitable	0.00 – 0.16	5,372.27	24.48
Unsuitable	0.16 – 0.29	5,591.74	25.48
Somewhat suitable	0.29 – 0.43	3,589.04	16.36
Suitable	0.43 – 0.58	4,658.45	21.23
Most suitable	0.58 – 0.92	2,731.89	12.45

4.3.4.2. Kenya

This model included annual rainfall, annual mean temperature, NDVI levels, soil type, topography, and the distance to waterways (Figure 4.5). Annual rainfall was the highest contributing variable to the model and had a high permutation importance (Table 4.8). Between 500 – 1400 mm/year was considered the most suitable range for pangolins. Topography was the next highest contributor to the model, with a range of above 750 m the most suitable for pangolins. Eight soil types were found to be highly suitable, and two unsuitable. Highly suitable soils included: calceric regosols, eutric planosols, chromic luvisols, eutric regosols, eutric vertisols, humic cambisols, haplic acrisols, and rhodic nitisols, and unsuitable included: haplic phaeozems and gleyic phaeozems. All other variables contributed less than 3% to the model and had low permutation importance. Less than 10000 m from waterways indicated reasonable suitability but this did not contribute strongly to the model. An NDVI score above 80 indicated the highest level of suitability but contributed little to the model (Figure 4.6). Annual temperatures between 17 – 29 °C were the most suitable. Throughout Kenya, 24.59% of land was found to have suitable habitat for pangolins (Table 4.9).

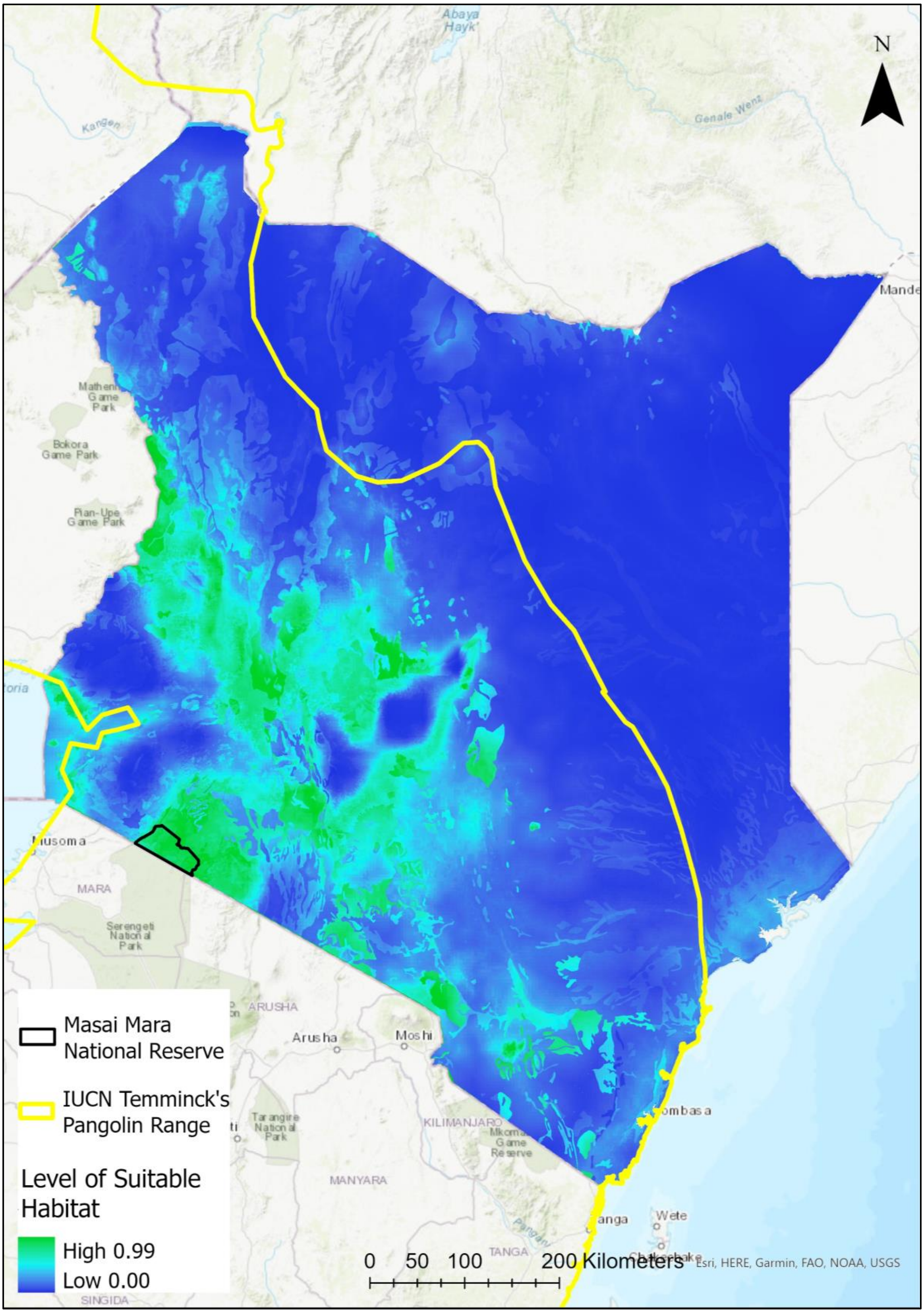
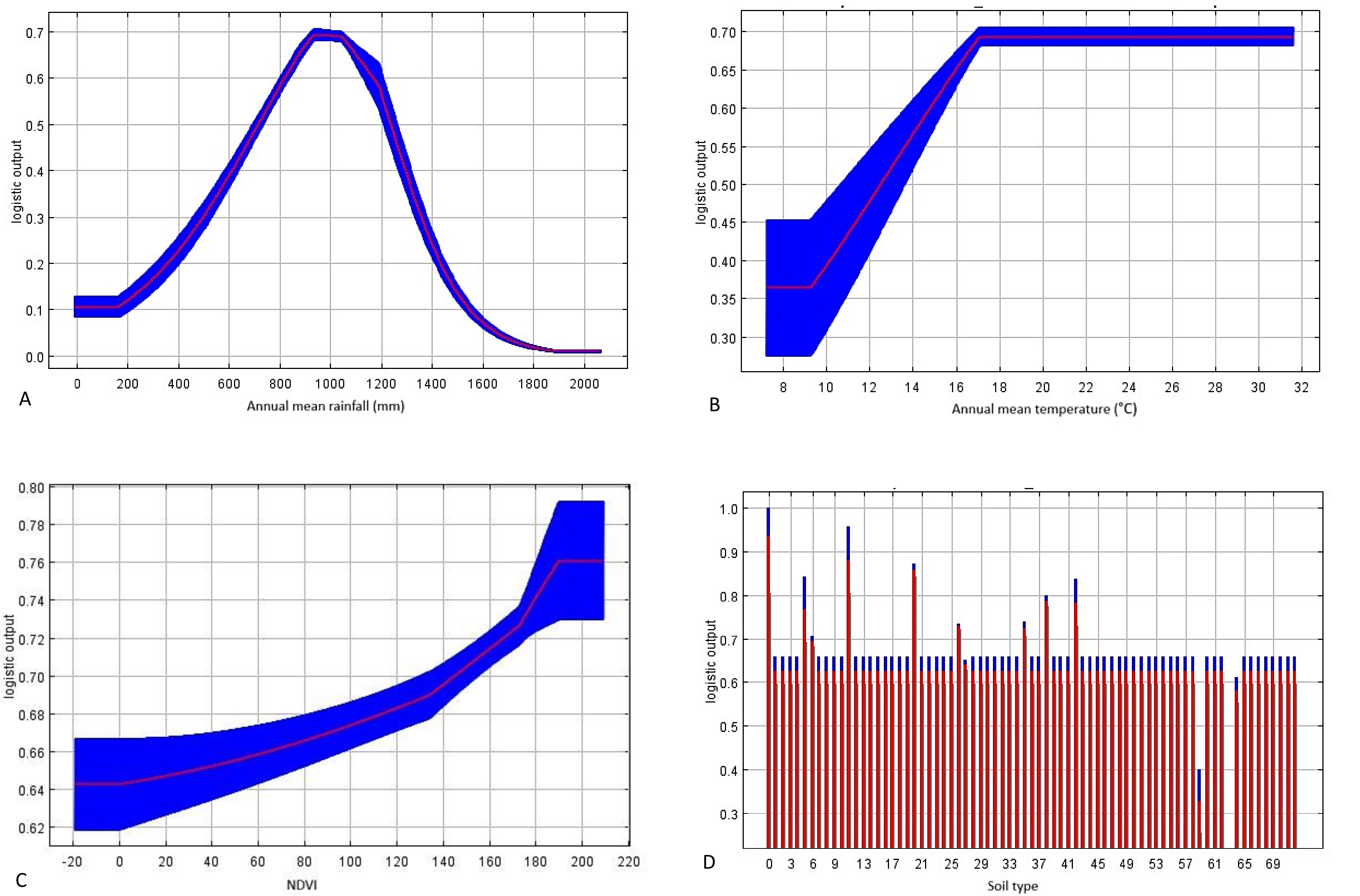


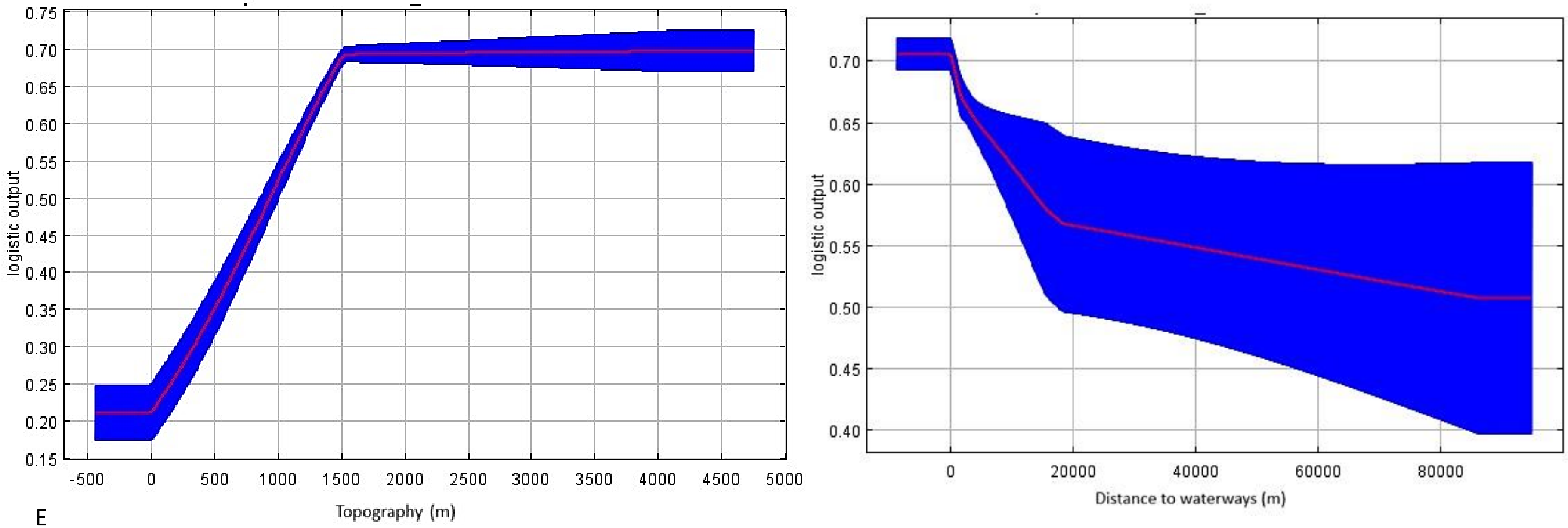
Figure 4.5 Kenya habitat suitability map. Variables include annual rainfall levels, soil type, annual mean temperature, NDVI, SRTM, and distance to waterways. Green indicates high suitability and dark blue indicates low suitability. AUC = 0.972. Border of IUCN pangolin range is shown in yellow (Pietersen, Jansen and Connelly, 2019). Masai Mara National Reserve is shown in black (UNEP-WCMC and IUCN, 2022).

Table 4.8 Kenya habitat suitability variable contributions to the MaxEnt model and permutation importance for each. AUC = 0.972.

Variable	Percent contribution	Permutation importance
Annual Rainfall	36.8	53.9
Topography	36.3	21.1
Soil Type	21.1	9.9
Distance to Waterways	2.7	11.7
NDVI	1.6	1.1
Annual Temperature	1.4	2.3



A
logistic output
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
0 200 400 600 800 1000 1200 1400 1600 1800 2000
Annual mean rainfall (mm)
B
logistic output
0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70
8 10 12 14 16 18 20 22 24 26 28 30 32
Annual mean temperature (°C)
C
logistic output
0.62 0.64 0.66 0.68 0.70 0.72 0.74 0.76 0.78 0.80
-20 0 20 40 60 80 100 120 140 160 180 200 220
NDVI
D
logistic output
0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
0 3 6 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69
Soil type



E

F

Figure 4.6 A – F Output from 10 times cross validation predicted probability of suitability changes as each risk variable is varied in Kenya, keeping all other environmental variables at their average sample value. Blue indicates the standard deviation. A soil type key is available in Appendix 6: Table A7. Logistic output is the probability that the species is present assigned by MaxEnt. A = annual rainfall; B = annual temperature; C = NDVI; D = soil type. E = topography; F = distance to waterways.

Table 4.9 The proportion of each habitat suitability type available within Kenya. Total area 591832 km². The percentage of each level is shown as well as the MaxEnt suitability value range.

Habitat Level	Value	Total area (km²)	Land percentage
Very unsuitable	0.00 – 0.08	3,19,530.10	53.99
Unsuitable	0.08 – 0.21	126,592.90	21.39
Somewhat suitable	0.21 – 0.38	65,515.80	11.07
Suitable	0.38 – 0.57	47,642.48	8.05
Most suitable	0.57 – 0.99	32,373.21	5.47

4.3.5. Risk Models

4.3.5.1. Narok County site

All variables (human population density, and distance to roads, fences and buildings) had moderate permutation importance contributions (Figure 4.7). Roads were the primary risk indicator (Table 4.10). This was followed by human population density, distance to fences and distance to buildings, in order of importance contribution. For roads, fences and buildings, a close distance to any of these indicated a negative association with pangolin presence. As distance from these variables increased the risk was shown to reduce. For population density, zero human presence was the lowest risk for pangolins, whereas above 500 people per square kilometre indicated a negative but non-linear correlation (Figure 4.8). The majority of land (71.83%) at the site was found to have moderate, high, or very high risk levels (Table 4.11).

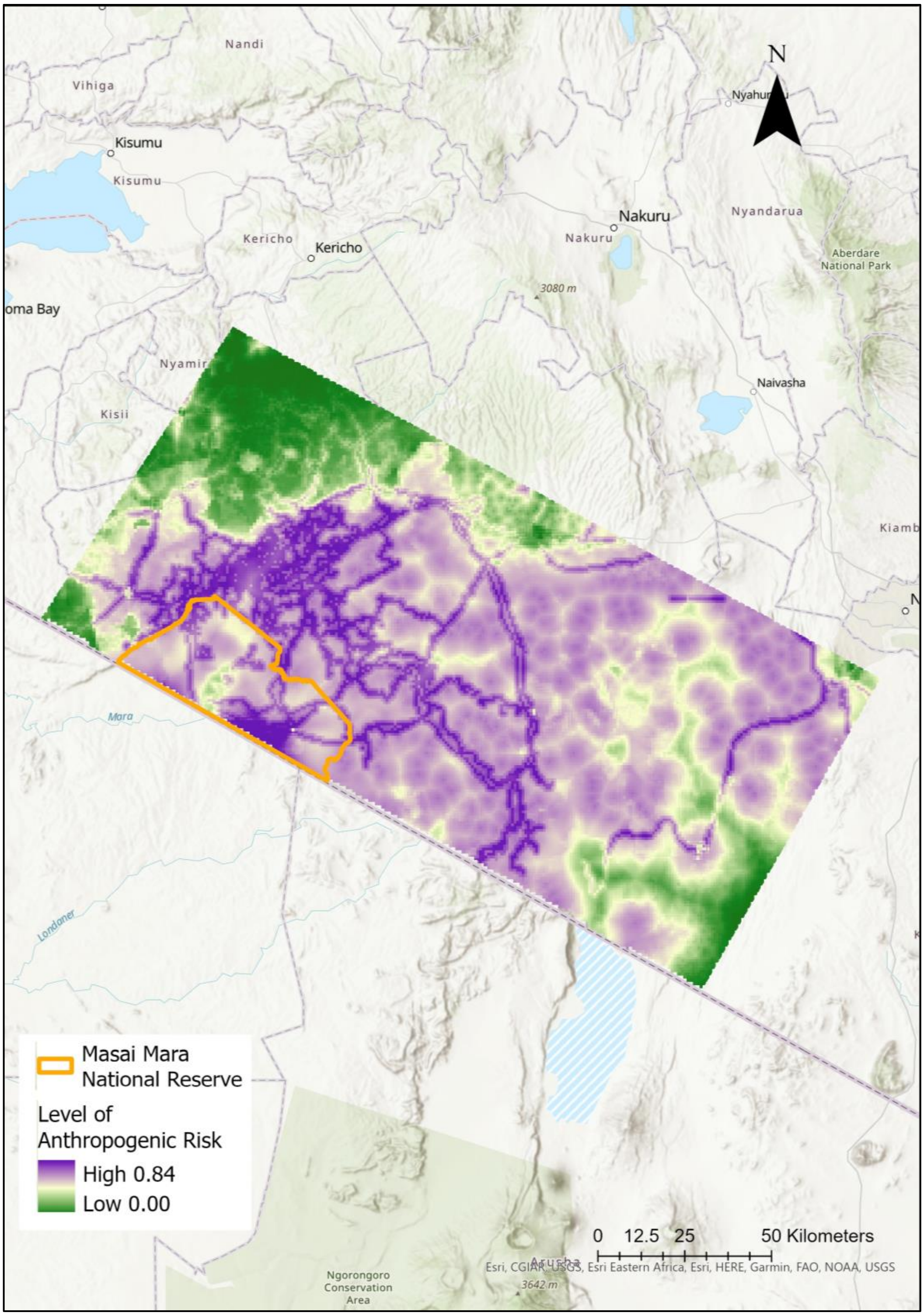


Figure 4.7 Anthropogenic risk distribution to pangolins in Narok County. Purple indicates areas of high risk and green indicates areas of low risk. AUC = 0.754. Masai Mara National Reserve is shown in orange (UNEP-WCMC and IUCN, 2022).

Table 4.10 Narok County risk variable contributions to the MaxEnt model and permutation importance for each. AUC = 0.754.

Variable	Percent contribution	Permutation importance
Distance to roads	40.9	23.3
Human population density	33.5	14.6
Distance to fences	14	37.3
Distance to buildings	11.6	24.8

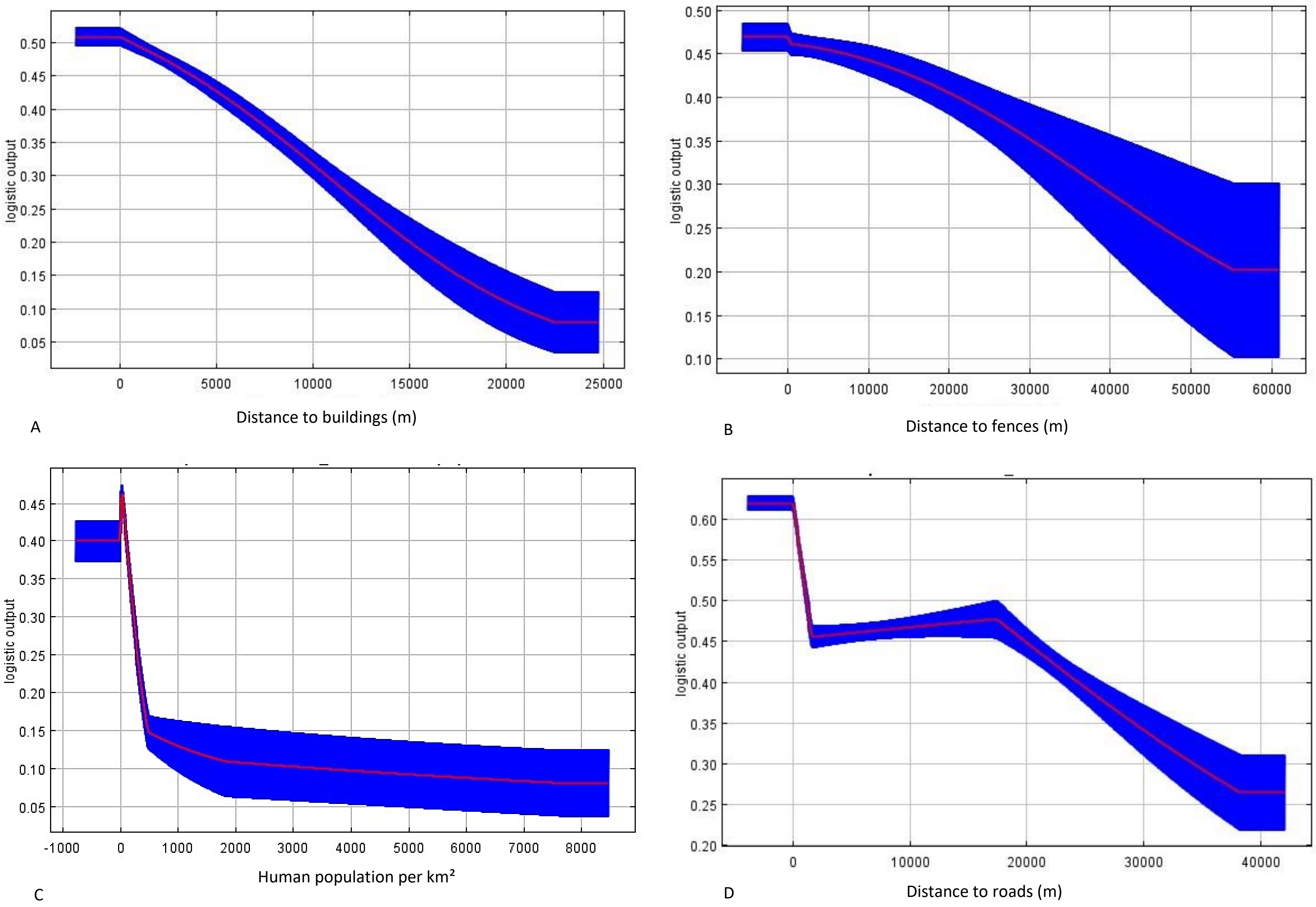


Figure 4.8 A – D. Output from 20 times cross validation showing how the predicted probability of suitability changes as each risk variable is varied in the Narok County site, keeping all other variables at their average sample value. Blue indicates standard deviation. Logistic output is the probability that the species is present assigned by MaxEnt. A = buildings; B = fences; C = human population density; D = Roads.

Table 4.11 The proportion of each risk category present and the amount of land present for each within the Narok site. Total area 21943.4 km². The land percentage and MaxEnt range values are shown.

Risk Level	**Value**	**Total area (km²)**	**Land percentage**
Very low risk	0.00 – 0.16	2,588.47	11.80
Low risk	0.16 – 0.32	2,713.31	12.37
Moderate risk	0.32 – 0.44	5,038.40	22.96
High risk	0.44 – 0.55	8,530.36	38.87
Very high risk	0.55 – 0.84	3,072.85	14.00

4.3.5.2. Kenya

Anthropogenic variables

Human population density was the predominant risk indicator with the highest contribution to the model with a moderate permutation importance (Figure 4.9 and Table 4.12). Buildings contributed the second most to the model with a high permutation importance, followed by distance to roads. For population density, zero human population was the lowest risk area and the risk rapidly increased with any human presence, indicating a negative non-linear correlation (Figure 4.10). For both buildings and roads, a close distance to these was considered a higher risk and this decreased with distance. Over half of the land in Kenya (52.06%) was found to have some anthropogenic risk for pangolins (Table 4.13).

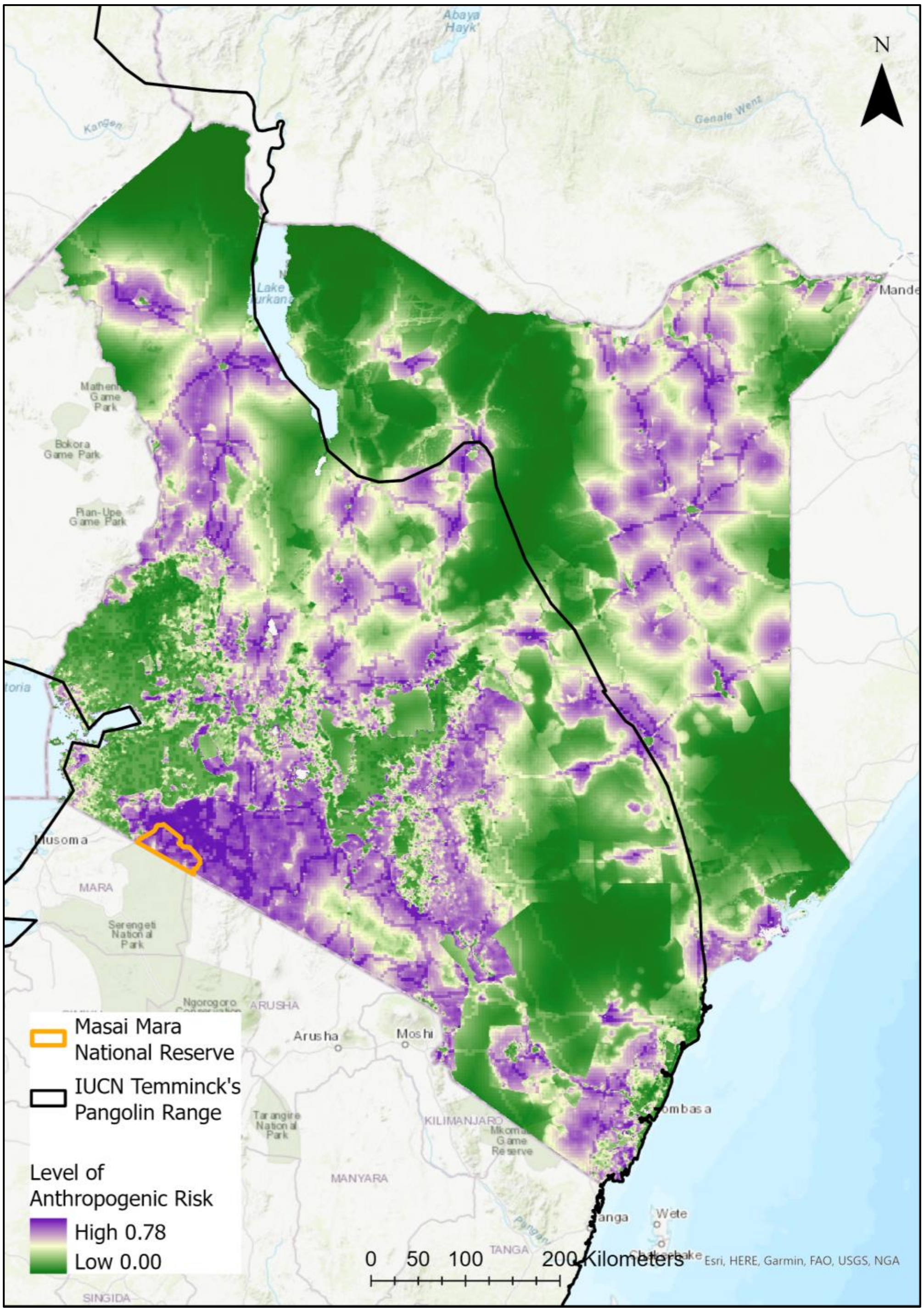
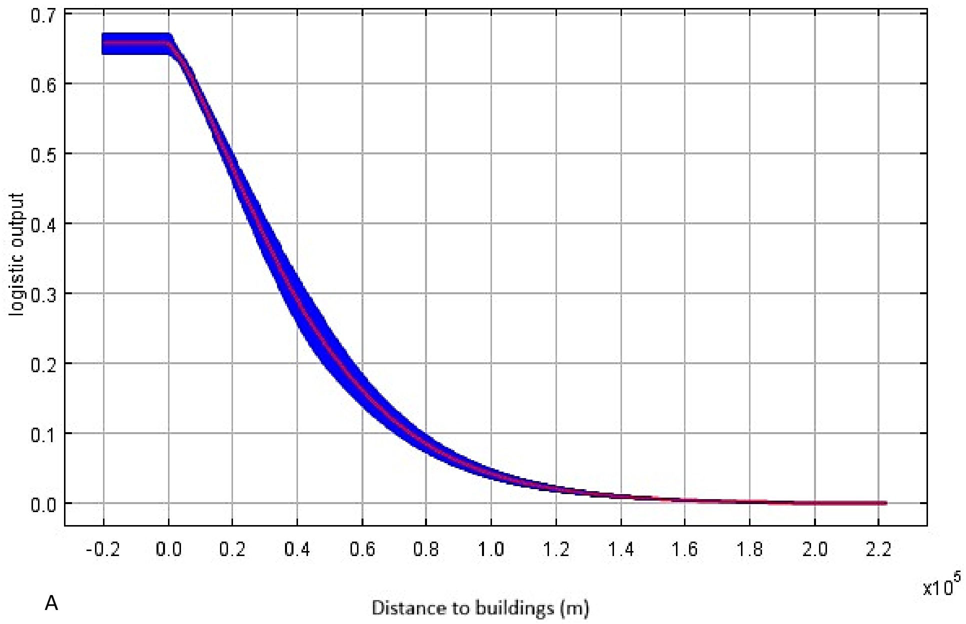


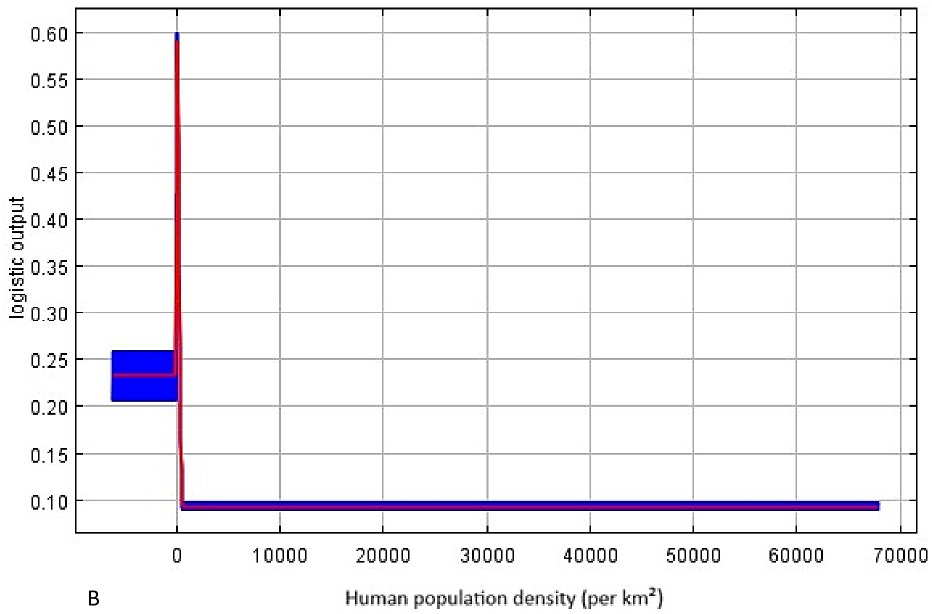
Figure 4.9 Anthropogenic risk distribution to pangolins in Kenya. Purple indicates areas of high risk and green indicates areas of low risk. AUC = 0.948. IUCN pangolin range is shown in black (Pietersen, Jansen and Connelly, 2019). Masai Mara National Reserve is shown in orange (UNEP-WCMC and IUCN, 2022).

Table 4.12 Kenya habitat suitability variable contributions to the MaxEnt model and permutation importance for each. AUC = 0.948.

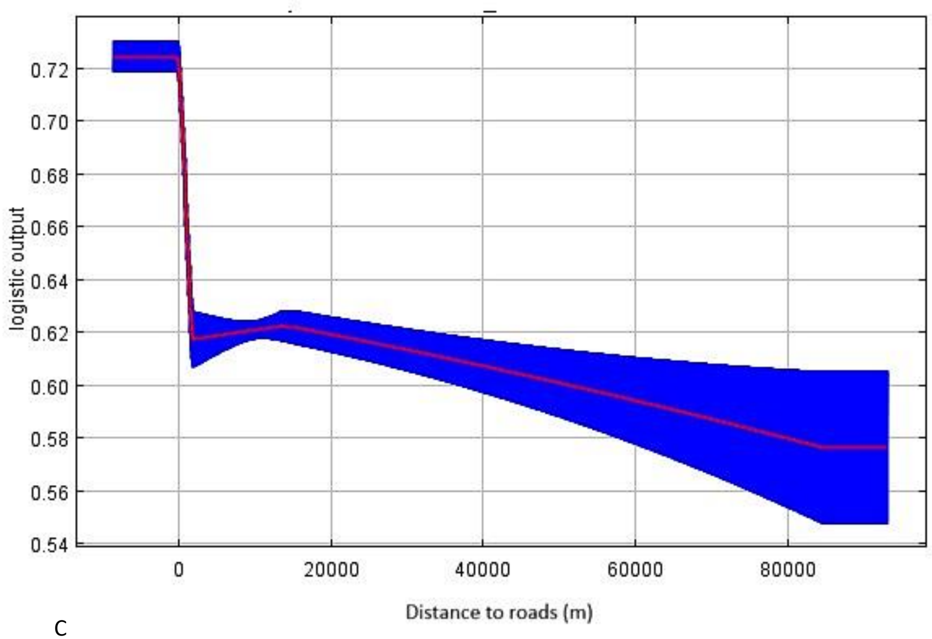
Variable	Percent contribution	Permutation importance
Human population density	49.9	36
Distance to buildings	32.3	57.1
Distance to roads	17.8	6.9



A



B



C

Figure 4.10 A – C Output from 10 times cross validation showing how the predicted probability of suitability changes as each risk variable is varied in Kenya, keeping all other environmental variables at their average sample value. Logistic output is the probability that the species is present assigned by MaxEnt. A = buildings; B = human population density; C = roads.

Table 4.13 The proportion of each risk type available within Kenya. Total area 591832 km². Land percentage and MaxEnt value ranges are shown.

Risk Level	Value	Total area (km²)	Land percentage
Very low risk	0.00 – 0.11	162,043.60	27.38
Low risk	0.11 – 0.25	121,538.60	20.54
Moderate risk	0.25 – 0.40	102,327.80	17.29
High risk	0.40 – 0.55	111,027.70	18.76
Very high risk	0.55 – 0.78	94,752.30	16.01

Risk Hotspot Model

Five range categories were used to evaluate the highest risk areas for pangolins. This analysis combined the most highly suitable areas with the highest risk areas to create a hotspot model and determine how much high-risk land exists within the study site and Kenya (Table 4.14, Table 4.15, and Figure 4.11, Figure 4.12). Within the study site, 37.70% of land had a moderate or above risk level, and within all of Kenya, this was 15.86%. Most land in the Narok site (62.30%) and Kenya (84.12%) was either low or very low risk.

Table 4.14 Risk level to pangolins and proportion of each risk category within the Narok site. Total area 21943.4 km². Land percentage and Maxent value range are shown.

Risk Level	Value	Total area (km²)	Land percentage
Very low	0.00 – 0.07	8,463.20	38.57
Low	0.07 – 0.16	5,206.46	23.73
Moderate	0.16 – 0.25	3,912.26	17.83
High	0.25 – 0.35	3,018.71	13.76
Very high	0.35 – 0.59	1,342.76	6.12

Table 4.15 Risk level to pangolins and proportion of each risk category within Kenya. Total area 591832 km². Land percentage and Maxent value range are shown.

Risk Level	Value	Total area (km²)	Land percentage
Very low	0.00 – 0.04	408,186.50	68.97
Low	0.04 – 0.12	89,650.71	15.15
Moderate	0.12 – 0.23	50,897.55	8.60
High	0.23 – 0.37	28,579.57	4.83
Very high	0.37 – 0.69	14,381.52	2.43

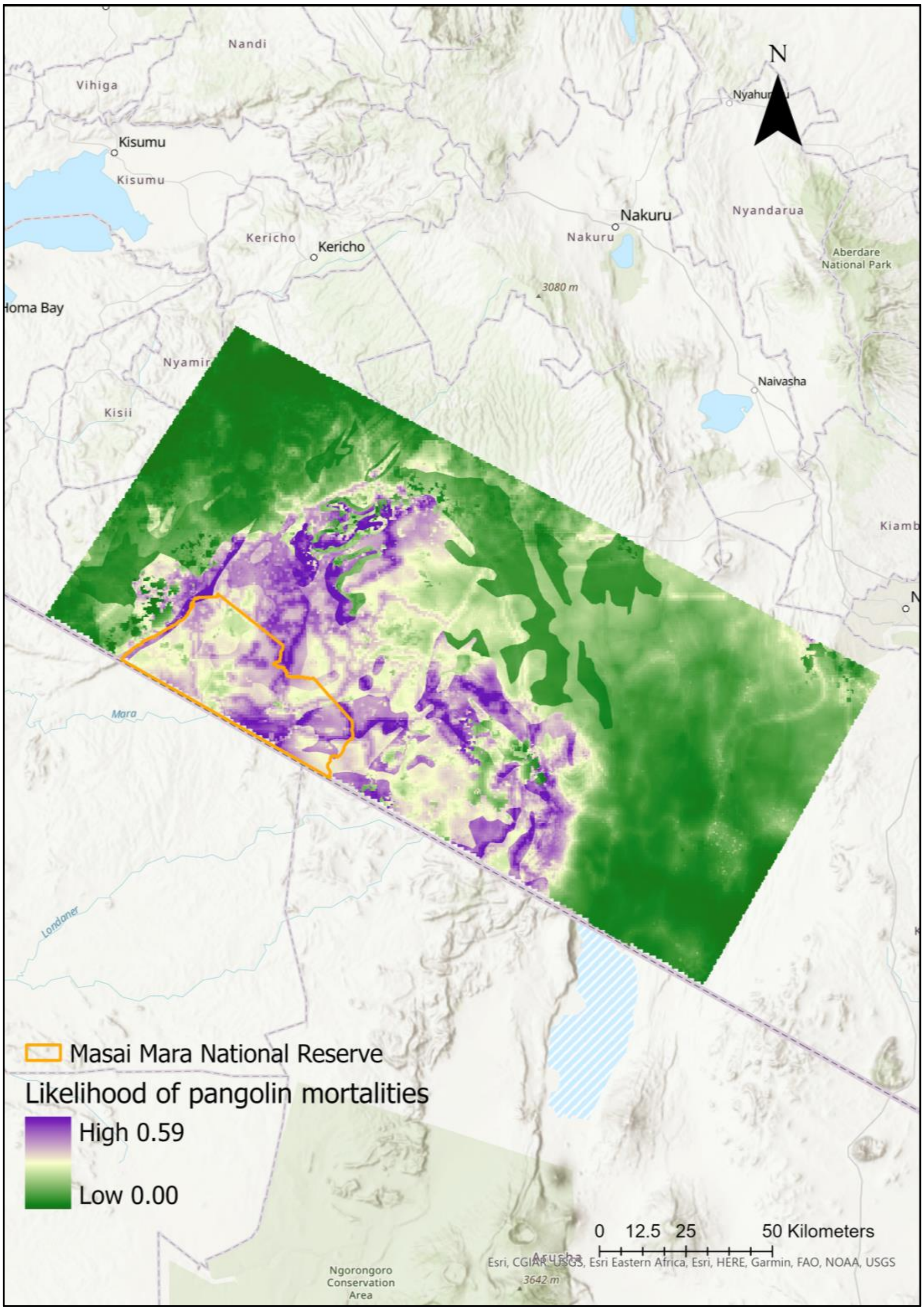


Figure 4.11 Map showing raster generated from habitat suitability and risk results for the Narok site. This is the combined output from multiplying the most highly suitable areas with the areas of highest risk. Deep purple indicates the highest level of risk, whilst green indicates low risk. Yellow areas indicate medium level risk. Masai Mara National Reserve is shown in orange (UNEP-WCMC and IUCN, 2022).

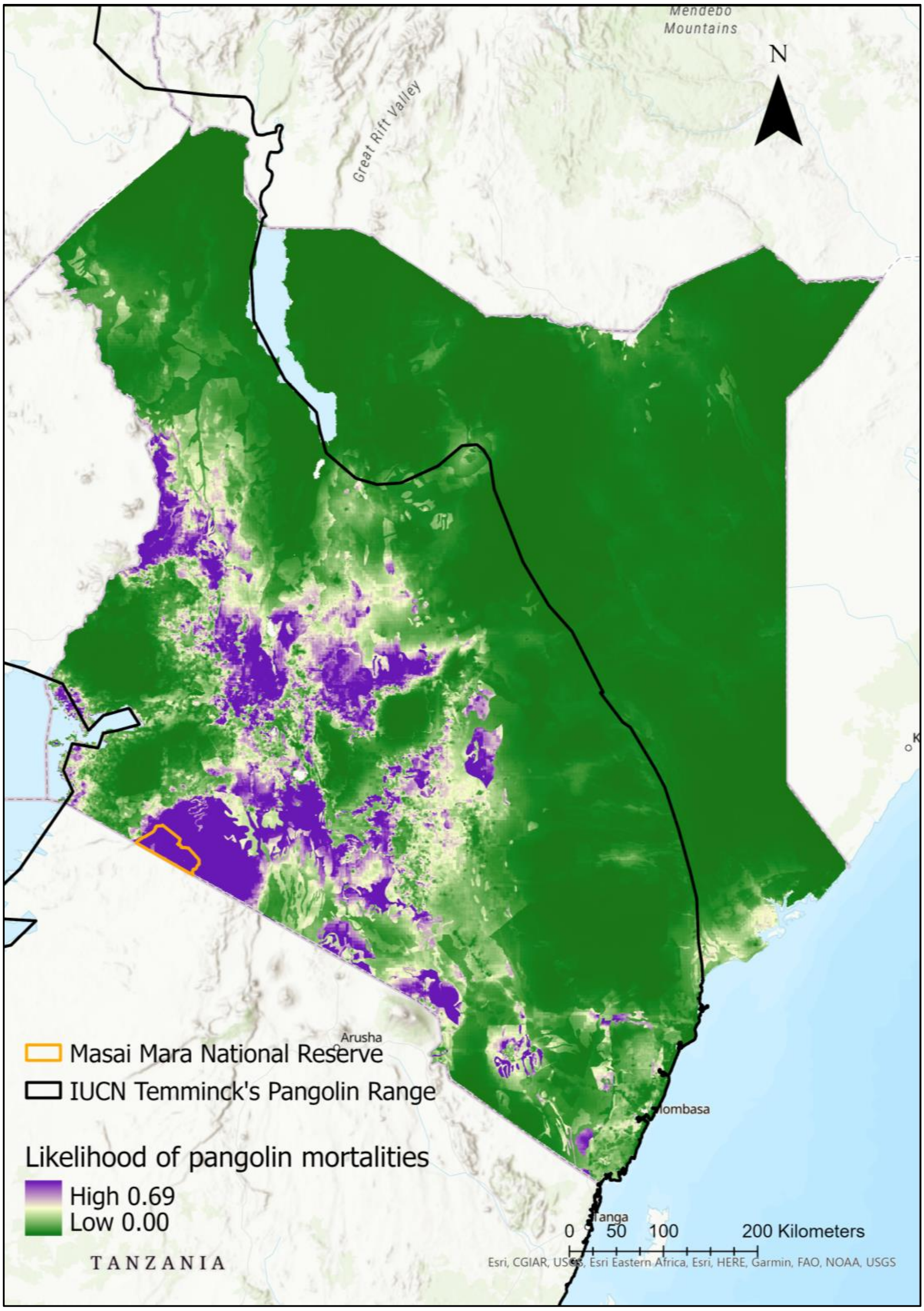


Figure 4.12 Map showing raster generated from habitat suitability and risk results for all of Kenya. IUCN pangolin range is shown in black (Pietersen, Jansen and Connelly, 2019). This is the combined output from multiplying the most highly suitable areas with the areas of highest risk. Deep purple indicates the highest level of risk, whilst green indicates low risk. Yellow areas indicate medium level risk. Masai Mara National Reserve is shown in orange (UNEP-WCMC and IUCN, 2022).

4.4. Discussion

Using citizen science sightings of pangolins, it was found that a range of environmental parameters affected their habitat use. Additionally, this study found that several anthropogenic variables were indicated as potential threats to pangolins in Kenya. Most pangolin sightings took place in the evening with overcast weather, and in grassland habitat and the most common behaviours recorded were moving or feeding. The distribution results found here may be an underestimation of distribution due to the link between behaviour and detection, for instance if pangolins were moving along corridors frequently utilised by humans. The prevalence of sightings in overcast weather may be linked to prey availability, as ants are often more active when there is increased moisture and humidity (Fotso Kuate et al., 2008). Within the Narok study site, soil type and rainfall were the biggest indicators of pangolin distribution. This pattern was repeated when the model was expanded to across all of Kenya, with topography also being important. In terms of predicting the most likely anthropogenic threats, within the Narok site, roads were the predicted largest threat, while proximity to humans was likely the biggest threat throughout Kenya. These results confirmed the hypothesis that roads are a potential threat to pangolins in Kenya, as roads have been implicated in numerous pangolin deaths in South Africa, whilst Kenya is the 7^{th} highest ranking African country in terms of pangolin trafficking (Pietersen et al., 2014; EIA, 2020). However, as almost all occurrences were recorded in the Narok and Masai Mara region, extrapolating results to all of Kenya is experimental and may not be as accurate as the results within the smaller study site.

4.4.1. Habitat suitability

Within the Narok County study site, soil was the most important indicator of suitable habitat for pangolins, meaning the presence of certain soil types is crucial for pangolin habitat use. Haplic acrisols, humic cambisols, and eutric regosols were identified as highly suitable soil types for pangolins, whereas haplic phaeozems and haplic greyzems were deemed unsuitable. Soil type can influence environmental conditions by offering varying levels of different nutrients and water retention (Jones et al., 2013), which impacts vegetation and prey distribution. Most pangolin sightings in this study were seen feeding, thus the distribution of records was likely heavily influenced by prey distribution. This result aligns with Pietersen et al (2021), who found soil to be one of the main factors influencing pangolin habitat suitability in South Africa, despite Kenya and

South Africa having different soils available (Jones et al., 2013). Within the study site, the landscape may seem homogenous on a wider scale, however soil differences mean small-scale habitat variation. Additionally, pangolins utilise burrows created by aardvarks as shelter (Pietersen et al., 2014b) and soil may be an important determinant of where aardvarks generate burrows (Whittington-Jones et al., 2011). In Chapter 3 of this thesis, aardvarks did show non-significant preference in soil type selection, which correspondingly impacted what soil was available for pangolins to choose from. Pangolins did not have a significant preference for a particular soil type in Chapter 3, possibly due to the availability of only two soil types. This chapter examined numerous additional soil types and found several to be suitable for pangolins. Furthermore, pangolins are known to feed on some ant species located very close to the surface of soil which may impact their habitat selection (Swart et al., 1999; Pietersen et al., 2020). The increased soil acidity and coarseness of soil was found to be important for giant pangolin habitat suitability (Mouafo et al., 2023) thus soil type may be important for other pangolin species that utilise burrows. Soil type was correlated with NDVI and temperature, which highlights the fundamental environmental relationship between these variables.

Mean annual rainfall was the second most important variable determining pangolin distribution. Moderate rainfall (600 – 1600 mm per year) was the most favourable, while low or high rainfall appeared to be unsuitable. For the Narok site, annual rainfall is typically 500 – 1400 mm (Mukeka et al., 2019) which is similar to the moderate rainfall result found in this study, so it is possible that the importance of rainfall is an artefact of the conditions available in Narok. However, rainfall likely has a close relationship with soil type in terms of pangolin distribution, as some soils will hold more water than others (Jones et al., 2013), which may impact burrow availability. Rainfall also impacts what prey species are available and is known to influence prey choice of pangolins in South Africa (Panaino et al., 2022). Interestingly, Pietersen et al (2021) found that rainfall did not strongly contribute to their model, however this may be due to variation in climate between South Africa and Kenya, as Kenya experiences more overall days of rainfall (WorldData, 2023). Temminck’s pangolins are water independent and primarily hydrate while consuming ants and termites, and only occasionally drink from water sources (Pietersen et al., 2020). However, this behaviour has not been studied outside of southern Africa. This variable was included in this study to determine if water independence is a behaviour that the species exhibits across its range. The unimportant contribution of distance to waterways in the current study is consistent with water independent behaviour, yet it is important to note that standing water sources were not included in this study. However, rainfall likely influences the distribution of ants and termites (Andersen, Del Toro and Parr, 2015), and correspondingly impacts pangolin distribution. Ants and termite species in southern Africa are known to decrease in abundance during the dry season, with highest abundance during the wet season (Davies et al., 2015; Munyai ad Foord, 2015). It was found that even though some species have different requirements, such as dietary niches, the impact of rainfall on termite presence does not differ largely between species (Davies et al., 2015). Pangolins are selective in the species they predate on however there have not been studies into which species they select in East Africa, thus further research is needed to ascertain if their distribution is influenced by specific prey species. Contrastingly, giant pangolins are documented to occur preferentially in areas closer to water sources and are known to be water dependent (Kingdon et al., 2013; Mouafo et al., 2023). This difference in water dependence may be due to the variation in prey species between giant and Temminck's pangolins, for example giant pangolins have been reported to consume water beetles directly from water sources (Kingdon, 1971). Despite being the closest relative to Temminck's pangolins, the two species occupy different habitats and climates (Hoffman et al., 2020; Pietersen et al., 2020), showing niche separation. Giant pangolins are found throughout West and part of Central Africa, whereas Temminck's are found in East and southern Africa (Hoffman et al., 2020; Pietersen et al., 2020).

A high NDVI, which is vegetation greenness, was preferred in general by pangolins, however this variable did not contribute much to the model. Pangolins do not feed on vegetation, and only occasionally seek shelter from it, preferring burrows (Pietersen et al., 2014b). This means the availability of green vegetation is unlikely to be important when determining their suitable habitat unless it influences other variables such as prey availability. They may utilise vegetation as cover from predators when feeding but this does not necessarily reflect NDVI levels. Interestingly, NDVI was found to be the most important predictor of distribution/presence for giant pangolins in Cameroon (Mouafo et al., 2023). NDVI was correlated with topography and temperature, thus vegetation greenness was likely influenced these. These correlations make it difficult to separate some of the abiotic and biotic variables used in this study, due to their high interaction within the ecosystem. Annual temperature also did not impact habitat suitability much, possibly due to the low variation in this across the study site, however preferrable range was 16 – 22 °C; by comparison the mean temperature in Narok county ranges from 7.3 – 28.5 °C (Mukeka et al., 2019). The same can be said for topography, which does not vary greatly in the study site (Bhandari, 2014). On a wider scale, these variables may be more influential. Temperature and topography were correlated, thus may have varied based on each other such as higher or lower temperatures at certain topographic levels. In the Narok site, half of the land was classified as suitable – very suitable for pangolins, with one quarter very unsuitable. This indicates that there is a moderate level of suitable habitat in this area for pangolins to utilise.

When considering pangolin habitat suitability across all of Kenya, the results were similar. Rainfall was the most key indicator of suitable habitat, with a range of 500 – 1400 mm being ideal. This estimate is slightly more conservative than Pietersen et al (2020), who state 250 – 1400 mm is preferred. For comparison, Kenya's total rainfall typically ranges from 250 – 2000 mm (Bryan et al., 2013). The importance of rainfall in both models shows the large role it may play in pangolin distribution. Rainfall may influence several factors that impact pangolin distribution, including the stability of aardvark burrows, the ability of pangolins to find prey in the soil, and vegetation growth which impacts the presence of ant and termite prey species. Interestingly, rainfall has not been found to strongly influence aardvark presence in South Africa (Epps et al., 2021). It is likely that rainfall impacts the overall ecosystem, which in-turn impacts pangolin resource availability. Rainfall was correlated with NDVI and topography, meaning precipitation levels were linked to location and vegetation presence and may be influenced by these. Temperature was also correlated with rainfall as these climate variables are linked. Topography was the second most influential environmental variable in this model. Temminck's pangolins are known to inhabit 0 – 1700m elevation (Pietersen et al., 2020), and Kenya has a wide range of elevation, from sea level to 5899 m (Coe and Botanist, 1967). Over 750 m was ideal and extremes in either direction were not suitable for pangolins. Soil type was moderately important but not as much as within the Narok study site. Many more soil types were available throughout Kenya (72 versus 25), and the same preferred soil types at the Narok site were also preferred throughout Kenya, which again may indicate the influence they have on prey distribution and water retention (Jones et al., 2013). However, it is important to remember that the presence points may be biased towards those soil types found in Narok, although this bias is reduced due to the use of the bias file. Most of the highly suitable soils for pangolins had high clay-contents (eutric planosol, chromic luvisol, eutric vertisol, haplic acrisol, and rhodic nitisol; Britannica, 2000; Britannica, 2016a; Britannica, 2016b; Britannica, 2016c; Britannica, 2018; ISRIC, 2023a; ISRIC, 2023b; ISRIC, 2023c; ISRIC, 2023d; ISRIC, 2023e; ISRIC, 2023f), which are nutrient rich and have good water retention characteristics (Jones et al., 2013) thus likely host a variety of insect species. Similar to the Narok site, distance to waterways, NDVI, and annual temperature did not influence the habitat suitability much across Kenya. The low influence of temperature may mean that pangolins are not distributed in Kenya based on thermoregulation.

Only 25.59% of the land across Kenya was classified as suitable – very suitable, with unsuitable areas notable in the most northern regions. This predominately matches current IUCN predicted pangolin distribution within Kenya (Pietersen et al., 2019; Pietersen et al., 2020) and may be due to variation in rainfall, elevation, and soil type. Several areas outside of the predicted IUCN range were also indicated to have suitable habitat, including the most northern coastal regions of Kenya. This difference in distribution estimates may mean there is suitable habitat but that the species is not present due to other factors, such as the presence of threats including human proximity. Alternatively, pangolins may be presumed falsely absent because the species has not yet been recorded in these regions. Both the IUCN estimate range and the results from this study are predictions and thus will vary, although the estimated ranges do primarily agree in this case.

The areas of high suitability should be the regions targeted for future conservation planning, when assessing where to prioritise activities and action plans. These areas include the most southern regions of the study site within Narok, and within Kenya encompass much of southern and mid Kenya, including MMNR, the south-western Ugandan border and the coastal regions. As pangolins are known to avoid agricultural land (Pietersen et al., 2020), it would be beneficial to focus efforts on existing protected areas or rural settlement areas in these regions.

4.4.2. Threats and risk distribution

Roads were indicated as the likely main threat, with close proximity meaning higher risk. How roads impact the overall landscape needs to be further investigated to fully evaluate their threat to pangolin habitat use. Across pangolin range, roads have been understudied as a threat but predictions in South Africa are 280 roadkill deaths per year, and two deaths of Indian pangolins were recorded in Pakistan between 2012 – 2014 (Akrim et al., 2019; Pietersen et al., 2020). The majority of roads in the Narok site were located outside of MMNR, in or around the neighbouring community conservancies. These consisted of both paved and unpaved roads with varying levels of traffic. A study which modelled roadkill risk for several species in Taiwan found that road-type strongly influenced the risk posed by roads (Chyn et al., 2021). Even the minor roads may contribute to roadkill levels, habitat fragmentation and corridor loss (Gregory et al., 2021), depending on the speed limit and level of traffic, thus further research should focus on this. A portion of the Narok study site encompasses MMNR, which has few major roads but many minor unpaved roads. Additionally, there are many roads bordering and in the immediate vicinity of MMNR. This may be particularly problematic because in neighbouring Tanzania it was found that wildlife road mortalities increased with road proximity to protected areas (Kioko et al., 2015). It will be important to establish the threat difference posed by roads in the residential communities of Narok County, and those within and immediately surrounding MMNR, including the community conservancies. Most roads within MMNR are utilised by tourism game vehicles, whereas outside of this area roads are used by residential and commercial vehicles so there is likely a difference in road mortalities. The former likely does not experience as many mortalities as the latter due to level general traffic levels, however more wildlife is inherently present within MMNR than outside of it. Those driving for game drives will also be more aware of wildlife in the roads so collisions are less likely to happen within MMNR than outside of it.

Human population density was predicted as the next biggest threat, and can be interpreted as a proxy for hunting and poaching (Pietersen et al., 2016a). Areas of over 500 people per square kilometre had the highest level of risk. There is a very low density of people within MMNR, so the threat indicated within the reserve itself is likely attributed to roads and fences rather than human population. Distance to fences, which pose the threat of entanglement or electrocution depending on fence type (See Chapter 5; Stracquadanio et al., 2023), was also a moderate threat. Most fences in Narok County are residential and there are few fences found throughout MMNR. Fences as a threat are understudied in Kenya but are commonly noted in South Africa (Pietersen et al., 2014a; Pietersen, 2022), as discussed in Chapter 5 of this thesis. However, there is a much higher fence density in South Africa than in Kenya and this needs to be considered when evaluating this threat. Buildings, which indicate areas of human activity, exhibited the least level of risk, yet their threat was still moderate. Most of the highest-risk areas were outside of MMNR in the neighbouring conservancy areas, however a moderate/high amount of risk was still found within some of MMNR. MMNR has few roads, fences, or buildings throughout, thus the level of threat indicated from this model means pangolins may be more at risk than initially thought. However, conservation priorities should be focused on areas and community conservancies outside of the reserve as the highest proportion of risk was found here, despite only 10.4% of pangolin sightings reported as near human settlements. This is further implied by the classifications of risk within the site, with 71.93% of land having moderate – high risk. The number of injuries or deaths experienced by pangolins in this region are undocumented and this information is necessary to accurately quantify these threats further. A similar result was seen for giant pangolins, immediate proximity to park boundaries thus roads and human settlements, were found to be unsuitable for these pangolins (Mouafo et al., 2023).

Throughout Kenya, human population density, proximity to roads, and buildings, were evaluated as threats. Fence data was not available for the entire country. Human population density was the biggest threat indicated, meaning poaching risk may be high throughout pangolin range in Kenya. This was followed by buildings (areas of human activity) as the next largest potential threat. Importantly, Nairobi was not highlighted as the primary area of threat in terms of human population or building density, which would be expected due to the distribution of human settlements within Kenya. This is likely a limitation of extrapolating the results across all of Kenya as nearly all records came from Narok County. After human population and activity, roads were considered a moderate level of risk throughout Kenya, but this needs to be further evaluated based on traffic level and the extent of fragmentation across the landscape caused by roads. There are many road types with varying levels of vehicular traffic thus risk will vary between them, and it was not possible to evaluate this in this study.

The areas of risk should be prioritised when improving conservation efforts for pangolins. The mortality likelihood predictions revealed these regions by evaluating the most suitable habitat alongside the highest-risk areas to estimate areas of greatest conservation concern for pangolins. Within the Narok site, the community conservancies that border MMNR were indicated as high-risk areas, as well as regions directly north of MMNR. Additionally, an area within MMNR to the southeast was also classified as high risk. When considering the results for all of Kenya, the highest risk areas were predicted throughout southern Kenya, with several patches of moderate – high risk in the western regions of West Pokot, and northern regions. However, habitat in the northern areas were unsuitable for pangolins thus they are likely absent from there. The mortality likelihood results indicated that southern Kenya, including MMNR should be the focus of conservation. Southern Kenya encompasses many existing conservancies and several national reserves, however, not all fall within suitable pangolin habitat or exhibited a high level of risk. For example, Tsavo East and West National Park was low risk to pangolins but was not indicated as highly suitable in terms of habitat. Areas classified as high risk with suitable pangolin habitat should be prioritised, which could include classifying areas as protected if they are not already and implementing anti-poaching schemes. However, pangolin presence should be confirmed first before initiating efforts, and further study should investigate the impact of these threats on the overall population.

These results offer insights into which threats may impact pangolins in Kenya the most, as little study has been conducted previously on this. Further research is needed to fully quantify these threats. It will be essential to introduce mitigation measures to reduce the level of threat in these high-risk areas. Reduction of demand for pangolin products will be key to achieving this and the best way to attempt this is through education of the public (Burgess et al., 2020). A study by Thomas-Walkers et al (2020) reviewed the effectiveness of such education initiatives and found most to be ineffective in changing behaviour on a large scale. This indicates that new mitigation strategies need to be developed with cultural, systemic and environmental factors considered throughout, as the drivers of the illegal wildlife trade are complex. cmIn terms of local use, this could be through participatory action in which members of the community, such as the Pangolin Ambassadors, interact with their fellow community members, address concerns, and have open discussions about poaching. It will be necessary to assess the mentality that drives the use of pangolin products and plan conservation initiatives accordingly. For example, income inequality and food insecurity influence the level of poaching that occurs. In Mozambique, the low level of employment opportunities, and the money available for rhino poaching means that some people are attracted to poaching (Lunstrum and Givá, 2020). Considering this in terms of both local and international trade is a challenge as it requires studying cultural uses across many different countries and mentalities. Regarding the international trade, Lunstrum and Givá (2020) conclude that it is the large economic differences between the poachers and buyers that drive the international wildlife trade. Without the money from buyers there is little reason for poaching (Lunstrum and Givá, 2020), except for possible local spiritual or bushmeat use. By comparison, the threats from road and fence mortalities may be more straightforward to mitigate against. However, it first needs to be understood which road and fence types cause injury and deaths of pangolins. This is discussed in Chapter 5 of this thesis in regard to fences (see Chapter 5). Rock barriers are one suggested method to prevent pangolins from touching low-level fence wires (Pietersen et al., 2014a), and a similar method may be applicable to roads in high-risk areas. There are generally two types of mitigation proposed for road mortalities: modifications that change motorist behaviour, or modifications that change animal behaviour. The former may include lowering speed limits or posting signs, whereas the latter can involve installing wildlife crossing structures or modifying roadside habitats, such as implementing wildlife crossing bridges or tunnels (Romin and Bissonette, 1996; Glista, DeVault and DeWoody, 2009). In particular, crossing structures have been found to reduce mortalities (Clevenger and Ford, 2010; Payan et al., 2013), however their construction is costly. Further study is needed to fully quantify these threats further before effective and cost-efficient mitigation can be developed, however the results from this study indicate where mitigation is most likely to be impactful to pangolin populations and where conservation efforts should be targeted.

4.4.3. Limitations

The main limitation of this study is the spatial bias towards Narok County due to the disproportionately high number of records collected there compared to West Pokot. Although a bias file was utilised to reduce this it did not remove the bias entirely. For this reason the results presented for Kenya as a whole are experimental and may not be as accurate as the smaller-scale Narok site results.

Another limitation arose during field data collection. The previous and current pangolin records were reported in slightly different ways because different questions were asked by The Pangolin Project. Previous refers to when an ambassador asked respondents if they had seen pangolins, whereas current refers to when a participant contacted an ambassador to report a recent or ongoing sighting. The previous sightings records varied in what level of information could be provided and it is possible that respondents may not have accurately remembered historic sightings. For both data types, several different ambassadors administered the questionnaire potentially resulting in observer bias. Data collection also partly relied on self-reporting by community members and the level of participation may have varied. Additionally, fence data for all of Kenya was not available thus this threat could not be assessed on a wide scale. All road types were merged and evaluated as equal meaning that it was not possible to tell which road types may pose the largest threats.

The time range over which the pangolin sightings were recorded (2012 – 2022) meant that there was some variation between this and when the variable datasets were collected. If a sighting point was collected in 2012 this means pangolin presence could have potentially changed at this location based on the creation of new human structures since then or human presence, as the population and road datasets were collected in 2018, and the building and fence datasets in 2022.

Several variables were found to be highly correlated during the Pearson correlation analyses. Annual rainfall was correlated with NDVI, temperature, and topography, annual temperature was correlated with soil type, NDVI, and SRTM, and NDVI with topography. These variables are all environmentally linked and a degree of correlation is expected amongst them. For instance, although rainfall was indicated as highly influential in terms of pangolin distribution, other variables may be linked to this. Overall, it is important to note that some variables are linked which may make it more difficult to interpret the results. This issue is reduced by MaxEnt's ability to limit collinearity amongst variables.

4.5. Conclusion

This study was the first to conduct habitat suitability models (HSMs) for pangolins in East Africa, and the first to generate risk models for any pangolin species, although other studies have quantified anthropogenic variables in HSMs. The main environmental factors influencing suitable habitat were rainfall, topography, and soil types, all of which likely impact the availability of prey species and shelter. A moderate level of rainfall was most suitable, along with a wide topographic range excluding areas with high elevation. There were eight highly suitable soil types, five of which had high clay contents. Roads and proximity to humans were predicted to be the biggest threats to pangolins, indicating that poaching has the potential to be a large threat in Kenya. Areas with high suitability and high potential risk, including MMNR and the surrounding community conservancies, and West Pokot, should be prioritised for future conservation efforts and research. It would be valuable to assess the number of deaths and welfare incidents associated with these threats and evaluate them in relation to suitable habitat.

Chapter 5 - Evaluating pangolin fence mortalities through a citizen science approach

5.1. Introduction

Historically fences have been used to denote land rights and usage (Beck, 2009). Land managers with wildlife conservation remits use fences to reduce poaching, spread of animal diseases, and human-wildlife conflict (Pirie, Thomas and Fellowes, 2017). Fences also mitigate risks to human by separating them and their crops or livestock from dangerous wildlife (Woodroffe, Hedges and Durant, 2014). However, fences can have negative impacts on wildlife, such as exclusion of resources, reduction in migration route possibilities (Woodroffe et al., 2014), or by causing animal deaths via electrocution (Beck, 2009). They can also impact gene flow, which may lead to local extinctions (Woodroffe et al., 2014). Given the ubiquity of fences across Africa and their widespread risks to wildlife there is a need to conduct studies into their potential impacts.

Several taxonomic groups including tortoises (family *Testudinidae*), snakes (suborder *Serpentes*), Temminck's pangolin (*Smutsia temminckii*), rock monitors (*Varanus albigularis*) and porcupines (*Hystrix africaeaustralis*) have been frequently reported dying on electric fences (Beck, 2009; Lee et al., 2021; Pietersen, 2022). Fences impact a range of species but quantifying and mitigating for these deaths is difficult because fatalities often occur in remote regions (Beck, 2009), and it is challenging to estimate the overall rate of fence deaths, or the locations and prevalence of the fences that cause them, which make mortalities difficult to predict. Pangolins are thought to experience a high number of mortalities on low electric wires, however, which fence wire configurations, and how these deaths influence pangolin populations are unknown (Pietersen et al., 2014a). Since fence types vary widely, assessing their impact on wildlife is challenging as there is little existing data on fence use and distribution (Jakes et al., 2018). Furthermore, the low density and elusiveness of pangolins makes surveying over large areas challenging. Citizen science, is an increasingly important tool in ecological studies (Linares et al., 2020) for collecting data that is otherwise logistically difficult and expensive to achieve. Citizen science efforts can be wide reaching and allow data to be gathered and accumulated quickly (White et al., 2005). Therefore, a citizen science approach provides a route to collect information on fence knowledge, and it is possible to collect electrocution reports directly from fence users in pangolin range. It is estimated this is the biggest threat to Temminck's pangolins in South Africa currently, even more so than trafficking or poaching, thus research is necessary to investigate these fatalities (Pietersen et al., 2014a).

5.1.1. The impact of fences on wildlife in rural Africa

Land use and property rights vary strongly across regions, which along with motivation and economic needs affect the degree and type of fencing within the area. Fences are predominantly used to demarcate a boundary, enclose livestock, or to keep wildlife and people out of an area, thereby reducing human-wildlife conflict (Jakes et al., 2018). The fence type a landowner or manager selects will vary depending on purpose and cost (Jakes et al., 2018), for example, a wire fence may be used to mark a residential boundary whereas an electrified fence may be used to keep wildlife dangerous to livestock out of a farm. The variety of fencing types makes it difficult to generalise the impact that fences have on wildlife (Jakes et al., 2018), however determining how and why each fence type is used may improve our understanding of this. For example, electric fencing is heavily used in South Africa because the country has 17 million hectares of private game farms, and 7.7 million hectares of protected areas (Taylor and van Rooyen, 2015; Taylor et al., 2016; Pietersen, 2022). There is an estimated 6 million kilometres of fences in South Africa (Pietersen, 2022). Whereas other countries, such as Botswana and Namibia, have historically used fences less, their usage has increased greatly over the last 40 years (Kashululu and Hebinck, 2020). It is difficult to estimate the extent of fencing in each country, however South Africa has the highest prevalence of fences around protected areas (Pekor et al., 2019), which likely extrapolates to a high use of electrified fences. Prior to the 1970s, most fences were made from barbed wire and metal posts, however, over recent decades electric fencing has become preferred over customary fencing in areas of conservation and ranches to keep dangerous wildlife in and poachers out (CapeNature, 2014; Diamond Fence Australia, 2020; Lee et al., 2021). It is also increasing in use amongst farmers to protect livestock and agriculture (Beck, 2009).

Fence regulations can differ across regions within countries, meaning fencing is rarely standardised. For example, in South Africa all nine provinces recommend different fence designs (Beck, 2009). Regulations and guidance are particularly variable for electric fences, as these fences can vary widely in voltage, height, and number of electrified wires (NCNCA, 2009; DEDECT, 2014; Bothma and du

Toit, 2010). Bothma and du Toit (2010) state recommendations for electric fences in South Africa are a voltage of at least 4000, especially if the land has elephants. Although the Northern Cape Nature Conservation Act (NCNCA, 2009) specifies that at least 9000 V should be used for elephants. Heights of electrified wires depend on the animal it is for but generally nose height of the target species is recommended (Bothma and du Toit, 2010). Base wires for the majority of fences are 250 – 300 mm off the ground (Bothma and du Toit, 2010), and many livestock farmers place wires at 100 – 300 mm (Pietersen et al., 2014a). Fences with electrified wire heights of 50 –200 mm are particularly problematic for pangolins as they can come into direct contact with electrified wires, causing injury or death (Pietersen et al, 2014a; Pietersen, 2022). Additionally, some provinces within South Africa require base/trip wires to be at certain heights. For example, the North West Province requires trip wires to be 200 mm from the ground (DEDECT, 2014) and the Western Cape Province requires trip wires at 100 mm if carnivores are present (CapeNature, 2014), whereas the Northern Cape Province recommends 200 mm from the ground (NCNCA, 2009).

5.1.2. Wildlife fence interactions

Fences have several impacts on wildlife, affecting distribution, migration, gene flow and resource access (Woodroffe et al., 2014; Jakes et al., 2018). Variation in fence location, length, perimeter-area-ratio (the ratio of fence length to the area enclosed by the fence, as proxy for fragmentation), electrification, overall density, and type all have the potential to influence how animals are affected. Fences can fragment continuous habitat into 'islands' creating isolated populations and limited gene flow between subpopulations, which then has demographic consequences, particularly for megafauna (Somers, Gusset and Dalerum, 2012). Genetic movement between subpopulations is essential for population survival because it aids in species dispersal and long-term fitness (Somers et al., 2012)**.** The presence of fences can also reduce the availability of movement corridors (Gregory et al., 2021). This can be difficult to overcome unless populations within fenced areas are managed intensely (Somers et al., 2012; Woodroffe et al., 2014; Pirie et al., 2017)**.** A common example of this has been with large carnivores. Since there is often conflict between carnivores, such as wild dogs (*Lycaon pictus*), and humans, many of these species are now restricted by fences which has caused high levels of population isolation and fragmentation (Somers et al., 2012). In the case of the wild dog, this species population size has declined significantly (Somers et al., 2012) as wild dogs do not breed with close relatives and will refrain from reproducing if they stay in their natal packs. Thus unless individuals are translocated by humans to other populations, breeding can be significantly reduced (Somers et al., 2012).

Additionally, erecting fences between areas with important resources, such as water, can limit the carrying capacity of an area, meaning that region can support fewer individuals and populations (Jakes et al., 2018; Pekor et al., 2019). Herbivores that require large areas to forage may over consume the food resources that are present which then causes cascading impacts on vegetation due to overgrazing (Woodroffe et al., 2014; Zhang and Zhao, 2015; Trouwborst, Fleurke and Dubrulle, 2016; Pirie et al., 2017). Migration can also be hindered by fences and animals may be excluded from accessing important seasonal resources (Pirie et al., 2017). In addition to fencing on private land, Botswana employs the use of veterinary fences across different regions to keep bovine foot-and-mouth disease under control (Woodroffe et al., 2014). This has limited the migration potential of large ungulates across the country. If an animal's migration is cut short by a fence this may lead to death through starvation or dehydration (Trouwborst et al., 2016) and can potentially cause population consequences (Jakes et al., 2018).

Furthermore, animal deaths can occur directly through electrocutions or entanglement (Beck, 2009; Pietersen et al., 2014a; Pekor et al., 2019). Many species have been frequently reported dying on electric fences, however, many more species than observed likely succumb to electrocutions. Beck (2009) recorded a total of 33 species electrocuted over a 12-month period at eight properties across South Africa, in Limpopo, Mpumalanga, KwaZulu-Natal, North West, and Northern Cape provinces (Table 5.1). Pietersen (2022) reported 27 species killed and 213 fatalities over five years in the Kalahari at one game reserve (Table 5.1).

Table 5.1 A list of the species recorded as electrocuted on fences in South Africa by Beck (2009) and Pietersen (2022).

Common name	**Scientific name**	**Beck (2009)**	**Pietersen (2022)**
Aardvark	*Orycteropus afer*	X	X
Bat-eared fox	*Otocyon megalotis*		X
Bells hinged tortoise	*Kinixys belliana*	X	
Black mamba	*Dendroaspis polylepis*	X	
Black spitting cobra	*Naja nigricincta woodi*		X
Black-backed jackal	*Canis mesomelas*	X	X
Boomslang	*Dispholidus typus*	X	
Bushpig	*Potamochoerus larvatus*	X	
Cape cobra	*Naja nivea*		X
Cape hare	*Lepus capensis*		X
Cape porcupine	*Hystrix africaeaustralis*	X	
Common duiker	*Sylvicapra grimmia*		X
Common ground agama	*Agama aculeata aculeata*		X
Common warthog	*Phacochoerus africanus*	X	
Flap-necked chameleon	*Chamaeleo dilepis*	X	
Fork-marked sand snake	*Psammophis leightoni*		X
Gemsbok	*Oryx gazella*	X	X
Giant bullfrog	*Pyxicephalus adspersus*	X	
Helmeted guineafowl	*Numida meleagris*		X
Honey badger	*Mellivora capensis*	X	
Horned adder	*Bitis caudalis*		X
Impala	*Aepyceros melampus melampus*		X
Kalahari tent tortoise	*Psammobates oculifer*	X	X
Klipspringer	*Oreotragus oreotragus*	X	
Kori bustard	*Ardeotis kori*		X
Leopard toad	*Sclerophrys pantherina*	X	
Leopard tortoise	*Stigmochelys pardalis*	X	
Lesser bushbaby	*Galago moholi*	X	
Lobatse hinged tortoise	*Kinixys lobatsiana*	X	
Mountain reedbuck	*Redunca fulvorufula*		X
Northern black korhaan	*Afrotis afraoides*		X
Olive grass snake	*Psammophis mossambicus*	X	
Puff adder	*Bitis arietans arietans*		X
Raucous toad	*Sclerophrys capensis*	X	
Red duiker	*Cephalophus natalensis*	X	
Rock monitor	*Varanus albigularis*	X	X
Small spotted genet	*Genetta genetta*	X	
South African hedgehog	*Atelerix frontalis*	X	X

Southern African python	*Python natalensis*	X	
Southern marsh terrapin	*Pelomedusa subrufa*	X	
Southern vine snake	*Thelotornis capensis*	X	
Spotted bush snake	*Philothamnus semivariegatus*	X	
Spotted hyaena	*Crocuta crocuta*	X	
Spotted thick-knee	*Burhinus capensis*		X
Springbok	*Antidorcas marsupialis*		X
Springhare	*Pedetes capensis*		X
Steenbok	*Raphicerus campestris*		X
Stripe-bellied sand snake	*Psammophis subtaeniatus*	X	
Striped polecat	*Ictonyx striatus*		X
Temminck's pangolin	*Smutsia temminckii*	X	X
Thick-tailed bushbaby	*Otolemur crassicaudatus*	X	
Vervet monkey	*Simia aethiops*	X	
Waterbuck	*Kobus ellipsiprymnus*		X

Electrocutions are primarily known to impact Temminck's pangolins because they are bipedal, therefore pangolins approaching fences contact ground-level trip wires. These wires come into contact with their exposed underbelly, and they receive an electric shock which causes them to exhibit a defence response of curling around the wires, typically leading to death (Pietersen et al., 2014a). Some electric fences that feature trip wires may be too high to elicit this behaviour, hence variation in fence design and characteristics may affect electrocution risk but there is no data on distribution or frequency of different fence types in the region. The study by Beck (2009) did not specifically investigate the fence types that caused pangolin mortalities but did indicate that electric wires of 200 mm or less caused the majority of reptile electrocutions. Furthermore, inter-individual variation in pangolin behavioural responses to fences are unstudied and it is thought that body size, species defence behaviour, and season are the best predictors of fence mortalities (Pietersen, 2022), with males and juveniles, and those without established home ranges, thought to be more prone to electrocution (Pietersen, 2013; Pietersen et al., 2014a).

The IUCN Pangolin Specialist Group state that electric fences are a major threat to pangolins currently and that fences with an electric wire height of 50 – 200 mm are the most dangerous (Beck, 2009; Pietersen et al., 2014a; Challender et al., 2014b; Pietersen, 2022). This is mentioned in several scientific publications but has not been thoroughly studied, with many records being anecdotal.

Previous studies into pangolin electrocutions have primarily taken place at game reserves with wire heights of 200 mm thus comparisons between mortalities on different fence types are lacking. Beck (2009) broadly studied electrocutions across numerous species at eight sites, and recorded four pangolin deaths over the course of the year at a single game reserve. Pietersen (2013) recorded 21 pangolin deaths over a three-year period at one game reserve in the Northern Cape. At the same location, another study by Pietersen (2022) found 28 pangolin deaths and 8 further fence interactions over a five-year timeframe. The Beck (2009) and Pietersen (2013) studies estimated that 0.033 and 0.09 pangolin individuals are killed on fences per kilometre per year in South Africa, respectively. These studies may indicate a relatively low electrocution rate for pangolins, yet it is likely electrocutions happen on a larger scale than they appear due to inconsistent fence monitoring (Pietersen et al., 2014a). Pietersen et al (2014a) suggests unless fence monitoring is constant it is possible that scavengers will remove carcasses before fatalities can be recorded, therefore it is important to consider monitoring frequency when assessing fence mortalities. Pietersen et al (2016a) infers from the data an estimate between 2 – 13% (377 – 1028 individuals) of pangolins die from electric fences within South Africa each year. This is based on the number of electric fences that overlap with known pangolin ranges throughout the country. This is an estimation from a single dataset, however it signifies the potential for this to be a large threat. A similar method is used to estimate the level of road fatalities, with a predicted 280 deaths per year. This is based on a rate of seven deaths recorded per year and the number of roads that overlap with pangolin ranges (Pietersen et al., 2016a).

The uncertainty of estimates for electrocution deaths means that more research is needed to estimate the severity of this threat. Impacts that influence overall population levels, such as reducing the number of reproducing individuals in an area, likely constitute a conservation concern as population processes would be inhibited, whereas occasional or sporadic mortalities, which do not impact population density, may indicate individual welfare concerns. Several mitigation methods have been proposed to limit electrocutions, such as rock barriers, although often these relate to other species that are prone to electrocutions, such as leopard tortoises (*Stigmochels pardalis*; Beck, 2009; Pietersen et al., 2014a). Landowners may opt to leave low wires out to protect pangolins, however, this would leave the base of the fence unprotected and vulnerable to burrowing animals such as warthogs (Bothma and du Toit, 2010). Swing gates are also an option to reduce fence fatalities of some species but are costly to implement. These are intermittent small gates that animals, such as warthogs, can use to pass through the fence and these often result in established mammal paths (Bothma and du Toit, 2010). It has been suggested that modifying trip wires can reduce pangolin mortalities by up to 69% (Pietersen et al., 2014a; Pietersen et al., 2016a), however this modification would likely be costly and may not be feasible on a wide scale. The African Pangolin Working Group suggests that a combination of three modified tripwires may reduce the problem, if the strands are 50 mm (live), 200 mm (ground) and 400 mm (live) off the ground. This would mean the live wires are too low and too high for pangolins to be electrocuted (APWG, 2019). Some land may already utilise mitigation to prevent fence deaths, and this must be evaluated when considering overall deaths and planning future mitigation methods.

5.1.3. Using citizen science to document fence use and wildlife mortalities

The high extent of fencing in South Africa means monitoring the electrocution rates of pangolins or any species would not be possible without records from individual landowners, managers, rangers and farmers. People who are directly involved in land management will be most likely to have witnessed electrocutions and be able to inform on how often they occur on their land or place of work. By collecting and collating reports from these individuals it will be possible to make a more accurate assessment of the problem.

The use of questionnaires can contribute invaluable, low-cost information to research (Zhang, 2019). They can ascertain knowledge from niche experts or novices in a specific field depending on who the target audience is. Questionnaires have a wide range of uses in science due to how flexible they can be, and they can attain either qualitative or quantitative data (Pushpanjali, Piddennavar and Mohan, 2011). It has become common for studies of wildlife distribution to include questionnaires (Linares et al., 2020), which can be useful particularly for elusive species. Often existing systematically collected data is sparse and does not provide enough information to accurately assess distribution (Bradter et al., 2018) so involving locals or experts can make the data more robust. Online surveys offer rapid data collection and are cost effective (Wardropper et al., 2021). They also provide ample time for the participant and confidentiality (Rea and Parking, 2014). A few important advantages of this method are that they can be easily given to specific populations, can be followed up by email and give the opportunity to present detailed visual aids (Rea and Parking, 2014; Wardropper et al., 2021). They also have limited researcher influence compared to in-person surveys. Participants may be more willing to engage over email as responding is easy and does not require access to postal services. When implementing online surveys access to the internet is a limitation and depending on the target population, can either increase or reduce bias (UN Educational, Scientific and Cultural Organization [UNESCO] and International Telecommunications Union [ITU], 2019; Wardropper et al., 2021).

Questions with pre-set answer choices are beneficial because responses are standardised and irrelevant responses are avoided but sometimes these questions do not allow for unique responses. However, open ended responses are not always comparable with closed ended responses due to the large variation in answers that could be given, although they can increase specificity (e.g., land location, or fence lengths; Machin and Campbell, 2005; Pushpanjali et al., 2011). Citizen science participation has the potential to be widespread over large areas due to the widespread distribution of humans (Zhang, 2019). Participants must have the level of knowledge or expertise necessary to collect the data and must have access to necessary equipment (e.g., mobile phones) and a means of relaying the data (Scott et al., 2014). Many local people, especially in rural areas, spend their time outdoors in nature and encounter wildlife on a regular basis, meaning they likely have proficient knowledge of the wildlife around them (Zhang, 2019). For elusive species, such as pangolins, there may only be a few very active reporters that participate rather than many occasional reporters. As distribution data is often presence-only, having a small number of active reporters can help infer absence areas (Bradter et al., 2018).

Landowners, managers and workers in South Africa have not previously reported on electrocution rates or fence types via questionnaires. There have been no studies that have reported pangolin electrocutions from any other pangolin range states, for any pangolin species. Therefore, it is important to incorporate a citizen science approach that directly involves local people to investigate how prevalent different fence types are and to determine which types may cause mortalities. It is probable that fence type will influence electrocution rate as electrified wire height can vary greatly. Additionally, it is vital to assess how fences are monitored in order to determine the accuracy of the mortality records they provide. Again, this is information best provided by the people who own or work on reserves or farms.

This study targeted individuals involved with land management throughout Africa, with a focus on South Africa because most reports of pangolin electrocutions (both anecdotal and from previous scientific studies) have been noted there (Beck, 2009; Pietersen et al., 2014a). Throughout Africa it was necessary to target the entire range of Temminck's pangolin, including all range countries, to comparatively assess the frequency and distribution of mortalities as fence use varies depending on country. Since numerous species have been reported as killed on fences (Beck, 2009) this study will evaluate all mortalities, with a primary focus on pangolin deaths.

5.1.4. Aims

This study aimed to utilise a quantitative citizen science questionnaire to investigate the threat posed to Temminck's pangolins by electrocution on electric fences in South Africa. Electric fences are a known threat in South Africa, however the extent of these mortalities and the fence wire configuration that cause these mortalities needs further evaluation.

Objective 1 investigated if there is an association between mortalities and fence location, perimeter-area-ratio, wire configuration, habitat type, or wire height. It was predicted that wire configuration and wire height would be the most influential characteristics and that low-level wires would cause the most mortalities. Objective 2 assessed the concern level of landowners and managers in relation to fence deaths and determine if current mitigation strategies are successful. It was hypothesised that concern level would be moderately high amongst participants and that several mitigation methods would be reported by participants, with varying levels of effectiveness.

5.2. Methods

A quantitative questionnaire was used to assess wildlife electrocution records and fence use across Temminck's pangolin range in Africa. South Africa was the focal country of this study because fences are most prevalent here compared to other areas of Africa (Pekor et al., 2019).

5.2.1. Questionnaire design

The questionnaire was created and distributed online using the Jisc Online Surveys platform (Jisc, 2021; www.onlinesurveys.ac.uk/). The questionnaire comprised 33 questions and was delivered to participants in two parts. Each part took approximately 10 – 15 minutes to complete. Part one contained 21 core questions for the purposes of this study including fence use and mortality data, while Part two comprised of 12 supplementary questions including participant concern level. The full version of the online questionnaire is included as Appendix 6.

Questions were presented in a way that would give non-subjective quantitative responses and enable consistent and comparable data analysis, a mix of question types were used including: single-answer multiple choice, multi-answer choice, Likert scales, and open ended questions that allowed the participant to fill in their own response. A Likert scale (1 – 10) was used to gather opinion data so that responses for a subjective opinion question were recorded in a quantitative way (Williams, 2003; White et al., 2005; Pushpanjali et al., 2011). Each question was optional due to the potentially sensitive nature of the information being gathered. For example, there were several questions that asked for data on fence design and monitoring, and these might be seen as investigating security although this was not the intention. By making each question optional participants could avoid any questions that made them uncomfortable. Phrasing of the questions was based on best common practice recommendations (Williams, 2003; White et al., 2005; Pushpanjali et al., 2011). Questions were presented in simple, jargon-free, clear language, without assumptions, so that participants of numerous reading abilities could understand. Language was written in a manner that best reduced bias, this included avoiding double-barrel and leading phrases. Abbreviations, slang, and emotional wording were avoided. The questionnaire was written in English using plain language to ensure participants non-fluent in English had a better chance of understanding the questions. Logistical and practical constraints prevented the questionnaire from being translated into other languages.

Participants were asked about deaths on fences that they had previously witnessed. This also included animals caught on or injured by fences. Participants were given six taxa choices to report the mortalities of: pangolins, lizards, snakes, tortoises, birds, antelope, and other. Participants were asked to report electrocutions for all species to understand the overall rates of electrocutions and use this to evaluate the concern level participants have related to these deaths. Participants could report as far back as memory allowed. Several diagrams of fence types were created to provide clarity to the participants. These were for questions that asked about what fence types are being used to ensure consistent understanding and responses across all participants. Additionally, participants were asked to identify a pangolin from four photographs to verify recognition of the species. These images were obtained through Creative Commons and the photographers were cited.

In part one, participants were asked to provide their occupation, land name, location and land use, as well as how long they have worked on this land. They were also used to provide their land income sources and land purposes (Table 5.2). These questions were asked to gather background information on the participants and provide context to their subsequent responses pertaining to fence use. To inform on fence use, the participants were asked what habitat types their land included, if fences were present, how they use fences, along with fence type, location, length, purpose, wire height, and voltage, to provide comprehensive information. They were asked to report on fence deaths and were asked about their fence monitoring activities and if they use modifications to prevent electrocutions. Part two asked participants about their habitat types, land size, wire placement, and concern level about electrocutions. Participants were also asked to list other land they worked on with pangolin presence and any related fence deaths. Each response from an individual providing data for multiple properties was considered separate.

Table 5.2 Land income and purpose categories provided as choices in the questionnaire. Participants could select multiple response.

Income categories	**Land purpose categories**
Tourism	Game ranch/reserve
Meat/livestock production	Farmland
Agriculture/farming	Residential
Trophy hunting	Other
Other	

An online interactive map was provided to each participant so they could mark where they have seen pangolin and non-pangolin animal deaths to create a mortality map. The map was created using Canvis.app (McGill, 2021; www.canvis.app), an app that allows participants to anonymously select points on a map for citizen science purposes. This map was featured on the last page of the online questionnaire after participants had submitted their other responses. The participation in this was optional. The map produced was communal, however, the participants could only see their own responses. This allowed for cohesive data collection that automatically collated all responses on one map. When placing a point on the map a drop-down list appeared where the participant could select a species, or 'other' and then could write in a response. This map did not capture the location of reserves with no electrocutions so it is not possible to assess hotspots of electrocutions from this map. Electrocution records reported on the map are automatically anonymous due to the maps being communal, however, the limitation with this approach is that points can be linked to responses given in the questionnaire, i.e., land name or location, by the researcher. This was only visible to the research team and was anonymised during the data analysis process. Mortalities recorded on the interactive map were recorded and analysed separately from the questionnaire reports.

5.2.2. Distribution of questionnaire

Pre-testing of the questionnaire occurred in two phases. In the first phase, the questionnaire was trialled by colleagues, friends and family of the researcher, to evaluate phrasing, grammar, and clarity. Pre-testing was also completed by colleagues at University of Brighton with expertise in questionnaire development. In phase two, questionnaire was pilot tested to give time to catch any issues like flow formatting or queries. No issues were reported so the questionnaire was then rolled out in full. The questionnaire was available from 13 July 2021 to 20 October 2021.

Anyone over the age of 18 was encouraged to participate. Participant selection relied primarily on self-selection and snowball sampling, although some potential participants were targeted based on their expertise. Selection criteria was outlined on a cover page with a participant information sheet (Appendix 6), and outlined suitable participants as landowners, land managers, wardens, conservationists, rangers, tour guides, volunteers, and interns, among other professions or anyone involved with land-related work. Although South Africa was the primary focal country, participants from any region of Africa within Temminck's pangolin range (Angola; Botswana; Burundi Central African Republic; Chad; Ethiopia; Kenya; Malawi; Mozambique; Namibia; Rwanda; South Africa; Sudan; South Sudan; Tanzania; Uganda; Zimbabwe; and Zambia) were welcome to complete the survey. All countries within pangolin range were accepted to inform comparatively on the different extents of fencing and fence types that exist across Africa, and how these related to electrocution rates. Additionally, animals may get caught and injured in non-electric fences. The questionnaire was advertised to people whether or not they had previously witnessed electrocutions as it aimed to ascertain if certain areas experienced few or no electrocutions overall.

The questionnaire was distributed online via email to individuals, game reserves, farms, and relevant association groups (Table 5.3). The questionnaire was also shared on social media, by sending it to several relevant associations on Facebook and Twitter. It was also distributed to conservation groups. In total, the questionnaire was shared to 152 emails and 33 social media pages and groups. Snowball sampling was used by suggesting at the end of the survey that participants share the online link with anyone relevant they know. Three respondents reported electrocutions via direct email and these were incorporated into the dataset. However, in many areas across Africa internet connectivity is lacking. This meant it was difficult to reach smaller farms or residential owners who may not have internet or email access and therefore means there was an inherent bias towards conservationists, commercial game farms and tourist attractions that would likely have better access to the internet. Online surveys were selected over postal surveys due to the low reliability of the local postal service and the increased wait time that comes with this method.

Table 5.3 Associations and conservation groups contacted during the questionnaire distribution. This does not include individuals contacted or private reserves/farms.

Associations and Conservation Groups Contacted
IUCN SSC Pangolin Specialist Group
Game Rangers Association of Africa
Southern African Wildlife Management Association
South Africa National Parks Honorary Rangers
Field Guides Association of South Africa
Rangers of Kruger National Park
South Africa Wildlife Network
Save The Pangolins
Kenya Wildlife Conservancies Association
Maasai Mara Wildlife Conservancies Association
International Ranger Federation

Game Rangers International
South Africa National Parks

A prize draw for a gift voucher was used to entice responses. Offering an incentive can increase response rates, particularly if there is a high chance of winning (Deutskens et al., 2004). The prize draw was offered to participants only within South Africa because South Africa was the focal country due to the high extent of fencing, and because a prize draw with a standardized prize across numerous African countries was not logistically possible. One entry to the draw was given for each part of the questionnaire answered. To further entice participants, a choice of voucher was provided and winners could select from PickNPay, Uber, Netflix or an app store voucher. Participants were given digital vouchers through email. There were 10 vouchers available each with a value of £12 (~250 South African Rand) and the prize draw took place in November 2021. This approach was used to provide a clear benefit of participating to potential respondents. Some respondents may work in conservation professions and thus understand the conservation benefit of participating; however, others may have been less inclined without a personal incentive. The benefits of providing an incentive are the increased number of responses and typically an increase in the quality of responses (Bonke and Fallesen, 2010).

Participation was entirely voluntary, and participants could opt out or finish at any time. This research received approval from the University of Brighton Tier 1 Ethics Review Process (19 May 2021, review reference number: 2021-8212-Stracquadanio). All data were anonymised and stored according to European GDPR regulations on the university OneDrive system. These protocols also address and cover South Africa's POPIA data protection regulations. All responses were stored within the University of Brighton OneDrive and each response was coded with a random number, with all identifying information, such as name and contact information, removed. This identifying information was only used for the prize draw, and was kept and stored separately to the dataset if participants indicated they wished to be contacted with the research results in the future. The researcher is from Western Europe rather than Africa therefore there is some inherent bias in the survey distribution and the perception of the survey. The online survey was biased towards those with access to internet. Additionally, the survey may have been perceived differently than if it had been conducted by someone from a local university.

5.2.3. Data analyses

All data analysis was computed in Jamovi (The jamovi project, 2023). ArcMap (Esri, 2020) and ArcGIS Pro (Esri, 2023) were used to create maps of the communal interactive map data. This data was collected at the end of the questionnaire on Canvis.app.

Responses came predominately from South Africa thus statistical analyses included only South African responses to avoid geographical bias. Data from other countries are summarised descriptively. Data were assessed for errors such as typos or incorrect coordinates and standardised prior to analysis. Temminck's pangolin was referred to as 'pangolin'. All other taxa were written as generic common names, e.g., 'tortoise' or 'bird'. Since questions were voluntary due to the sensitive or personal nature of some data being collected the number of responses between each question varied greatly. Any blank or 'prefer not to say' responses were filtered out. Depending on the research question being answered, data were filtered accordingly and blank cells removed. When categorical data was present (such as yes or no data), these were transformed into numeric groups, e.g. Yes = 1, No = 2. Data did not follow a normal distribution or was ordinal data or counts of frequencies. Nonparametric tests were used and all analyses were two-tailed with all alpha levels set at 0.05. Chi-square Goodness of Fit test was used to analyse the differences between categorical variables, while Mann-Whitney U tests, and Spearman's rank tests were used to analyse continuous data.

<u>Land use, habitat use and fence type</u>

To investigate geographic fence distribution, participant location (country and province) was analysed with the type of fences they use and the number of mortalities they experienced. If more than one fence type was given by a participant their location was duplicated and the fence types were entered separately. To provide context into why different fence types are used, land use and income sources were collected categorically and analysed using Chi-square Goodness of Fit tests. Habitat types were recoded into 12 numeric groups to investigate fence distribution and ascertain if mortalities could be influenced by habitat. Several habitat types were only reported once therefore subsequently these were removed from the analyses (boscia plains, flood plains, fynbos, gallery forest, mopani shrub, riverine thickets, and semi-arid savannah). If participants reported more than one fence type per habitat these were listed as separate responses and all other data for that participant was duplicated. Responses with no fence deaths reported were removed, as were habitat types with only one response.

Fence type

Participants were asked about the reason for their fence use to inform on why different fence types are utilised. Many participants provided more than one reason and thus these results were analysed cumulatively rather than individually per participant. Six fence types were provided for the respondents to select from. From this, fence types were grouped into two categories: with ground-level electric wires and without ground-level wires, as shown in Table 5.4. Ground-level wires were defined as ≤ 200 mm above the ground (Beck, 2009; Pietersen et al., 2014a). This was done to compare mortalities between different types of electric fencing. Participants who responded ‘other’ gave descriptions of this fence type and where possible these were added to the existing groups, or additional categories were added. This was the case for the ‘multiple wires excluding ground level’ category, which was created when multiple participants described this fence type, it was not listed as a questionnaire response. All other responses in the ‘other’ category were removed from analysis. Additionally, participants could select more than one fence type if present on their land.

Table 5.4 Fence category types that were provided during the questionnaire. New fence category refers to when fence types were grouped. Those with electrified wires ≤ 200 mm above ground level are grouped into ‘with ground-level wires, and those without were grouped into ‘without ground-level wires’.

Original fence category	**New fence category**
No electric wire	Not grouped
Ground level wire only	With ground level wires
Multiple wires with ground level	With ground level wires
Multiple wires excluding ground level	Without ground level wires
Top wire only	Without ground level wires
Other	Grouped when possible or removed from the analyses. For example, several respondents listed ground level wires on a fence type not

	included in the original categories so these were grouped together with ground-level wires.

To investigate if wire type influences the number of fence deaths, the categories ‘horizontal and vertical’ and ‘horizontal only’ were coded into numeric categories. A Mann-Whitney U test was run for this analysis. To calculate PAR, total fence perimeter (km) was divided by the land’s total area (km^2). Land area was converted from hectares to square kilometres and outliers with non-feasible PAR size were removed from the dataset, for instance if the PAR did not match with the land size provided by the respondent, i.e., it was too small for land of that size. Spearman’s rank correlation was run to assess if the number of species killed was correlated with fence perimeter-area-ratio. The PAR results were then grouped into 5 categories and analysed for a correlation with deaths using Chi-square Goodness of Fit tests. Groups included: 0.0 – 0.24; 0.25 – 0.49; 0.5 – 0.74; 0.75 – 1.

Fence mortalities

This was collected to determine if particular fence types cause more frequent fence deaths than others. Data for all fence types and species were collected as yes/no presence data, therefore the number of each species killed was not known. If more than one fence type was present, it was not possible to know which fence type caused their reported animal deaths and these responses were excluded from the data analysis. Data were filtered to only include responses with known pangolins present on their land. It was assumed all other species were present on all land because of the commonality and wide variety of these animal groups. Chi-square Goodness of Fit tests were run for each animal group: pangolin, snake, lizard, tortoise, bird, antelope, and other. The number of pangolin deaths were compared against the number of other taxa killed. Fence types were categorised into 'ground level' and 'no ground level' electric wires. Non-electric fences and the 'other' category were removed from this analysis. The number of taxa killed on electric and non-electric fences was analysed using a Mann-Whitney U test. This was also tested with the aforementioned ‘with ground level wire’ and ‘without ground level wire’ groups.

Fence monitoring, mitigation, and concern level

Spearman's rank correlation was used to evaluate if the monthly rate of monitoring correlates with the number of species being killed. This was done to assess at what frequency of monitoring all species are detected. Only reserves with known pangolin presence were included in this analysis. During this analysis timescale was taken into consideration to reduce bias. Each participant was asked how long they had owned or worked at their land for, this varied greatly between participants from a few months to several decades. All times given were converted into months and then monthly rate of animal deaths was calculated from this. Some participants reported the use of modifications to reduce fence deaths. A Mann-Whitney U test was run to analyse this. Modification data was presented as yes/no data and this was analysed with the count number of killed species reported.

Concern level pertaining to fence deaths was collected on a Likert scale of 1 – 10, with 10 being the highest level of concern. The overall number of species killed was evaluated with concern level to determine if a high number of species caused an increased concern level amongst the participants. This was analysed using a Spearman's rank correlation. This was also tested to determine if concern level was influenced by the number of weekly monitoring events conducted by each participant. Concern level was also analysed with yes/no modification data in a Mann-Whitney U test to determine if the use of modifications impacted concern level. If participants did not report on modification use or did not report their concern level they were excluded from this analysis. Further, concern level was evaluated for each animal group. For this analysis, data was filtered to ensure pangolins were present on each piece of land. It was assumed all other species were present on every piece of land.

5.3. Results

A total of 41 participants were recruited via the online questionnaire form. Three additional responses were conveyed via email to the researcher giving a total sample size of 44, with 29 of these engaging with part two of the survey and listing additional land areas as subsequent responses. This generated 73 responses overall. Additional responses refer to any extra pieces of land that a participant answered for, such as previous land worked at. The majority of responses (N =

52) came from South Africa and are the focus of this results section. Since all questions were voluntary the number of responses between questions was unbalanced (Appendix 7: Table A1).

5.3.1. Land use, habitat use, and fence type

Five southern African countries and one East African country were recorded (N = 70). These were: South Africa (74.3%, N = 52), Botswana (11.4%, N = 8), Tanzania (7.14%, N = 5), Zimbabwe (4.28%, N = 3), Mozambique (1.42%, N = 1), and Namibia (1.42%, N = 1). Of all responses, 54 participants provided their province. Where more than one province was indicated by a participant, this is represented in Appendix 7: Table A2 with a hyphen. Within South Africa the most common province (N = 44) surveyed was Limpopo (40.74%, N = 22), followed by the North-West (12.96%, N = 7), Northern Cape (9.26%, N = 5), Mpumalanga (7.41%, N = 4), Gauteng (5.56%, N = 3) and KwaZulu-Natal (5.56%, N = 3). 70.83% (N = 17) of responses feature tourism as a form of land use (N = 24). The most common purpose was game ranch/reserve use, with solely conservation purposes being the least common land purpose (N = 30; Appendix 7: Tables A3 – A4 and Figures A1 and A2).

There was a significant difference between the type of fences used across South Africa by province (N = 42). These results are for all fences reported, regardless of province and known pangolin presence. Unelectrified fences were reported 19% (N = 8) times, while the remainder had at least one electric wire, with 14% (N = 6) having only ground-level wires, 54.75% (N = 23) having multiple electric wires including ground-level, 7.14% (N = 3) having multiple electric wires without ground-level, and 4.76% (N = 2) having only top-level electric wires (Appendix 7: Figures A3 and A4). When assessed by province, Limpopo had a higher than expected presence of multiple (including ground-level) electric wires (χ^2 = 24.0, df = 6, p = < 0.001). Whereas no other fence types differed in presence between province (non-electrified (χ^2 = 8.00, df = 6, p =0.238); ground-level only (χ^2 = 8.67, df = 6, p = 0.193); multiple electric wires excluding ground-level (χ^2 = 8.67, df = 6, p = 0.193); and top-level only (χ^2 = 5, df = 6, p = 0.544). When assessing with the consolidated fence groups, there was a significantly higher presence of ground-level wires in Limpopo and the North West Province (χ^2 =

26.3, df = 6, p = < 0.001), and no significant difference in the presence of fences without ground-level wires (χ^2 = 6.50, df = 6, p = 0.370; Appendix 7: Figure A5 and Figure A6).

The most common reason to have fences was to keep animals in, followed by marking a land boundary and security uses (Appendix 7: Table A5). Fence use differed between land use, with non-electrified fences used significantly more for residential and ranching purposes (χ^2 = 10.7, df = 4, p = 0.031), ground-level wires used significantly more for ranches (χ^2 = 50.7, df = 4, p = < 0.001), and multiple wires (excluding ground-level) used significantly more for ranches (χ^2 = 12.0, df = 4, p = 0.017). There was no difference in use between ground-level (χ^2 = 2.33, df = 4, p = 0.675) or top level only (χ^2 = 3.00, df = 4, p = 0.558). Ten habitat types were reported by 28 participants (Appendix 7: Table A6). Savannah was the most common habitat (N = 21, 60%), followed by grassland (N =11, 31.42%). The mean number of species killed per habitat type did not vary largely (Appendix 7: Table A7).

5.3.2. Fence type and wildlife mortalities

A total of 89 death reports were recorded across all countries in the questionnaire, with 82 of these reported by 32 respondents in South Africa. This is the cumulative number of times that participants selected 'yes' for all of the six species choices provided, rather than a total number of mortalities. Pangolin mortalities (19.51%, N = 16) were the second most reported species, after tortoises (26.82%, N = 22; Table 5.3), while 84.61% (N = 45) of respondents reported pangolin presence on their land. Six species were reported only once under the 'Other' category, these included: bat-eared fox (*Otocyon megalotis*), giraffe (*Giraffa giraffa*), cheetah (*Acinonyx jubatus jubatus*), aardvark, common warthog (*Phacochoerus africanus*), and wild dog (*Lycaon pictus*). Over half of the respondents (61.53%, N = 32) reported animal deaths on fences, and 25 of 37 (64.86%) of fences reported feature ground level electrified wires (200 mm).

Most participants (71.15%; N = 37) reported use of fences with 81.57% utilising electric fences (N = 30; Appendix 7: Table A8). Fences with ground level wires were the most commonly used fence type, whether these were the only wire on a fence or one of multiple wires. The total number of taxa killed on non-electric compared to electric fences did not differ (U = 20.0, p = 0.196), nor did the number of taxa killed on fences with ground-level wires compared to all other fence types ($U = 17.5$, $p = 0.1584$). Sixteen participants had fences but had never witnessed any species mortalities.

The number of mortalities on different fence types differed significantly between species. When comparing non-electrified and electrified fences, more pangolins and tortoises were killed on electric fences than non-electric ($\chi^2 = 8.00$, df = 1, $p = 0.005$; and $\chi^2 = 9.94$, df = 1, $p = 0.002$, respectively. This did not differ for any other species (Lizard: $\chi^2 = 2.00$, df = 1, $p = 0.157$; Snake: $\chi^2 = 2.00$, df = 1, $p = 0.157$; Bird: $\chi^2 = 0.200$, df = 1, $p = 0.655$; Antelope: $\chi^2 = 2.87$, df = 1, p – 0.096; and Other: $\chi^2 = 2.00$, df = 1, $p = 0.157$). When considering fences with ground-level electric wires and those with electric wires of other heights, again pangolins and tortoises experienced more than expected deaths on fences with low-level wires ($\chi^2 = 8$, df = 1, $p = 0.005$; $\chi^2 = 10.3$, df = 1, $p = 0.001$, respectively). This did not differ for any other species (Lizard: $\chi^2 = 3.57$, df = 1, $p = 0.059$; Snake: $\chi^2 = 3.57$, df = 1, $p = 0.059$; Bird: $\chi^2 = 1.00$, df = 1, $p = 0.317$; Antelope: $\chi^2 = 0.143$, df = 1, $p = 0.705$; Other: $\chi^2 = 2.00$, df = 1, $p = 0.157$; Figure 5.1 and Figure 5.2, Table 5.5). When considering all fence types (non-electric, ground-level wires, multiple wires including ground-level, multiple wires excluding ground-level, and top only), the number of deaths per species differed. Pangolins, lizards, snakes, tortoises and antelopes experienced significantly more deaths on fences with multiple wires including ground-level (Pangolin: $\chi^2 = 17.0$, df = 3, $p = < 0.001$; Lizard: $\chi^2 = 15.0$, df = 3, $p = 0.002$; Snake: $\chi^2 = 18.0$, df = 3, $p = < 0.001$; Tortoise: $\chi^2 = 22.7$, df = 1, $p = < 0.001$; Antelope: $\chi^2 = 17.9$, df = 5, $p = 0.003$; Appendix 7: Figure A7 and A8). Whereas bird and other species deaths did not differ with fence type (Bird: $\chi^2 = 3.76$, df = 3, $p = 0.300$; Other: $\chi^2 = 3.00$, df = 3, $p = 0.392$). Three respondents reported deaths of lizard (N = 2), snake (N = 2), tortoise (N = 2), bird (N = 2) and antelope (N = 2) on non-electric fences. There was one pangolin mortality reported on a non-electric fence in Botswana and no other pangolin mortalities reported in any other country (Table 5.6).

Table 5.5 Number of times each species was reported as killed on a fence in South Africa. Responses given in the 'other' category are listed.

Species	**N**
Tortoise	22
Pangolin	16
Antelope	14
Snake	12
Lizard	8
Bird	5
Other	5 (bat-eared fox (*Otocyon megalotis*), Southeast African cheetah (*Acinonyx jubatus jubatus*), common warthog (*Phacochoerus africanus*), South African giraffe (*Giraffa giraffa*), and African wild dog (*Lycaon pictus*))

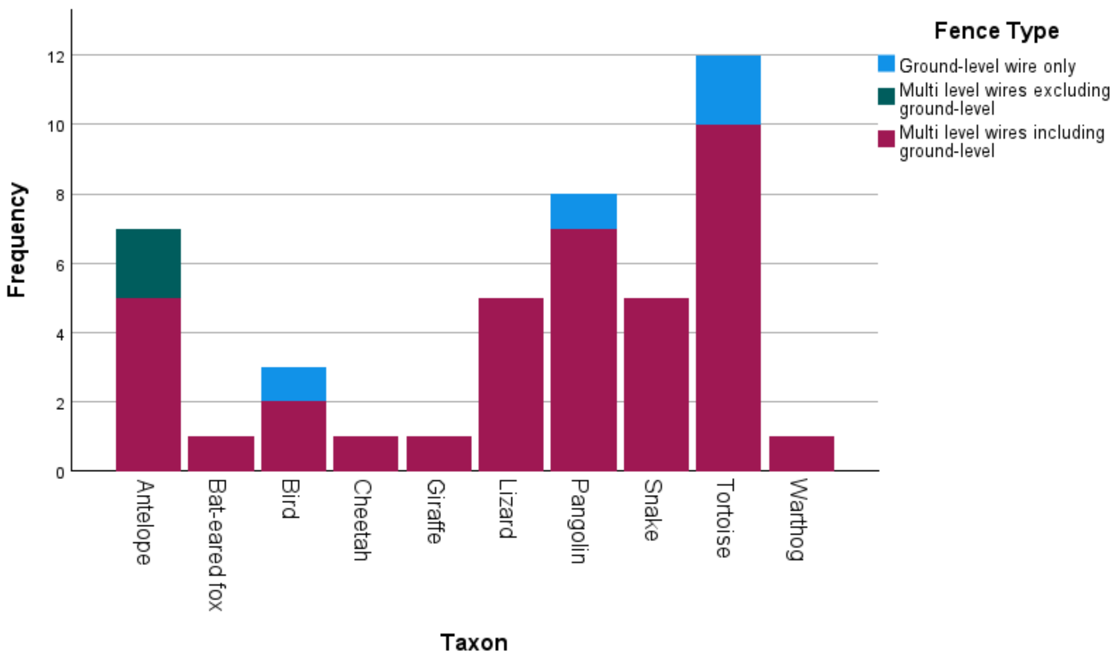


Figure 5.1 Frequency of fence deaths by vertebrate taxon grouped by presence or absence of ground-level electrified wires in South Africa based on an electronic questionnaire survey. One African wild dog (*Lycaon pictus*) record was on an unspecified fence type and was thus excluded.

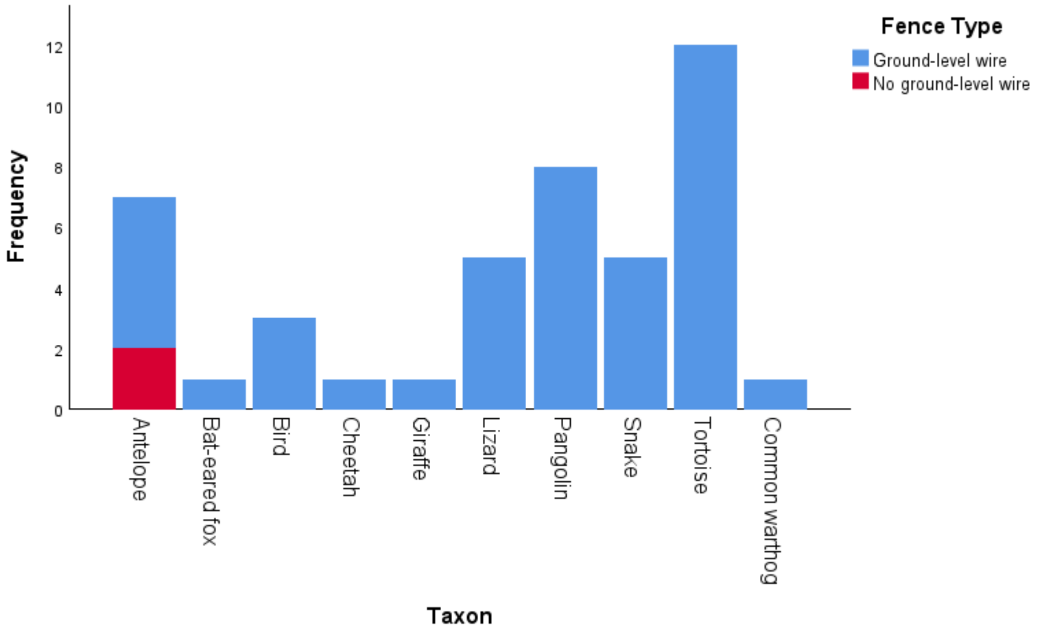


Figure 5.2 Frequency of fence deaths by vertebrate taxon grouped by presence or absence of ground-level electrified wires in South Africa based on an electronic questionnaire survey. One African wild dog (*Lycaon pictus*) record was on an unspecified fence type and was thus excluded.

Table 5.6 Fence use and fence-related taxa mortalities for non-South African countries based on an electronic questionnaire survey.

Country	Responses	Fence types	Fence mortalities
Botswana	8	1 multiple wire excluding ground; 5 non-electric; two with no fence	Pangolin (non-electric); snake, tortoise, antelope, other (fence type unreported)
Tanzania	5	1 multiple wire excluding ground; 3 unelectrified; one with no fence	None
Zimbabwe	3	1 top-only electric; one unelectrified; one with no fence	None
Namibia	1	None	None
Mozambique	1	None	None

The use of horizontal or vertical wires did not significantly influence the number of species reported electrocuted by a participant (U = 32.00, p = 0.411; Appendix 7: Figure A9). The number of electrocutions did not differ significantly across land with different PAR (Spearman's rho = 0.020, p = 0.949; Figure 5.3). PAR was then grouped into ranges (0 – 0.24, 0.25 – 0.49, 0.50 – 0.74, 0.75 – 1) and the analysis was rerun and there was a significant difference between groups. Those with a PAR in the lowest group of 0 – 0.24 experienced significantly more deaths than other categories of higher PARs (χ^2 = 19.2, df = 3, p = < 0.001). Low PAR may indicate longer stretches of each single fence.

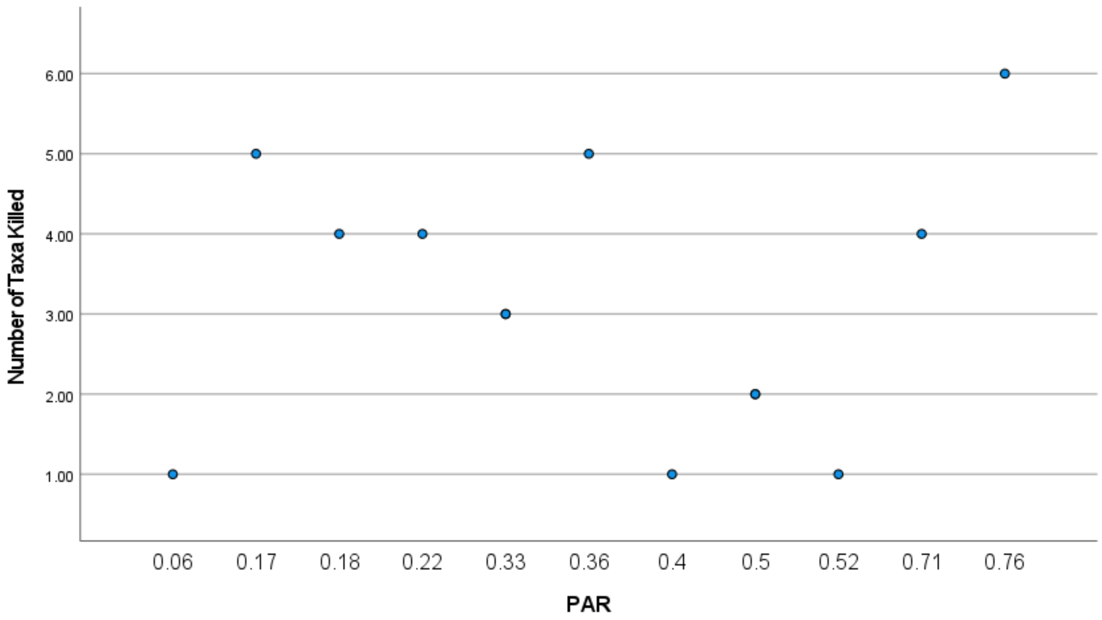


Figure 5.3 Scatter plot showing the Perimeter-Area-Ratio (PAR) reported by each respondent and the number of species electrocuted at each PAR value.

5.3.3. Mortality map

Nine different species were reported as killed by fences on the Canvis map, with a total of 76 deaths mapped. Deaths were primarily in South Africa (82.5%, N = 63) and the remainder in Botswana (17.5%, N = 13; Figure 5.4). A cluster of these deaths, including pangolin, was reported in the Phalaborwa area, and a cluster of pangolin deaths north of the Rustenburg region, of the North West

Province (Figure 5.5). Limpopo comprised over half of all deaths (51%, N = 39), and 63.6% (N = 7) of pangolin deaths. Three (27.3%) pangolin deaths were recorded in North West, and one (9.1%) in Mpumalanga.

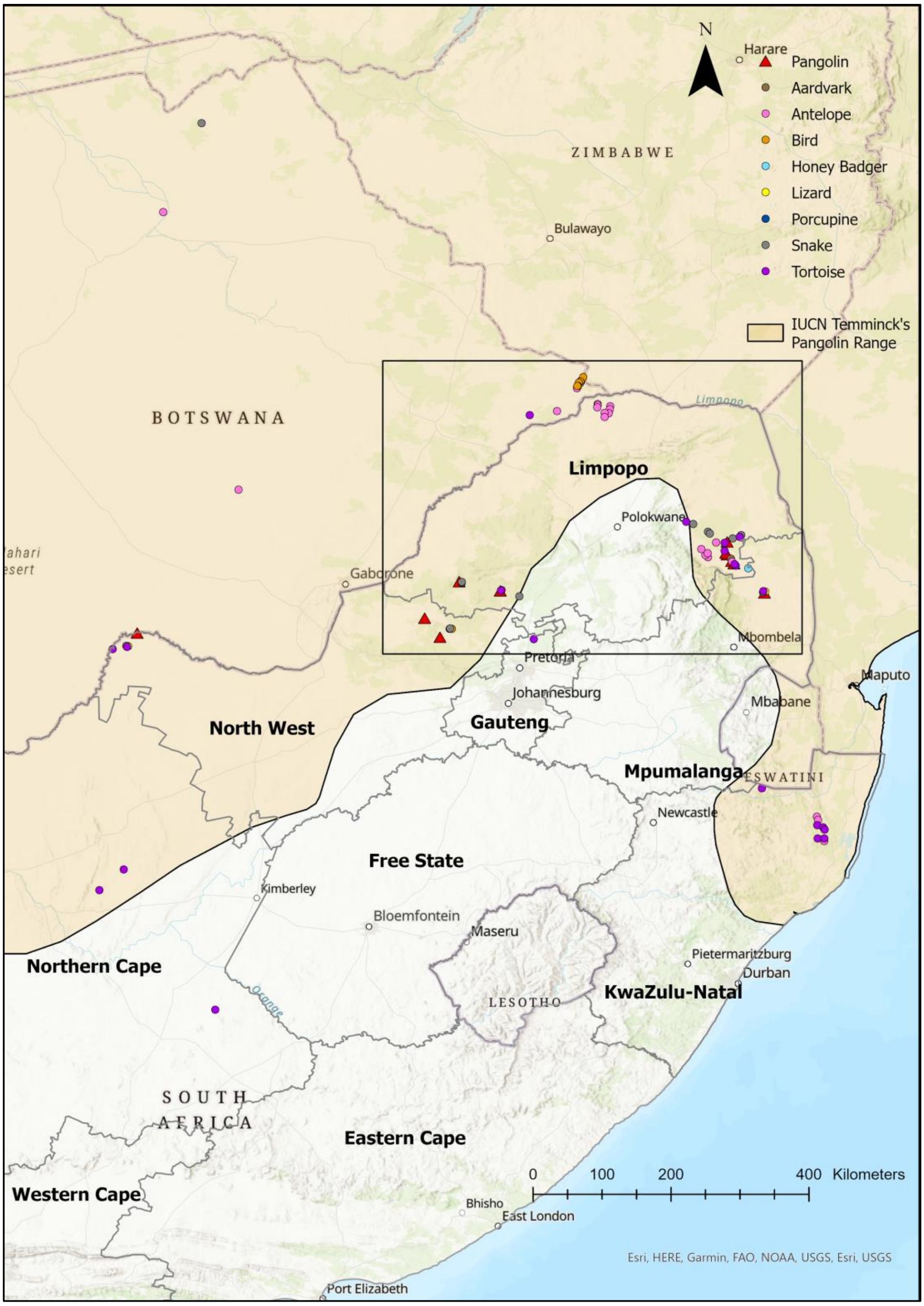


Figure 5.4 Reported animal fence deaths from South Africa and Botswana collected using Canvis.app. The IUCN Temminck's pangolin (Smutsia temminckii) range is shown (Pietersen et al., 2019). South African province is displayed (SEAON, 2011). The black rectangle is enlarged in Figure 5.5.

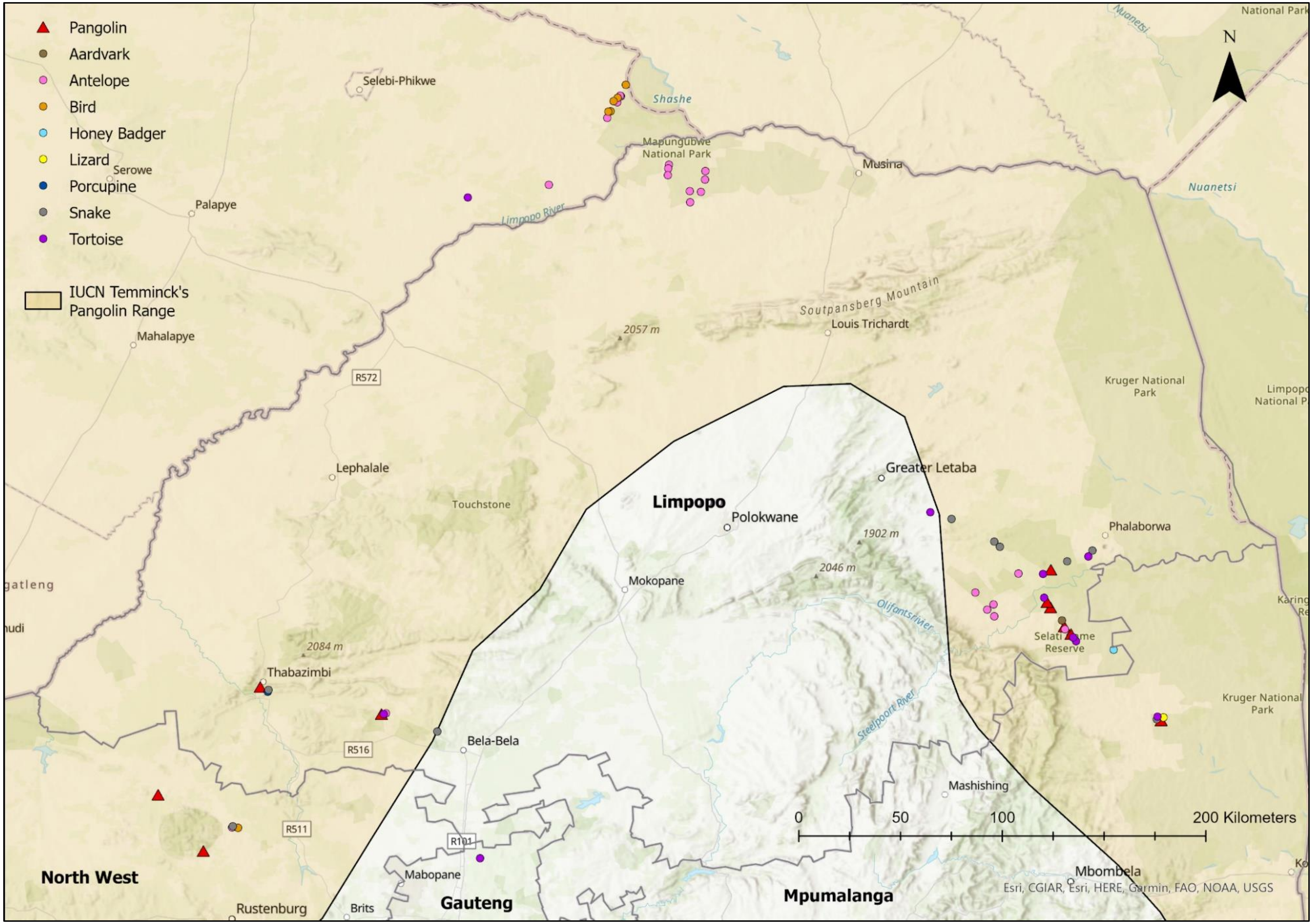


Figure 5.5 Animal fence deaths recorded from northern South Africa and southern Botswana using Canvis.app. The IUCN Temminck's pangolin (Smutsia temminckii) range is shown north of the black line (Pietersen et al., 2019). Provincial boundaries shown in grey (SAEON, 2011).

5.3.4. Fence monitoring, concern level, and mitigation use

One third (32.69%; N = 17) of participants reported the frequency of their fence monitoring. Mean monitoring rate equated to approximately just under one monitoring event per day (Table 5.7). There was no significant correlation between the number of monitoring events conducted by a reserve and the number of species reported killed (Spearman's rho = -0.116, p = 0.598; Figure 5.6). Of 26 respondents, just under half (46.15%; N = 12) utilised modifications. Reported fence modifications included modifying tripwires (58.33%, N = 7) by removing (N = 3), raising (N = 2), or lowering (N = 2); installing physical barriers (16.66%, N = 2); and using earth wires instead of low electrified wires (8.33%, N = 1), low voltage wires (8.33%, N = 1), or tunnels under the fence (8.33%, N = 1; Appendix 7: Table A9). However, the presence of modifications did not influence the mortality rate (U = 83.5, p = 1.000). Most participants (96.15%, N = 25) were unsatisfied with current methods and were interested in alternative mitigation.

Table 5.7 The range and mean number of fence monitoring events reported by participants.

	Daily	Weekly	Monthly
Range	0.14 – 3	2.5 – 15	4 – 75
Mean	0.98	7.87	30.57
Standard error ±	0.17	1.06	4.67

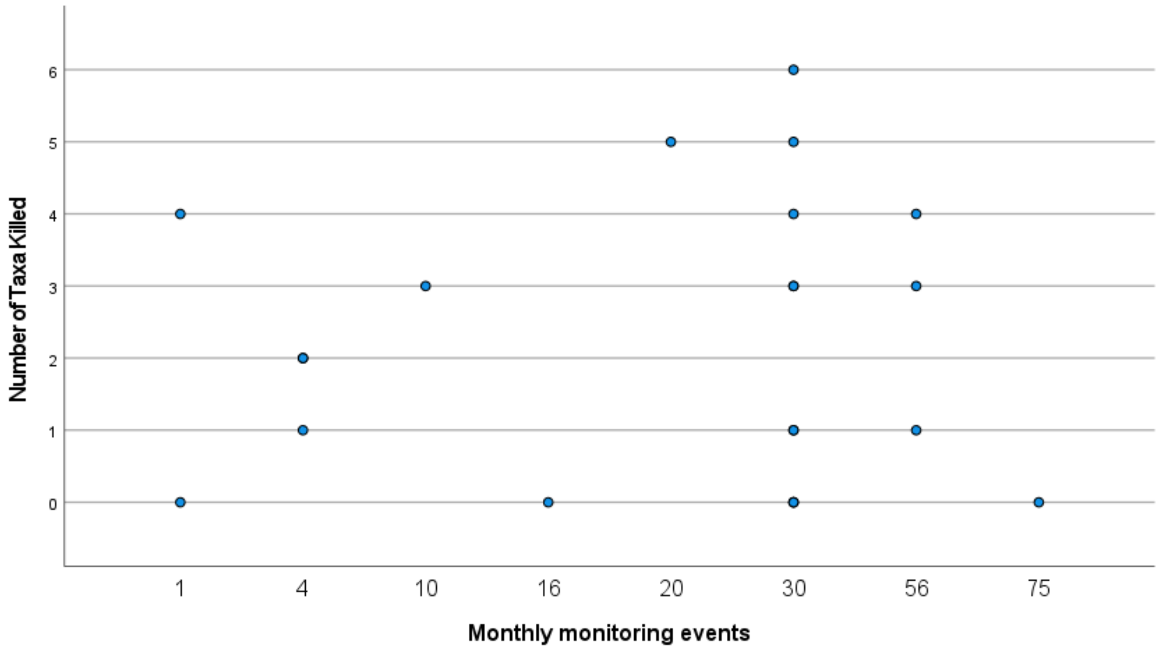


Figure 5.6 The number of monthly fence monitoring events compared with the overall number of species reported killed on fences. Species reported was calculated as the monthly number of species killed throughout the participants time worked on the land.

Participants (N = 26) answered whether they have experienced fence damage by animal deaths, with 15.4% (N = 4) reporting damage occurring, 53.8% (N = 14) reporting no damage, and 30.8% (N = 8) unsure. Among the respondents surveyed, 44% (N = 26) reported their concern level about fence deaths (Appendix 7: Table A10). Concern level varied, with 23.1% extremely concerned (score of 10), while 34.61% expressed low concern (score of 1 – 3; Table 5.8 and Figure 5.7). Mortalities did not influence concern level (Spearman's rho = 0.379, p = 0.056), however, an increase in deaths was seen to increase with concern level. There was no significant correlation between concern level and number of electrocutions (Spearman's rho = 0.379, p = 0.056). Concern level did not differ depending on the taxa electrocuted, thus no species, including pangolins, caused respondents to experience a higher level of concern (Pangolin: $\chi^2 = 12.0$, df = 9, p = 0.213; Lizard: $\chi^2 = 4.00$, df = 9, p = 0.911; Snake: $\chi^2 = 8.00$, df = 9, p = 0.534; Tortoise: $\chi^2 = 7.00$, df = 9, p = 0.637; Bird: $\chi^2 = 5.86$, df = 9, p = 0.754; Antelope: $\chi^2 = 9.00$, df = 9, p = 0.437; Other: $\chi^2 = 9.00$, df = 9, p = 0.437).

Table 5.8 Likert responses from participants who also reported the number of killed species they have witnessed. Table also shows the mean number of killed species per each Likert response. 1 = the lowest level of concern and 10 = the highest level of concern.

Likert score	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Number of respondents	4	3	2	2	5	1	2	0	1	6
Mean number of species	4	2.5	1	1	2.2	5	6	0	4	3

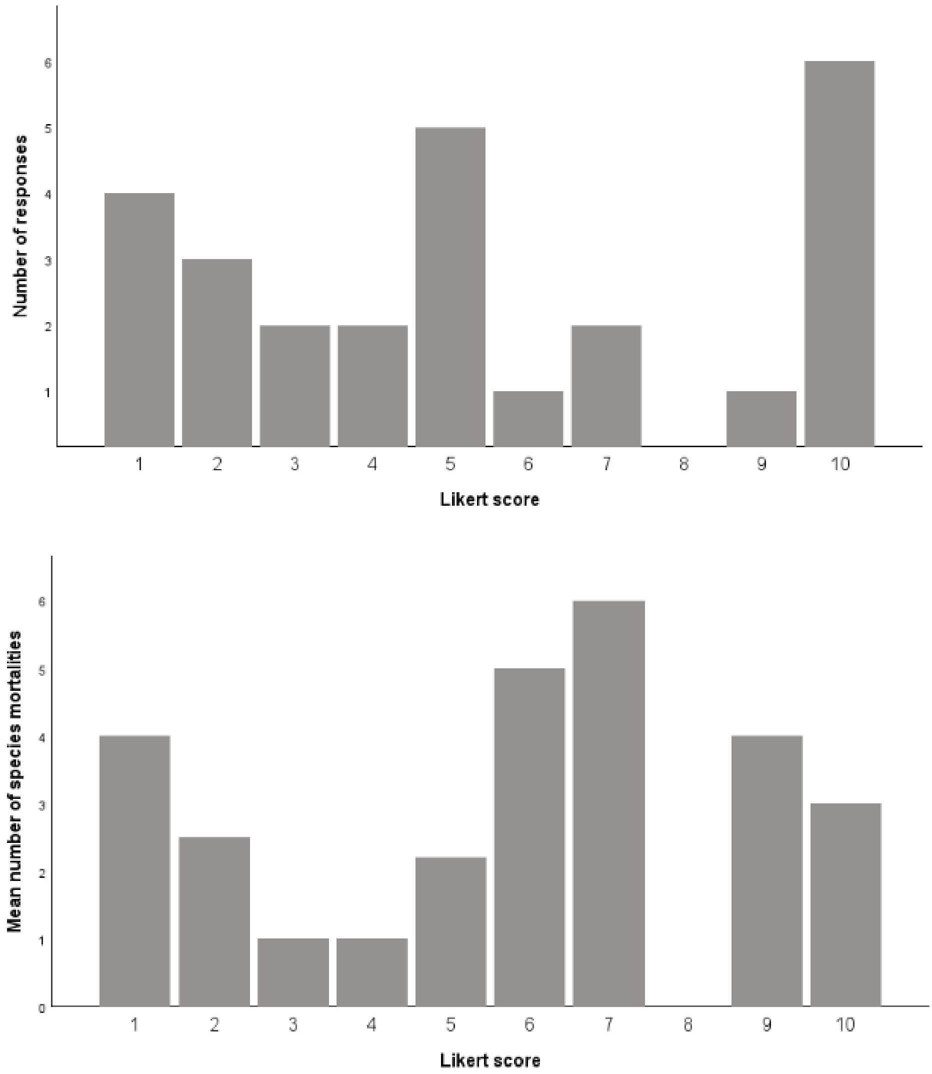


Figure 5.7 The number of participants who witnessed at least one animal electrocution and their Likert level of concern (top); and the mean number of species witnessed killed for each Likert concern level (bottom).

5.4. Discussion

This study attempted to understand the extent of fencing and animal deaths by surveying land managers in Africa. The use of fences throughout Africa has become increasingly common over the last century, and has included the use of electric fences over the last several decades (Arnot, 2017). Despite this, electric fences were found to not be universal and ubiquitous throughout southern Africa. Fence use is challenging to quantify and monitor because individuals do not need to report fence use and new fences can easily be erected or changed as needed (Jakes et al., 2018). The extent of fencing is known to cause habitat fragmentation and reduce the availability of corridors for movement (Gregory et al., 2021). Pietersen (2022) reported 6 million kilometres of fencing in South Africa. This study found 45% of participants utilised electric fences, meaning up to 2.7 million kilometres of electric fencing may exist. However, this estimate does not take land use into account, such as game reserves compared to residential fences. Pangolins were found to be the second most reported animal killed on fences after tortoises and the majority of deaths occurred on fences with multiple heights of electric wires including ground-level electric wires. One pangolin death occurred on a non-electric fence in Botswana. This threat, combined with over-exploitation from the wildlife trade and bush meat hunting, could lead to a negative impact on the sustainability of pangolin populations. Fence mortalities may become particularly problematic if they impact dispersal of pangolins across the wider landscape, therefore it is vital that further monitoring is conducted and that appropriate mitigation strategies are developed. The majority of citizen science reports in this study came from Limpopo province in South Africa thus the main conclusions are most relevant to this region and may not be applicable to all of South Africa.

Although more than eight fence types were reported overall, the most common types all featured a ground level wire, approximately 200 mm above the ground, and these were exceedingly common in South Africa. These wires are a height that makes it easy for pangolins, tortoises, and other medium sized animals to accidently come into contact with them (Beck, 2009). Other countries, such as Mozambique, did not report any fence use or did not use electric wires. Fourteen different animal groups were reported killed on or near fences in 165 reports over multiple sites, between the questionnaire and interactive map responses. This was over an unrecorded and unstandardised period of time as participants could report as far back as memory allowed. For an indirect comparison due to differing time frames and study sites, Pietersen et al (2022) recorded 27 species and 213 mortalities over five years at one Kalahari property, whereas Beck (2009) recorded 33 species over one year across eight sites in South Africa.

Self-reporting from non-specialists limited the availability of species-level data and it is not possible to evaluate whether taxa such as ‘bird’ represent a range of species or a singular one for each participant. Tortoises were the most frequently reported, followed by pangolins. As tortoises are widespread and common (Branch, 1998), the rate they are witnessed may be proportional to this, although the rate of deaths likely indicates a welfare concern. Tortoises, birds, lizards, and snakes are species-rich groups that are inherently widespread (Branch, 1998; Roberts et al., 2005; Skinner and Chimimba, 2005). Pangolins in South Africa are a single species which occurs in low densities (Pietersen et al., 2020). Due to their scarcity, the level of pangolin deaths witnessed indicates that their actual number of deaths is likely even higher than reported. Being the second highest reported species in this survey indicates a welfare concern and a conservation issue for this IUCN-listed vulnerable species as pangolin deaths likely occur much more than suggested by these results as there are likely more pangolins killed than are ever witnessed by people. Pangolins, tortoises, lizards, and snakes experienced the most deaths on electric fences with numerous wires including those at ground level. This indicates that it is ground-level electric wires that cause the majority of wildlife deaths and endanger animals. Properties with a low PAR experienced higher overall mortality levels, which may be attributed to longer stretches of each single fence present.

Fence use varied between country, primarily between South Africa and elsewhere, which is likely due to the higher level of private game ranches and reserves across South Africa (Beck, 2009) overall, compared to other countries. Within South Africa, the provinces Limpopo, Gauteng, and Mpumalanga featured the most electric wires, and Limpopo reported the most pangolin deaths, however, the number of participants from these areas was high in comparison to other provinces. Although participants throughout Temminck’s pangolin range were welcome to take part, the large majority were from South Africa. This was due to increased online connectivity in South Africa compared to other countries (Stork, Calandro and Gillwald, 2013) and the inherent number of game reserves present online from this. Correspondingly, there were significantly more electrocutions reported from South Africa compared to other countries. The highest proportion of pangolin deaths and overall deaths were recorded in Limpopo province. This cluster is likely attributed to the study design as Limpopo had the highest number of survey participants. More than 75% of participants stated their land's main income source involved tourism and more than 83% of these land areas were reported as game reserves or game ranches. The most common response for fence purpose was to keep animals in, which again, is due to the high number of game reserves that took part in this questionnaire. Types of fences used in each reported habitat type were investigated to identify future risk sports. This revealed that both savannah and grassland areas had more low level ground wires than other habitats and this may indicate a higher chance of animal deaths. However, the level of each habitat type reported may be spatially biased as these habitats are common in Limpopo province.

The number of daily, weekly, and monthly monitoring events did not influence the number of species reported electrocuted. The majority of participants monitored their fences approximately once a day, meaning most killed animals would probably be noticed unless they had already been removed by scavengers or people. This is supported by those participants who monitored their fences multiple times a day yet did not report higher levels of killed animals, signifying that once a day is likely enough to accurately assess the number of fence deaths occurring. For those who monitor fences less frequently, but still reported deaths it may indicate a higher prevalence of deaths on that land. However, these results must be considered carefully. Without a standardised monitoring protocol in place, it is difficult to evaluate the correlation between monitoring events and mortalities.

Just under one quarter of participants in South Africa currently use mitigation to reduce fence deaths. These mainly consisted of fence modifications, such as changing trip-wire height or removing trip-wires, but also included using barriers to block animals for coming into contact with low wires. However, there was no difference between the number of taxa killed on land with or without these modifications, indicating that current methods are not effective. The great majority (96.15%) of participants were interested in future methods to reduce fence deaths which implies they are not satisfied with how current methods are working. There were a variety of concern levels pertaining to fence deaths amongst the participants. The minority of participants thought the fence was being damaged by animals, however, the majority were concerned about animal conservation and welfare. Concern levels reported by participants with and without mitigation did not differ much, meaning the use of modifications has not reduced participant concern and deaths are not being reduced at a satisfactory level. The most common mitigation tried was the modification of tripwires, either by raising, lowering, or removing it. Removing this wire may subsequently reduce the effectiveness of the fence to contain dangerous wildlife, and also increase the security risk to the property by allowing people to access the property more easily. The installation of rock and tyre barriers were utilised, as well as using earth wires as an alternative to low-level electric wires, and using low voltage wires. Creating tunnels under the fence was also a tried method. It is likely that new and different mitigation methods are needed in order to reduce these deaths and improve concern levels. No widescale mitigation methods have been tested to reduce mortalities. Previous studies have suggested that raising the level of ground wire heights, creating a physical rock barrier in front of ground-level wires, or switching power off during certain times of the day may be effective (Beck, 2009; Pietersen et al., 2014a), however both adjusting wire height and physical barriers were already being used by participants in this study and did not reduce mortality levels. Future studies are needed to work on developing more effective mitigation methods. There is currently ongoing research into modifying fence designs to reduce fence mortalities (Pangolin.Africa, 2021), however results are not yet published. Any method use must be low-cost and easy to implement on a wide scale. Based on this research, an appropriate method may be raising the tripwire slightly, to above 300 mm. This is above the height that impacts pangolins and would still ensure the wire is intact for security purposes. However, whilst this may be effective for reducing pangolin mortalities it may still mean other wildlife species are still electrocuted.

5.5. Limitations

Limitations of the study include that most respondents were from tourism-focused game reserves in Limpopo, which limits ability to draw conclusions for other regions and land use types, including the game ranching industry. The online nature of the questionnaire, due to COVID-19 pandemic travel restrictions, limited participation to those with internet access (Wardropper et al., 2021). This bias could not be overcome as other distribution methods were not practical or available at the time of this study. This was a common limitation for survey research over the pandemic period (Wardropper et al., 2021). Due to this, a large proportion of the sampling population may have been missed. In particular, commercial game ranching farms, which cover much of pangolin range in South Africa and utilise primarily electric fencing, were under-sampled.

The questionnaire was only offered in English due to logistical constraints thus non-English speakers were excluded unless their web browser offered an automatic translation. Further biases include a high occurrence of self-selection (Vicente and Reis, 2010; Rea and Parking, 2014), meaning that respondents were not representative of the whole target population (Fogli and Herkenhoff, 2018). This means participants that have a particular interest in the study topic are more likely to respond than those with less of an interest (Santori et al., 2021). In this case it is probable that conservationists, those interested in pangolins, or people who experience higher levels of fence deaths on their land, are more likely to be interested in participating. Managers and landowners were the primary participants, likely because many reserves and organisations were contacted directly via email by the research team. Although these demographics are ideal for this survey, they are biased due to those who run game reserves for tourism and probably have an inherent interest in conservation. Since the majority of participants were landowners or managers the deaths noted may be under reported as it is more typically rangers and guides who work in the field near fences.

Each question was voluntary to ensure all participants were comfortable with the information they submitted. This meant it was impossible to control how many responses were obtained for each question, which led to an uneven response rate for the majority of questions. In the future it is recommended to require responses for all questions except those with sensitive information. This study also relied on participant memory, which introduces possible bias, as “valuable” species like pangolins may be more memorable than other species. Reporting deaths of protected species, including pangolins, is a sensitive topic, leading some landowners to choose not to participate to avoid association. Together these limitations highlight the importance of incorporating stratified sampling into future studies if results are to be considered representative (Fogli and Herkenhoff, 2018). Finally, the researcher was from a western European country and the perception of this survey may have differed if it had been conducted by a researcher local to the target audience.

5.6. Conclusion

This study was the first to use citizen science across pangolin range in South Africa to evaluate fence use and associated electrocutions. Since the majority of participants were landowners or managers the deaths noted are likely under reported as it is more typically rangers and guides who work in the field near fences. Therefore reports from these individuals may be more valuable and accurate, particularly in land catering to tourism. Fourteen taxa, including birds, mammals, and reptiles, were reported as killed on fences. However, the number of pangolins reported is concerning given their low density across the landscape, threatened status, and reported levels of population decline. Electric fences with multiple levels of wire, including ground, caused the majority of deaths. This result confirms the findings of previous studies and indicates that these fences require future mitigation. A negative association between PAR and mortalities suggests that longer fence stretches experience more deaths. Current modifications used by the participants do not appear to be working and have not reduced the concern levels of the users, thus new methods are needed to improve the situation, such as slightly raising tripwires to 300 mm. This study has highlighted the need for further research into pangolin fence mortalities and mitigation methods.

Chapter 6 - General Discussion

6.1. Introduction

Pangolins are collectively the world's most trafficked mammals (Challender et al., 2014b; Gaubert et al., 2020) yet the amount of research into their ecology is well below what is needed to develop appropriate conservation actions (Challender et al., 2014b). All eight pangolin species have undergone predicted declines in population, solely due to human activities (Pietersen et al., 2014a; Heinrich et al., 2016). Pholidota are an elusive and little understood taxonomic group that face extinction if evidence-based conservation interventions are not enacted. Information is lacking regarding their general ecology, habitat use, and distribution (Heighton and Gaubert, 2021), thus scientists and conservationists need this information to make effective action plans. This is particularly true for Temminck's pangolin and the three other African species, as they have been the focus of little research to date in comparison to the four Asian species (Heighton and Gaubert, 2021). An improved understanding of pangolin ecology is required in order to fully understand, evaluate and mitigate these threats. Conservation resources are often limited thus it is vital to integrate evidence-based findings into conservation planning. Specifically, my thesis investigated the environmental and anthropogenic factors that influence pangolin habitat use and distribution, and evaluated how these relate to known threats to address these knowledge gaps. This research focused on fences as a threat that is well-known but understudied. This chapter will summarise the findings of each research chapter and the overall thesis. The conservation implications and limitations will be discussed.

As discussed throughout this thesis, the majority of research into Temminck's pangolins have been geographically limited to southern Africa, primarily South Africa (Pietersen et al., 2020; Pietersen and Challender, 2020; Heighton and Gaubert, 2021) with a resultant literature gap in all other regions that this species inhabits, including East Africa. Most existing research has focused on the illegal wildlife trade, hunting for bushmeat consumption, or the traditional uses of pangolin products. Temminck's pangolin appear to behave differently in terms of dietary requirements, mating behaviour, and home ranging, depending on habitat and environment, in different parts of their extensive range (Pietersen et al., 2020), thus research in regions outside of southern Africa, including East African habitats is vital to understand this variation. Distribution and habitat suitability models have only been generated for South Africa (Pietersen et al., 2021), thus there is not much information on what influences their distribution at different scales in terms of habitat use within home ranges (4th order selection). Current research demonstrates that hunting for spiritual and medicine uses, and the illegal wildlife trade, are the most prevalent threat to Temminck's pangolins, however other threats such as fence mortalities have been implicated in numerous deaths in southern Africa (Beck, 2009; Challender et al., 2014b; Pietersen et al., 2014a). There has been little investigation into local threats to pangolins within Kenya, as it is primarily thought to be a transit country for the illegal wildlife trade (Heinrich et al., 2016; Challender et al., 2020) and the proportion of trade originating in Kenya is unknown. Additionally, threats of local use within East Africa are known in bordering countries, thus it is probable that they also occur in Kenya (Kingdon, 1974; Soewu et al., 2020). Overall, there is vital need to further investigate pangolin ecology and how this is impacted by threats. My thesis demonstrates that by considering all known anthropogenic threats to pangolins alongside their ecological habitat preferences it is possible to establish where geographically to target conservation efforts.

6.2. Summary of findings

The key results from this thesis indicate that at the landscape scale, pangolin distribution in Kenya is primarily influenced by annual rainfall, with pangolins more likely to be present in areas with moderate levels of rainfall, eight soil types, and moderate to high topographic levels. The former two variables influence insect prey distribution (Andersen et al., 2015; Pietersen et al., 2020; Panaino et al., 2022) which explains why pangolins may be sensitive to them. At the home range scale, within MMNR, pangolins are generalists when it comes to burrow use however, they do exhibit predator avoidance by apparently choosing small burrow entrances. Despite their generalist distribution and burrow use, they often utilise burrows within termite mounds, further indicating that prey presence is likely an important factor for their distribution and habitat use. In the primary study site in Narok County, roads were found to be a likely threat to pangolins, yet across all of Kenya, poaching was indicated as the largest potential threat. Fences are not a major threat within Kenya, as their use is limited and often non-electric, in comparison to South Africa, where this threat is much larger and impacts numerous species. In Kenya, threat mitigation should focus on poaching levels whereas in

South Africa increased focus should be on electric fence mortalities. When considering threat assessment, it is essential to understand pangolin habitat use, including the findings from Chapters 3 and 4, to evaluate where interventions should be prioritised. This combination of ecological knowledge and threat evaluation will ensure that conservation practices are well informed by allowing the development of evidence-based approaches.

6.3. Habitat use and environmental requirements

Overall, my study (Chapter 3) found that pangolins were burrow generalists and are not influenced by burrow characteristics such as soil type, grain size, or entrance aspect. Burrows are generated by aardvarks thus pangolins must select a subset of what is available to them which means they have adapted to use a variety of burrow types. However, the distribution of both aardvark and pangolin burrows was not random in the environment thus a level of selection must have occurred for both species. Aardvarks likely choose burrow locations based on environmental factors that influence their distribution such as prey availability (Whittington-Jones et al., 2011), and pangolins subsequently choose from the available burrows. The one characteristic that did affect pangolin burrow use was entrance size; pangolins avoided large burrow entrances. This behaviour likely reduces predation as the burrow size will restrict entry of large carnivores, which in-turn increases pangolin survival and fitness. Thermoregulation may also influence pangolin burrow use, however the results from my study support that the primary influencing factor is entrance size for predator avoidance. Burrow use may also be impacted by social factors, as pangolins are known to be solitary animals with home range overlap varying depending on region and season (Pietersen et al., 2020; Prediger, 2020). The primary limitation with the burrow study was that it was not possible to monitor or collect characteristic data for all 281 burrows within the study site, thus some burrows may have been utilised but were not recorded. This means it is possible that certain burrow characteristics which are important to pangolin choice may have been undetected or under-detected. Further work should therefore deploy a comprehensive monitoring system, with numerous camera traps deployed systematically in a grid formation, to ensure all burrows uses are simultaneously recorded. Additionally, it would be useful to evaluate burrow climate variables, including temperature and humidity. Despite these limitations, this is the first study in East Africa to evaluate pangolin burrow use, and one of the first to do so for Temminck’s pangolin.

Wider landscape factors were found to influence pangolin distribution and will undoubtedly also affect small-scale distribution if their variation is high within home ranges. Within a home range, factors like topography and proximity to resources, or threats, may impact pangolin habitat use. Thus Chapter 4 investigated the landscape-level environmental variables that are most important for pangolin distribution by using citizen science reports. As mentioned throughout this thesis, it is likely that prey availability is the most important driver of selection as pangolins are habitat generalists (Pietersen et al., 2016b; Pietersen et al., 2020). The key findings were that rainfall and soil type were the most important factors indicated during habitat suitability modelling; however, pangolins are water independent (Pietersen et al., 2020), obtaining their hydration during feeding, thus rainfall is vital to prey selection. Pangolins avoided very low (sea level) or very high topographic elevations, although this variable contributed weakly to the model. Soil type influences which prey species are available and ease of prey access, based on depth, hardness of soil, and water retention (Rawls and Brakensiek, 1982; Swart, et al., 1999; Andersen, 2015). Temminck's pangolin are not powerful diggers and thus prefer prey close to surface level, which may also be why they often select burrows readily within termite mounds (Swart et al., 1999). These results differ slightly from Pietersen et al (2021) who conducted a HSM for Temminck's pangolin in South Africa. Vegetation type and soil type were the most important factors for pangolin distribution, while annual rainfall contributed the least to the model. However, Pietersen (2021) included vegetation type whereas my study included NDVI, so whilst these variables are similar the results are not directly comparable. The variation between these results and the study may also come down to geographic region, as pangolins are known to exhibit different ecological behaviours based on region (Pietersen et al., 2020). Studies should be conducted to capture the variations in these requirements across their range.

The results from this study also differed from habitat suitability models for other pangolin species, confirming that each has their own environmental requirements and ecological niche separation (Sharma et al., 2020b; Suwal et al., 2020; Waseem et al., 2020; Mahmood et al., 2021; Mouafo et al., 2023). For instance, as stated in Chapter 4, giant pangolins, the closest relative to Temminck's, were primarily influenced by NDVI and distance to human settlements, with elevation and soil influencing predictions to a lesser extent. Temminck's pangolins are thought to avoid cultivated areas (Coulson, 1989; Pietersen et al., 2014a), whereas Chinese and Indian pangolins seem to prefer these areas due to prey availability (Sharma et al., 2020a; Waseem et al., 2020; Mahmood et al., 2021). Additionally, temperature was an important predictor for Chinese and Indian pangolins, while my study did not find it to be an influential variable for Temminck's pangolin in Kenya. This research found that 25% of Kenya's land is at least somewhat suitable for pangolins, and this is likely decreasing due to habitat loss from increased agricultural farming, logging practices, and human populations (Mizutani et al, 2005; Kirui, 2022). This loss is predicted to have caused a 68% decline in wildlife in less than 40 years due to human expansion (Ogutu, 2018), and it is currently ongoing. If conservation efforts are not effective it may lead to the extirpation of pangolins and other wildlife species.

6.4. Threat and risk prediction

It is vital to relate predicted distribution and the associated characteristics to the level of threat that pangolins may experience within their range. Utilising ecological data to evaluate threats means more effective conservation plans can be developed. Threats within Kenya have not been fully quantified, including the level of poaching for both local and international use and trade. In South Africa, mortalities on both roads and fences are thought to likely kill a large proportion of the population (Pietersen et al., 2014a) but this had not previously been considered in Kenya or elsewhere within the species' range. Within the Narok County site, the current study found that roads were indicated as the biggest threat and fences were indicated as a low threat. In terms of MMNR, there are not many residents, nor are there many fence lines, so the roads are the most prevalent infrastructure. It is possible that some pangolins may succumb to road mortalities in the Narok County site, but further study is needed to quantify this and examine how this differs between within MMNR boundaries, and within the community conservancies where there are more roads present. In terms of Kenya overall, human proximity was found to be the largest potential threat, which may indicate a high possibility of poaching (Pietersen et al., 2016a). This aligns with predictions of Kenya's level of involvement in the illegal wildlife trade and interceptions of poached pangolins have increased here in recent years (Africanews, 2023). Urgent conservation initiatives are needed to reduce this threat as pangolin range is reported to have already decreased throughout Kenya (C. Okell, personal communication, 2022). Based on the results from this thesis, the areas of primary focus for conservation efforts should include the communities immediately surrounding MMNR, southern Narok, and West Pokot. The main limitations of this study were the inability to collect absence data, nor consistently collect immediate sighting reports which may result in inaccuracies of locations. Additionally, this study could not take individual pangolins into account so it is possible that the same pangolin was witnessed several times, rather than a different pangolin each time. This study demonstrated that citizen science is a valuable tool for understanding species distribution and threats, especially for elusive species like pangolins. It was the first study in East Africa to do so and is one of the first pangolin studies in this region.

Fences were not considered a major threat to pangolins in Kenya, which may be due to the limited extent of electric fencing within the country. Conversely, the IUCN SSC Pangolin Specialist Group has stated that fences are a major threat to pangolins in South Africa (Challender et al., 2014b; Pietersen et al., 2014a) and this is also applicable to other areas where fences are heavily utilised. Chapter 5 of this thesis evaluated this threat with a focus on South Africa. This threat is primarily attributed to electric fences, which cause mortalities through electrocutions (Beck, 2009; Pietersen et al., 2014a). My study found that electric fences with ground-level wires are the most deadly for pangolins and numerous other species, with occasional deaths caused by those with higher electric wires, and non-electric fences causing deaths through entanglement. A total of 14 taxa were recorded as killed on fences which indicates a high level of mortalities overall as many of these groups included multiple species (e.g., 'birds' or 'lizards'). The number of pangolins found to be killed on fences in this study indicates a conservation issue as opposed to simply a welfare concern, as the study was relatively small scale. The small number of participants and short timeframe of this study found 16 pangolins killed, which likely extrapolates to much higher number across pangolin range. However, the relative importance of these mortalities in relation to the wider population is unknown as there is an absence of causal link between fence electrocution and population decline. There is an estimated 2 – 13% of the population killed annually (Pietersen et al., 2014a), but how these deaths impact overall population persistence has not been studied.

Overall, fences with low-level electric wires pose the greatest threat to pangolins, and other species, and the development of mitigation and modifications of fences are necessary to reduce these mortalities. My study further confirmed Beck (2009) and Pietersen et al (2014a)'s statements that low electric wires cause the most pangolin electrocutions by evaluating reports from a range of individuals across South Africa. This methodology showed that citizen science can be an invaluable tool in this context and its use should be expanded. For example, online or mobile phone monitoring systems may be useful to achieve this.

My study did not take timeframe into account and participants could report as far back as memory allowed thus it is difficult to predict how frequently mortalities actually occur and over what time frame. The main limitation of this study was the requirement to conduct it entirely online as COVID-19 restricted travel and in-person data collection in the country. This restricted the participant numbers to those with internet access and to those who were contactable online, which primarily included those in South Africa. Participants were predominately from Limpopo, which limits the ability to infer findings for other provinces. Despite these limitations, the findings from this study contribute valuable knowledge into fences as a threat to pangolins because it is the first to comparatively assess which fence types cause mortalities. It was also the first to collect electrocution reports from a variety of members of the public, across pangolin range in South Africa.

Pangolins in Kenya are likely to be found in regions with moderate rainfall (500 – 1400 mm annually), soil types of haplic acrisols, humic cambisols, and eutric regosols, and with a large availability of burrows to choose from and change between. Conservation planning should focus on areas with these characteristics. It will additionally be necessary to quantify the true level of mortalities caused by roads and human proximity. Although these were indicated as the potential largest threats to pangolins this study did not include mortality data, which is necessary for fully understanding these threats. Fences may pose a minor threat in Kenya due to the relatively low amount of electric fencing infrastructure, however in South Africa, mitigation and fence modifications are needed to prevent electrocutions.

6.5. Conservation Implications

Given the documented declines across pangolin range and their IUCN status, concerted and increased conservation actions are needed to reverse this. A multifaceted approach that deals with multiple anthropogenic threats would be ideal. The distribution of pangolins within Kenya predicted from this study should be utilised to plan conservation action for pangolins. This can include determining which areas to focus on for habitat protection to ensure enough suitable habitat exists for pangolins. The areas with habitats of the highest suitability and the presence of suitable burrows should be prioritised for practical conservation measures, which should include engagement with the local communities. My research indicated that poaching caused by close proximity to humans may be a large threat in Kenya, thus it will be necessary to focus efforts on reducing this, and if local communities are appreciative of and enthused about wildlife then this may reduce hunting pressure on pangolins. However further research is needed to establish the level of this threat in Kenya. It may be beneficial to increase land use protections and anti-poaching efforts in the highly suitable regions indicated in this study, especially in the areas where human proximity was indicated as the primary potential threat. Protected areas are likely important for pangolin conservation as they are known to avoid agricultural land (Pietersen et al., 2020).

It will be necessary to involve local communities in the target areas and ensure they know that wildlife conservation benefits their communities and the economy, as well as the target species. This approach may not be successful for all communities, but it has been effective when establishing the community conservancies around MMNR. Pangolin poaching occurs for two purposes: international trade, and local use (which may include: bushmeat, spiritual uses and medicinal uses), and both must be targeted differently (Pietersen et al., 2014a; Pietersen et al., 2020). The international wildlife trade is fuelled by international demand and the willingness of buyers to pay high prices for pangolin products (Burgess et al., 2020). The best methods to combat this may be through stakeholder engagement, firstly of buyers to reduce demand, and secondly of the local communities in pangolin habitat. This trade is rooted in cultural beliefs and social research is necessary to establish what form of engagement would be most effective (Burgess et al., 2020). Relaying facts to the public may be ineffective, however, a hands-on approach is more likely to work. For example, it may be possible to suggest alternative traditional medicine treatments that do not involve pangolin scale use. The involvement of celebrities or locally recognised people to promote the cause would be more beneficial than scientists ('t Sas-Rolfes and Challender, 2020) as actors may be seen as relatable.

Local use is also ingrained in cultural beliefs that can be difficult to change (Burgess, et al., 2020), however if communities can see pangolins as more valuable alive than dead, such as by bringing in tourism, then this threat may be reduced. A study of eco-tourism in southern Africa found that tourists are interested in seeing pangolins and willing to spend money to see them (Di Minin and Hausmann, 2020), however, at the moment there are few tourism businesses or projects that focus on pangolins. Only one is known in Kenya, Sala’s Camp, which is a tourist lodge in MMNR that advertises frequent pangolin sightings (Styne, 2015). The primary challenge with increasing tourism is developing methods that benefit the local community. Sala’s Camp is not owned by local communities so it may only indirectly benefit them by bring tourists to their area. Additionally, as pangolins are elusive by nature the chance of tourists, seeing them in the wild is low, which may hinder developing ecotourism practices.

Within local communities, “participatory action” is a valuable approach because it entails having discussions with the communities to engage with them. An example of this is the ‘Pangolin Ambassador’ initiative used by The Pangolin Project alongside data collection for Chapters 3 and 4 of this study. PP sought local volunteers to interact with fellow community members in relation to pangolin conservation, which included delivering key conservation messages. The aim of this was to empower local communities to become pangolin stewards through conservation education and training (The Pangolin Project, 2023). Encouraging members of the community to be involved is likely much more effective than receiving views from outsiders (Skinner et al., 2020). Community members can hold open discussions and develop conservation plans to reduce human-wildlife conflict, and increase local appreciation of wildlife, including pangolins. For instance, this has been done with the Namibian Lion Trust and Long Shields in Zimbabwe, who have employed community members to reduce human-wildlife conflict by working with fellow citizens to understand and respect lions, while ensuring livestock are safe from predation (Namibian Lion Trust, 2023; WildCRU, 2023). In Nepal, the Western Terai Fishing Cat Project has worked to engage local communities by encouraging them to become involved with fishing cat conservation, and thereby reduce human-wildlife conflict (Fishing Cat Conservation Alliance, 2023). This form of action would likely be effective in reducing the local hunting of pangolins. Overall, such changes are not straightforward and will require much thought and research into the socio-ecological interactions that influence both local and international poaching. The results from this thesis provide a starting point for where to select communities for this action, as they indicate baseline criteria of habitat requirements that are ideal for pangolins in Kenya.

Results of investigation into smaller-scale habitat use in Narok County informed by the HSM can also contribute to local conservation planning, such as improving habitat or implementing mitigation to prevent road and fence deaths. Pangolins have the ability to be widespread if the overall habitat conditions are suitable and they likely are found where aardvarks occur and where suitable prey is available. Land managers can work to conserve aardvark burrows or even manually create burrows to entice pangolins to utilise a wider area, and potentially increase their range. However, further knowledge of pangolin movement, such as tracking data, would be necessary to make informed conservation prescriptions. It would be especially useful to determine how they use human-influenced landscapes, such as rural and urban. Using community engagement to increase the appreciation of aardvarks as ecosystem engineers via burrow creation will subsequently mean more burrows remain intact for pangolin use. They are a low-density species and many people may not be away of their importance as ecosystem engineers. Aardvarks are listed as Least Concern on the IUCN Red List (Taylor and Lehmann, 2015), however as their burrows are vital to pangolins in Kenya it would thus be valuable to increase their conservation efforts. In terms of limiting road mortalities, although roads were indicated as the largest threat within Narok County, further research is needed to establish the true level of this threat. Many roads exist in this region but there has been no investigation into pangolin road mortalities. It is essential to establish the true level of threat before considering mitigation options. If found to cause many mortalities annually, the modification of how roads are constructed may need to be considered. Building rock barriers or trenches to separate wildlife from the road may be a solution on a small scale (Romin and Bissonette, 1996; Glista, DeVault and DeWoody, 2009) but the cost versus effectiveness of such mitigation also needs to be considered carefully.

Within South Africa, it is evident that fence-related mortalities need to be reduced, for pangolins and many other species, such as tortoises. Many taxa succumb to electrocutions globally, whether on fences or power lines but the majority of studies to date have focused on bird species (Bevanger, 1994; Dwyer, Harness and Donohue, 2014; Pérez-García et al., 2017). Few studies have aimed to inform on the potential impact of fences on pangolins and this research should aid conservationists in understanding this threat. The use of fences is unlikely to ever be reduced due to their widespread use in urbanised and ranching environments, thus changes to the fencing protocol are needed to reduce these mortalities and injuries. It will be necessary to make landowners aware of this issue and the significance of it. Fence mitigation is currently being tested in South Africa but results have not yet been published (Pangolin.Africa, 2021). It may be possible to implement mitigation that reduces both fence and road mortalities together, however any methods suggested to landowners must be easy to implement and cost-effective otherwise they will discourage people from trying them, unless governmental or conservation organisations supplement the cost. Simple modifications may be the most straightforward and least costly, such as using rock barriers to block low-level wires or access to roads (Pietersen et al., 2014a), or by raising low-level wires up a few centimetres to prevent electrocutions. However, it would be further beneficial to change the fence requirements throughout South Africa, to ensure landowners must mitigate for fence mortalities from the outset, i.e., when installing a new fence. Additionally, there are currently provincial regulations that limit the fence designs that can be implemented (NCNCA, 2009; DEDECT, 2014; Bothma and du Toit, 2010). Disseminating scientific evidence to influence the change of this legislation in regards to fence wire height would be invaluable. Additionally, before erecting new fences, landowners should consider the need for this fence, along with overall fence mortalities and the implications they may have on wildlife populations.

6.6. Opportunities for Future Research

My study has expanded knowledge of behavioural ecology of Temminck's pangolin in Kenya, and has evaluated their little-studied threats. It has also identified several additional aspects that could be the foundations for further study. These are: 1) To further establish the relationship between aardvark presence and pangolin presence. A higher or lower density of aardvarks will undoubtedly impact the number of burrows available for pangolin use. Pangolins may become less generalist in their choice if more burrows are available and select burrows more specifically suited to their ecological niche, or if fewer burrows are available become more generalist. This may also mean the supporting capacity of the area changes based on burrow availability, with more burrows meaning more pangolins can be supported and vice versa. It is likely that pangolin presence relies on the presence of aardvarks and other burrowing species, and it may be possible to predict their distribution based on this. However, pangolin social structures and territory spacing may intrinsically influence distribution. 2) To conduct this study in other habitats, as the savannah and grassland habitats in MMNR offer little shelter in terms of vegetation, thus burrows are the primary shelter source for pangolins. A habitat with a less homogenous environment may mean that pangolins in other parts of their range may find other shelter resources, such as rock piles or caves (Pietersen et al., 2014b), especially if aardvarks are not present. Pangolins utilise several habitats, including desert, woodlands, thickets, and mopane forests (Heath and Coulson, 1997, Pietersen et al., 2020), thus it would be useful to conduct a similar study in these habitats and investigate how burrow use compares. If attempting to repeat this research, a recommended improvement would be to utilise camera traps on a larger scale to increase burrow monitoring abilities.

3) To tag multiple pangolins simultaneously to assess social interactions between individuals, which was beyond the scope of the current study. Social interactions are likely to influence their small-scale distribution. The interactions and home range overlaps of males and females seem to vary by region, and males are known to display antagonistic behaviours when new males enter their home range (Pietersen et al., 2020; Prediger et al., 2020). Young disperse from their mothers between 3 – 12 months and this may also impact home range establishment (Smithers, 1983; Swart, 2013; Pietersen et al., 2020; Prediger et al., 2020). Little is known about sex biases in dispersal or density-dependent effects. Due to the difficulty of locating pangolins to tag, an alternative approach to studying social interactions could potentially be genetics-based. Non-invasive genetic sampling can be used to collect and amplify DNA to identify pangolin species (IUCN SSC Pangolin Specialist Group, 2018). Breeding ecology and population dynamics of Chinese pangolins have been studied using DNA techniques, whereas eDNA of Sunda pangolins has been used to confirm the presence of Sunda pangolins in Borneo (Willcox et al., 2019). However, there is limited genetic reference material that exists to study populations currently, as much of the existing reference DNA has come from trafficked scales of unknown origin, and because eDNA (from hair, scat, and soil) is difficult to collect due to their lack of field signs (Willcox et al., 2019). Nonetheless, genetic analyses could be a valuable tool if proper reference databases can be developed.

4) To geographically extend habitat suitability and risk modelling. This should be done for each country or habitat that the species inhabits. Varying climates and environments mean pangolin habitat suitability likely differs between each region, as they are known to inhabit a wide range of habitats overall. What is suitable for pangolins in one region may not be suitable for individuals from another, which is demonstrated by their prey selectivity. These behavioural differences may

influence the primary risks that pangolins face in different regions. It would be useful to do this for each country across the species' range so that conservation interventions and legislation can be developed locally. It would also be invaluable to do this for each habitat that the species uses so that the variation in ecological behaviour between each can be compared, however this would likely involve transboundary research and logistically may be difficult. The variables used in this study were effective in estimating pangolin distribution, however additional variables, such as habitat type, may be important to add in regions where there is more habitat variation. If the data is available, it would also be useful to include prey presence or distribution, or aardvark burrow presence, so that pangolin resources can be evaluated.

Further, 5) it is necessary to evaluate the prey selection of pangolins across different habitats and regions to establish how this impacts their distribution. It would be useful to conduct a similar study to this habitat suitability research across more of their range and involve many more local communities to collect a detailed dataset of sightings. This could be conducted by using a remote reporting systems to capture real-time sightings. These results can also help conservationists in determining where they might find pangolins for future ecological studies.

6) It would be beneficial to then assess the anthropogenic risks in each region to determine which need conservation focus. As information on the extent of anthropogenic threats is lacking in Kenya, it will be necessary to comprehensively investigate this. There is very little data on the local and international trade of domestic pangolins and conservation efforts cannot be effectively planned without this. It is vital to establish if Kenya is only a transit country for pangolin products from other countries, or if local pangolins are being trafficked. The results from this will inform on the subsequent conservation strategies and determine if their focus should primarily be on reducing importation and transit from other countries, or on reducing local poaching, or a combination of both. Monitoring social media, such as Facebook groups, is becoming increasingly popular for tracking the illegal wildlife trade (Panter and White, 2020) and may be valuable for assessing the extent of trafficking in Kenya. To investigate local use, community engagement and participatory action may be a useful approach, whereas evaluating the international trade may be more difficult if unable to prove where a pangolin or pangolin products have originated from. There have been recent strides in using genetic analyses to identify where pangolin products retrieved from the illegal

wildlife trade have come from, however there a comprehensive reference database for geographic origin is lacking. This means even if DNA is extracted from a sample, it may not yet be possible to identify which population or region it came from (Willcox et al., 2019; Kotze et al., 2020). Further work is needed to improve this database to enable the use of genetic analyses. It would be helpful for researchers to take samples from pangolin individuals of known populations during field work, such as telemetry tracking. This would greatly enhance the genetic reference library for pangolins (Willcox et al., 2019; Kotze et al., 2020).

Techniques such as stable isotope analyses may also be useful if a reference database for pangolins in Kenya can be generated. This approach measures the variation in the ratio of elemental stable isotopes, such as carbon, hydrogen and oxygen (Kotze et al., 2020). These ratios are a unique elemental profile for a geographic region. These isotopic profiles are found in the underlying geology and vegetation of an area, as well as in biological tissue (Kotze et al., 2020). Thus, this technique could compare the isotopic profiles of pangolin scales to those of different geographic regions, meaning origin could be determined (Vogel, Eglington and Auret, 1990; Kotze et al., 2020). This may have applications for returning living pangolins that are retrieved from the trade back to their geographic origin. However, this has similar challenges to genetic analyses. Isotopic databases for each region first need to be established, which is costly in terms of both money and effort. Both genetic and stable isotope analyses have the potential to identify where trafficked pangolins have originated from but currently both techniques require comprehensive reference databases to be established.

It is well-established that fences cause pangolin mortalities and that there is a need to reduce these. Thus, 7) future research should focus on developing and testing mitigation strategies to improve this situation. The challenge will be developing cost-effective solutions for this issue that are easy for landowners to use and can be widely implemented. An in-depth study of South Africa that includes as many landowners as possible within pangolin range would provide a deeper understanding of this threat within the country. A reporting system for these mortalities that also records fence type would be beneficial in achieving this, as the overall extent of each fence type throughout Africa is not known. This study built a foundation of understanding how these deaths occur in South Africa and this can be expanded to other regions.

6.7. Final statement

The conservation of Temminck's pangolins requires a multifaceted approach that addresses the variety of threats that the species faces. Methodology used must be evidence-based and informed by a species' ecology, behaviour and distribution. By decreasing the demand for local and international pangolin products, utilising effective mitigation measures for fence and road deaths, and by conducting further research, we can reduce the decline of this species and prevent their extinction.

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Appendix 1 – Chapters 3 and 4: Memorandum of Understanding with PP

University of Brighton

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Memorandum of Understanding (MoU)

Between:

1. The University of Brighton [UoB] (Mithras House, Lewes Road, Brighton BN2 4AT UK)

   and

2. The Pangolin Project (PO Box 15156, Langata 00509, Kenya) [PP]

   This agreement is entered into for the purposes of collaborative research aimed at informing pangolin conservation efforts, whereby:

   PP agrees to share specified datasets and their metadata (“the data”) on pangolin occurrence and ranging behaviour with UoB in the context of doctoral studies undertaken by PhD student Lea Stracquadanio. The data remain the intellectual property of PP.

   UoB agrees not to share the data with additional parties without permission from PP, nor to publish the dataset without the consent of PP. UoB agrees to conduct statistical analysis on the data in order to answer relevant scientific questions, and to include appropriate named PP individuals as co-authors on any subsequent outputs.

   The agreement will terminate on 01/12/2023 after which time revision may be made and/or the agreement renewed.

   Signed,

   UoB representative
   Dr Kirsty Smallbone

   Acknowledgement of terms by PhD student

   7/12/2021 Leandra Stracquadanio

   PP representative
   Claire Okell

Appendix 2 – Chapter 3: Methods diagram, raw data and exploratory graphs

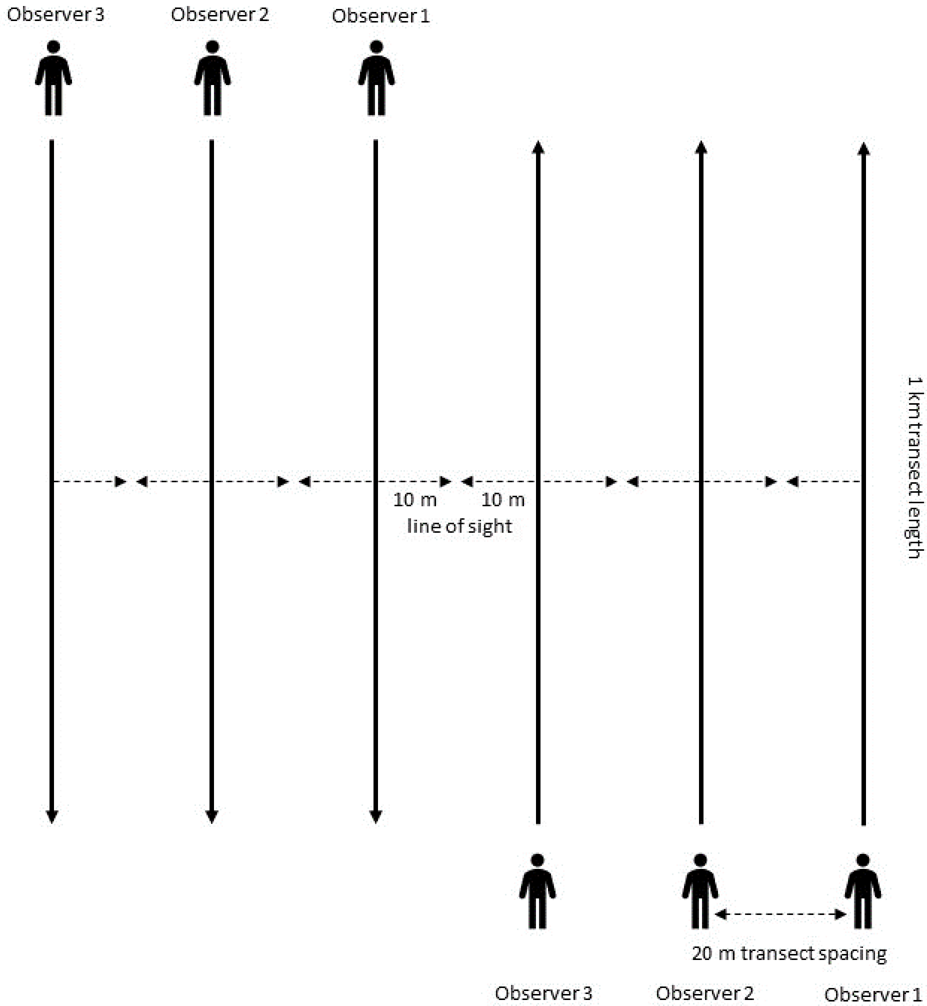


Figure A1 Diagram showing the transect method used to collect burrow records and characteristics. 1 km transects were utilised throughout the Sala's Camp study site. These were spaced 20 m apart with an observer line of sight of 10 m on either side of each transect. Observers walked parallel transects at the same time. They alternated between walking south to north and north to south transects. Three of the six observers are shown.

Table A1 Frequencies of the predictor variables of burrow characteristics, including aspect, termite mound presence, soil type, and soil grain size.

Aspect (N = 281)	**Frequency**	**Percentage**	**Pangolins presence frequency**	**Percentage**
Southwest	53	18.86	8	16
West	50	17.79	5	10
South	48	17.08	12	24
East	34	12.10	8	16
Southeast	31	11.03	4	8
Northwest	25	8.9	4	8
Northeast	23	8.19	6	12
North	17	6.05	3	6
Termite mound (N = 281)				
Yes	171	61.9	32	64
No	107	38.1	18	36
Soil Type (N = 281)				
Eutric planosols	225	85.6%	24	75%
Luvic phaeozems	38	14.4%	8	25%
Soil grain size (N = 263)				
< 1mm	236	89.73	27	84.4
All 2-5mm	15	5.7	2	6.2
Some >2mm	11	4.18	3	9.4
5mm	1	0.38	0	0

Table A2 The range and means of the height and width of burrow entrances. Cross section calculated as a metric of height and width. N = 281.

Size	**Total Range (cm)**	**Total Mean (cm)**	**Pangolin range (cm)**	**Pangolin mean (cm)**
Height	15 – 76	38.2	17 – 60	35.8
Width	16 – 78	42.4	16 – 67	42
Cross section (H x W)	272 – 4680	1690	272 – 3780	1550

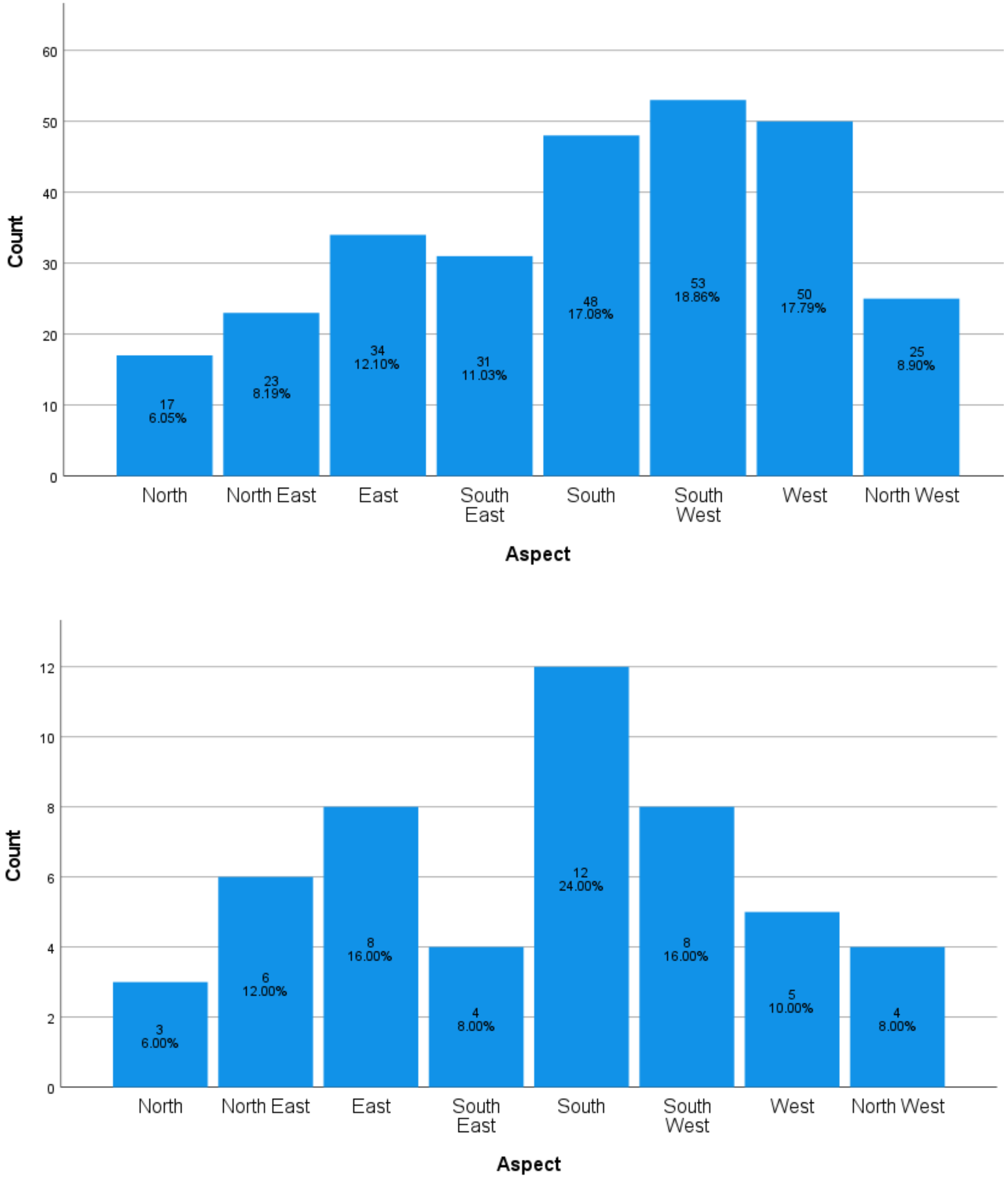


Figure A2 Bar charts displaying the frequency and percentage each aspect category. The top chart is aardvark burrows and bottom is pangolin-used burrows. N = 281

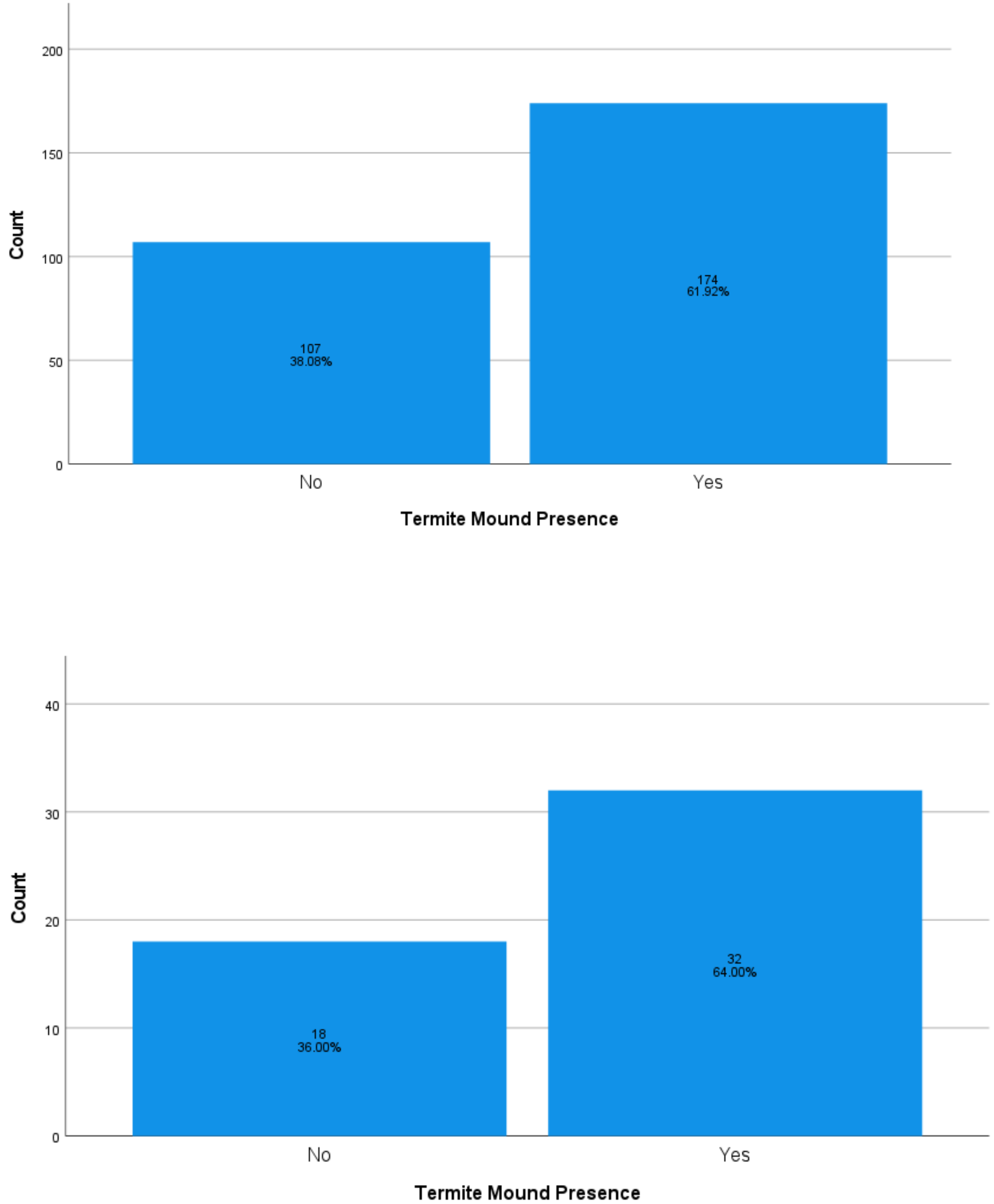


Figure A3 Bar charts displaying the frequency and percentage of termite mound presence and absence. The top chart is aardvark burrows and bottom is pangolin-used burrows. N = 281

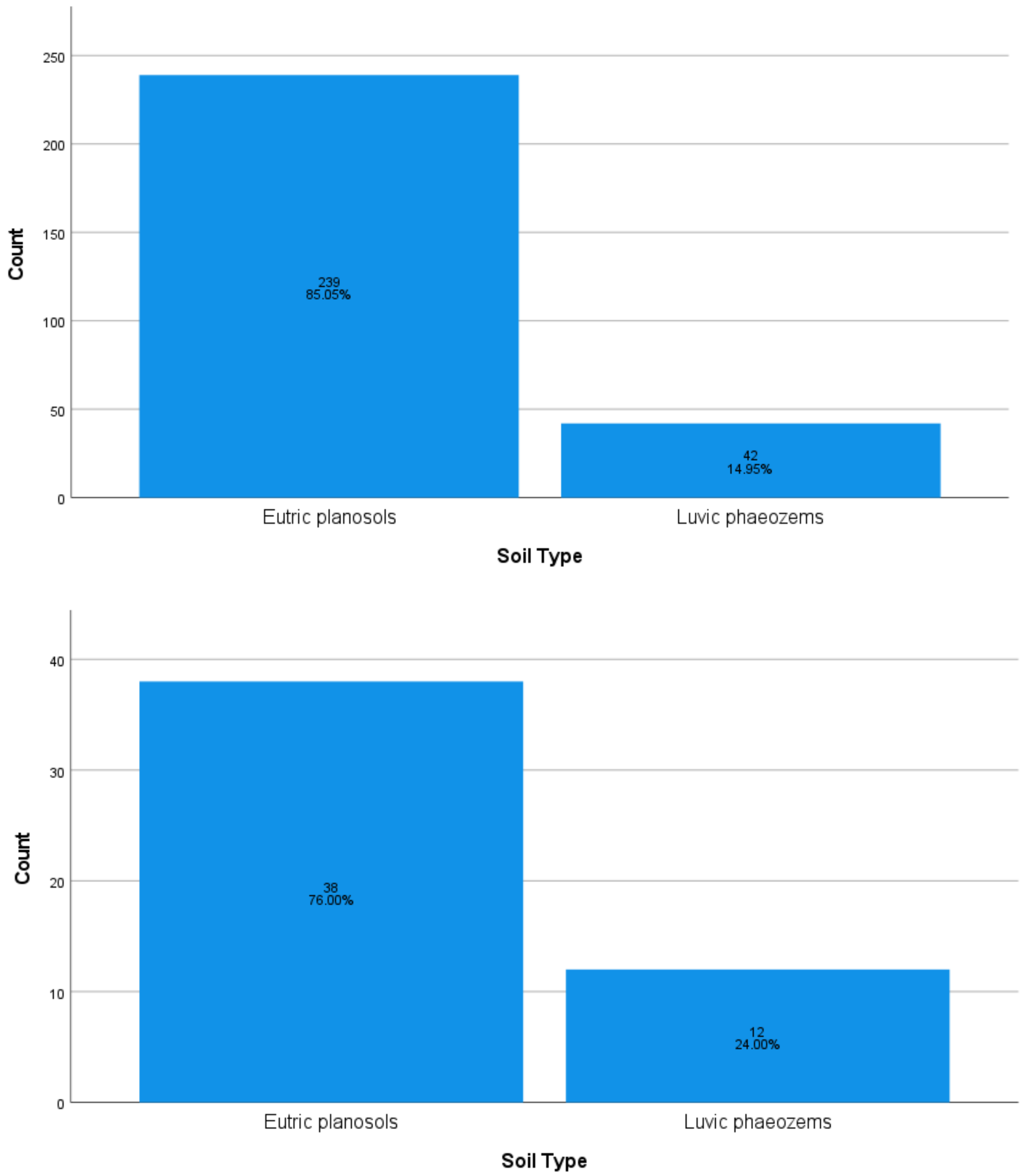


Figure A4 Bar charts displaying the frequency and percentage of each soil type. The top chart is aardvark burrows and bottom is pangolin-used burrows. N = 281

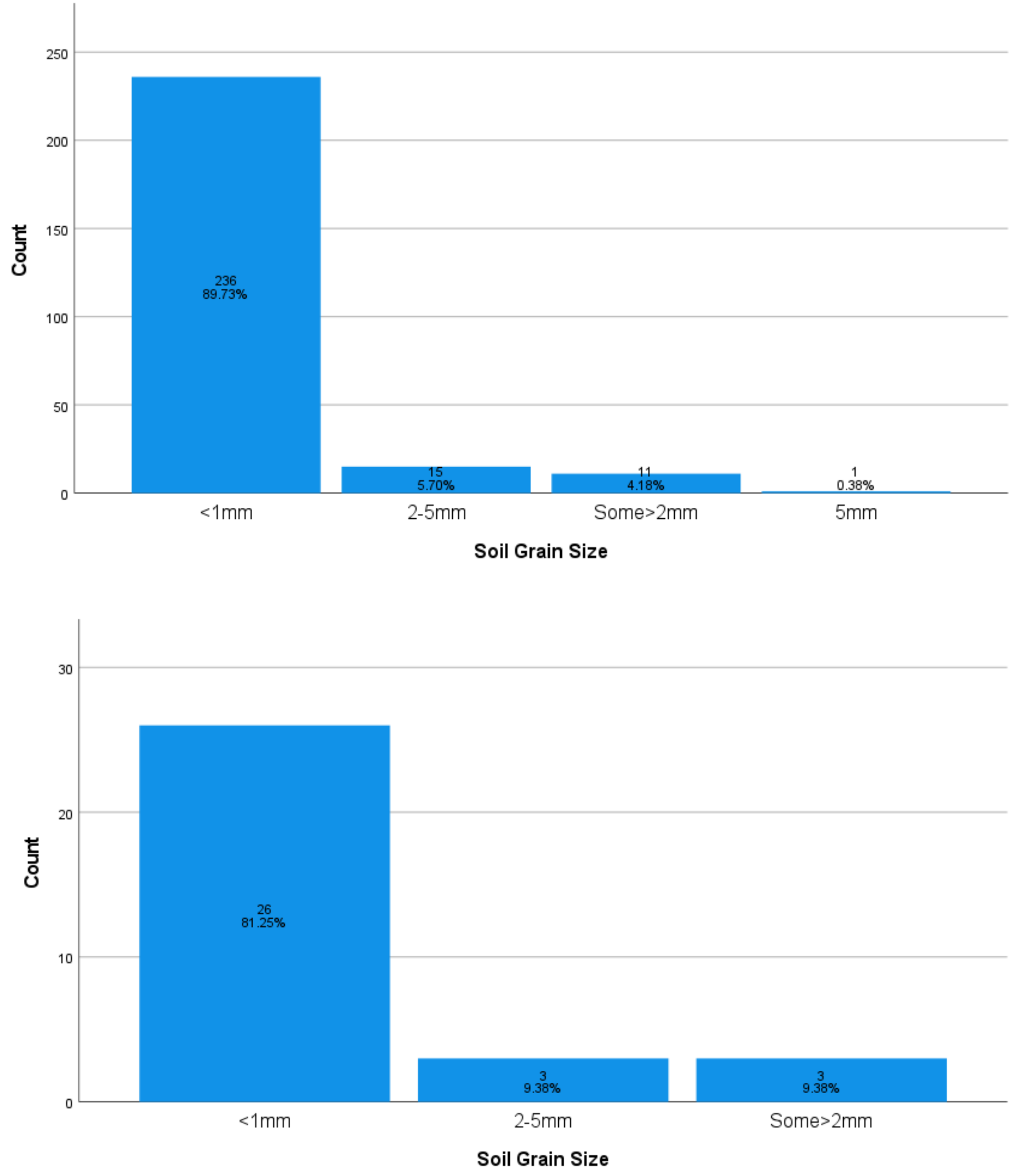
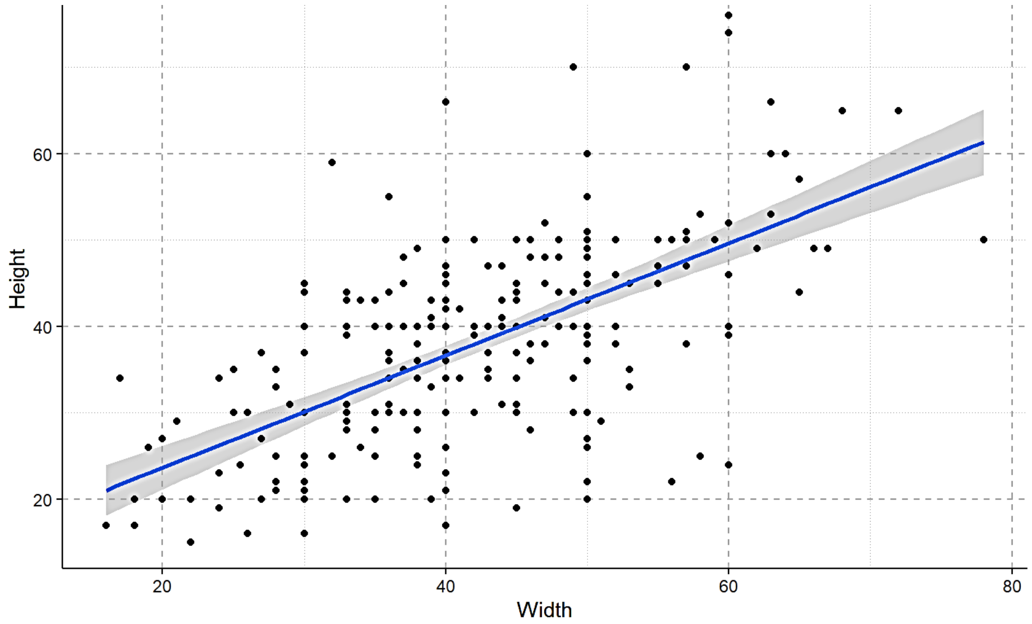
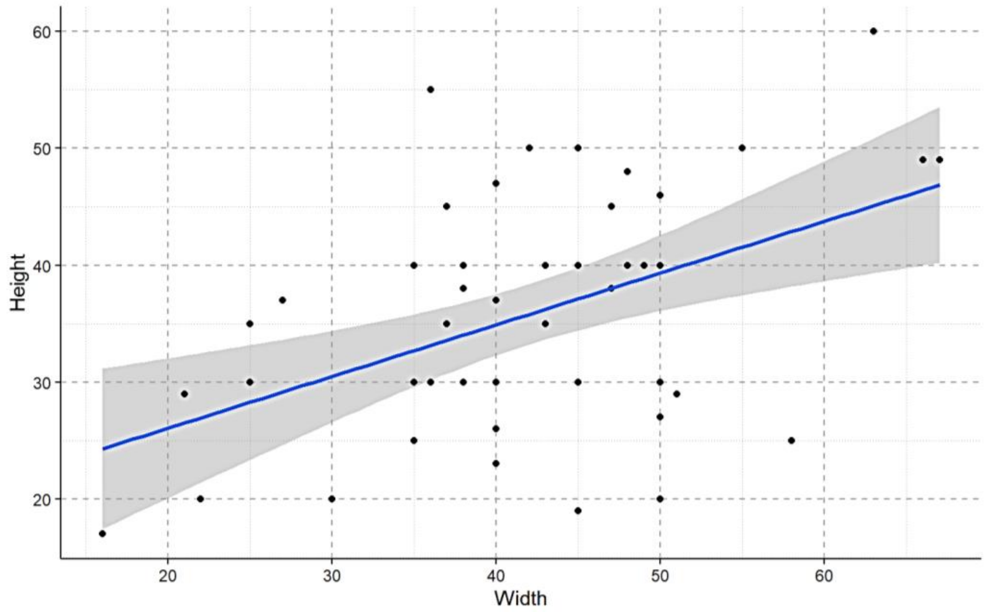


Figure A5 Bar charts displaying the frequency and percentage of each soil grain size. The top chart is aardvark burrows and bottom is pangolin-used burrows. N = 263.





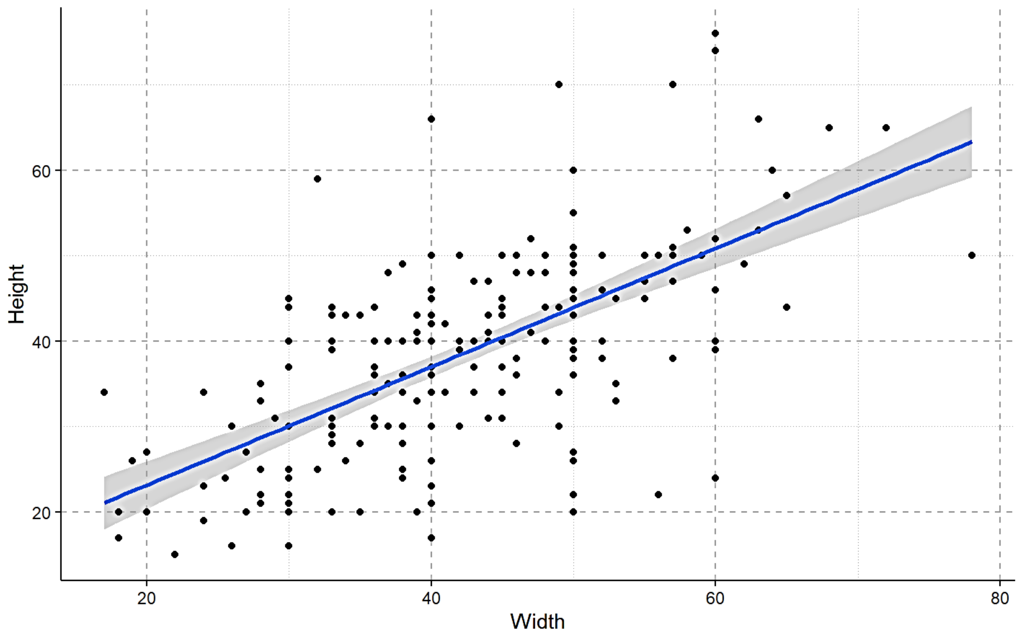


Figure A6 Bivariate scatter plot of the height and width of each burrow with best fit line. Top left is the full dataset, top right is pangolin presence burrows, and bottom left is pangolin absence burrows. N = 281

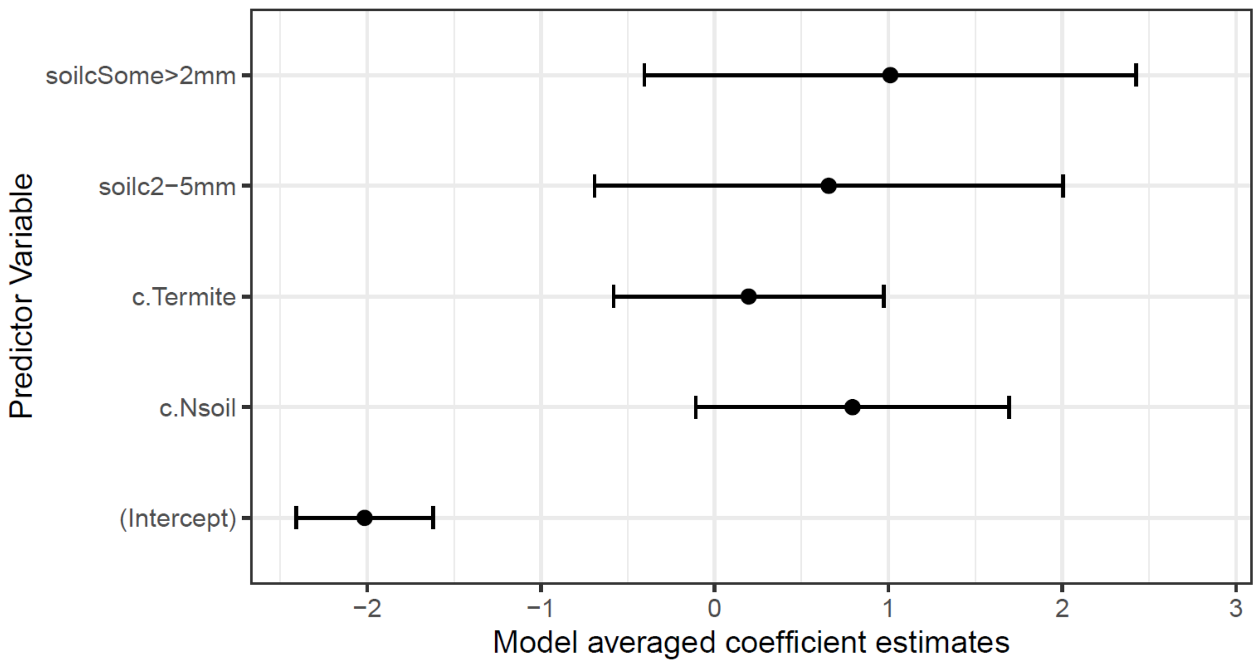


Figure A7 Confidence intervals of each burrow characteristic for the average top models, identified during model averaging of the five variable GLM. Points represent the standardised coefficient estimate from the averaged top models. Soilc refers to sail grain size, Nsoil refers to luvic phaeozem soil types.

Table A3 Generalized variance inflation factor (VIF) scores calculated to test collinearity between the burrow predictor variables. Scores of >3 are considered collinear. Full GLM model.

Collinearity Statistics		
	VIF	**Tolerance**
CSA	1.02	0.981
Aspect	1.01	0.986
Termite	1.04	0.959
Grain size	1.02	0.979
Soil type	1.06	0.943

Cluster 1 descriptive tables and graphs

Table A4 Breakdown of predictor burrow characteristic variable frequencies and percentages in Cluster 1.

Aspect	**Frequency**	**Percentage**
Southwest	9	16.89
West	7	13.21
South	12	22.64
East	6	11.32
Southeast	8	15.09
Northwest	4	7.55
Northeast	5	9.43
North	2	3.77
Termite mound		
Yes	33	62.26
No	20	37.74
Soil Type		
Eutric planosols	44	84.6
Luvic phaeozems	8	13.6
Soil grain size		
< 1mm	45	84.91
All 2 – 5mm	4	7.55
Some > 2mm	4	7.55

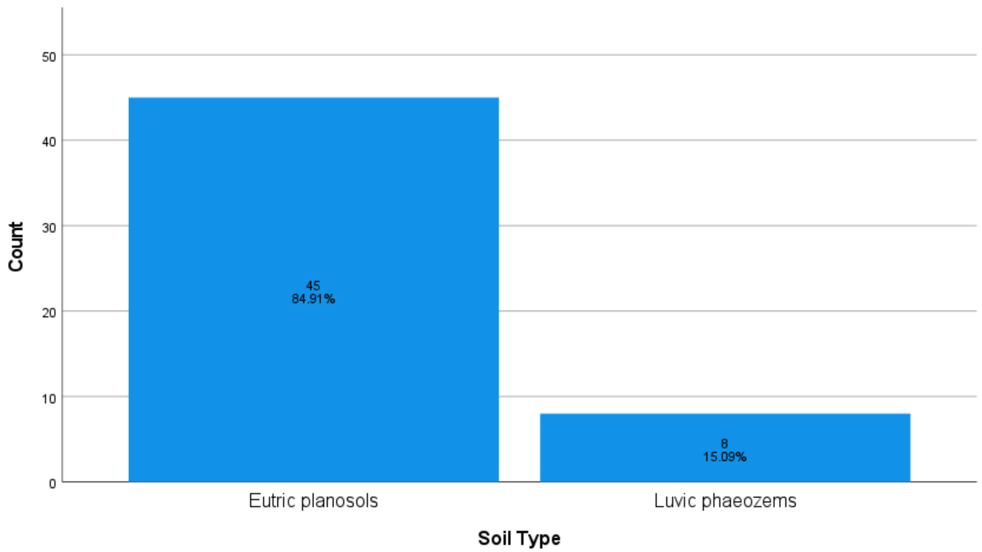


Figure A8 Frequency of each soil type present within Cluster 1.

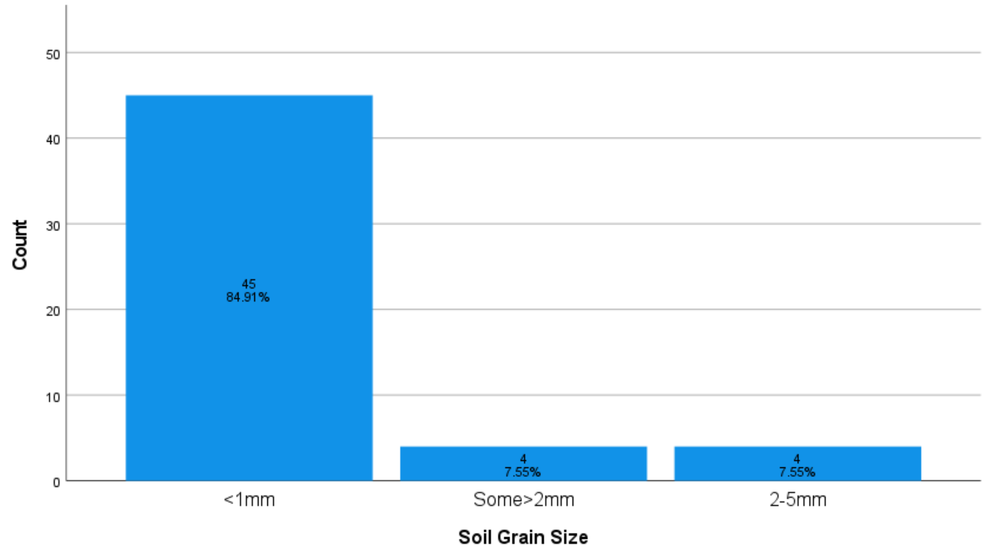


Figure A9 Frequency of each soil size category present within Cluster 1.

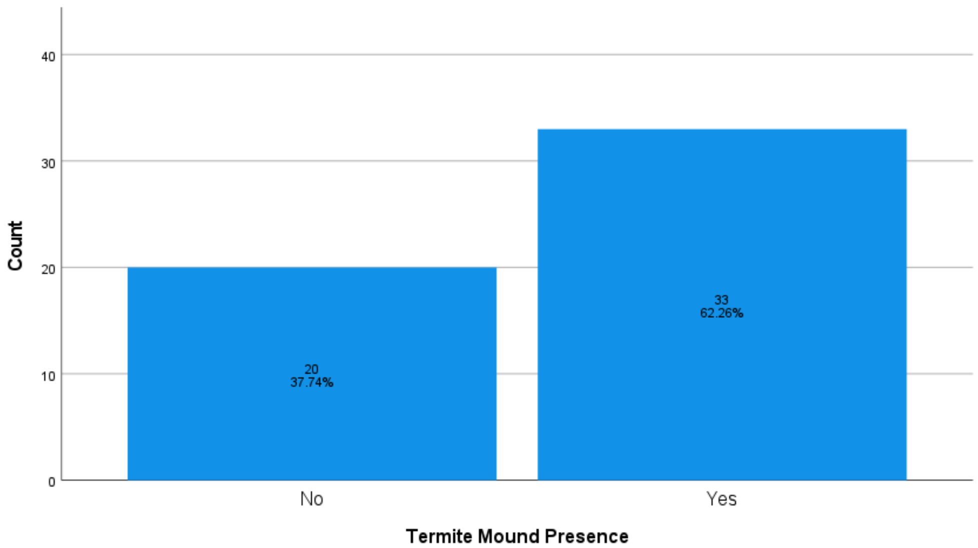


Figure A10 Frequency of termite mound presence within Cluster 1.

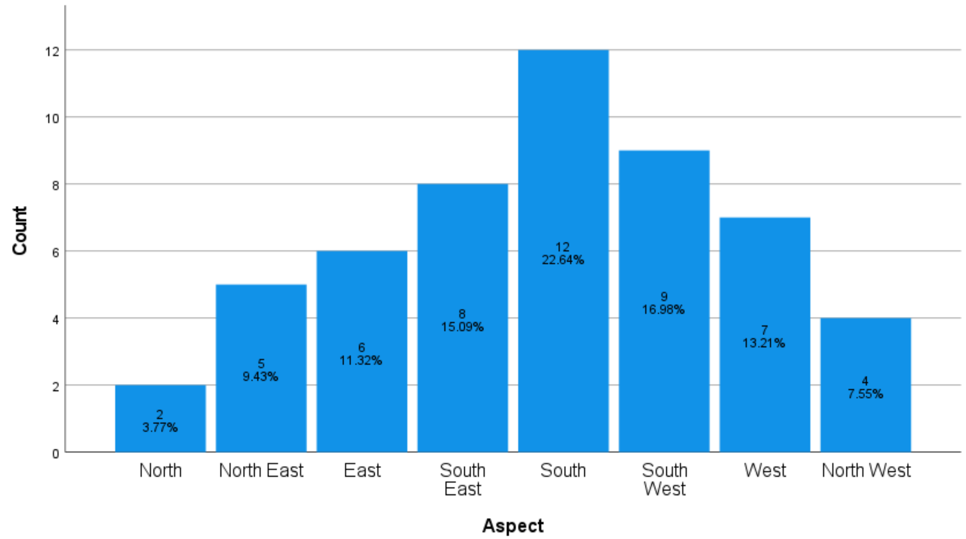


Figure A11 Frequency of each aspect category present in Cluster 1.

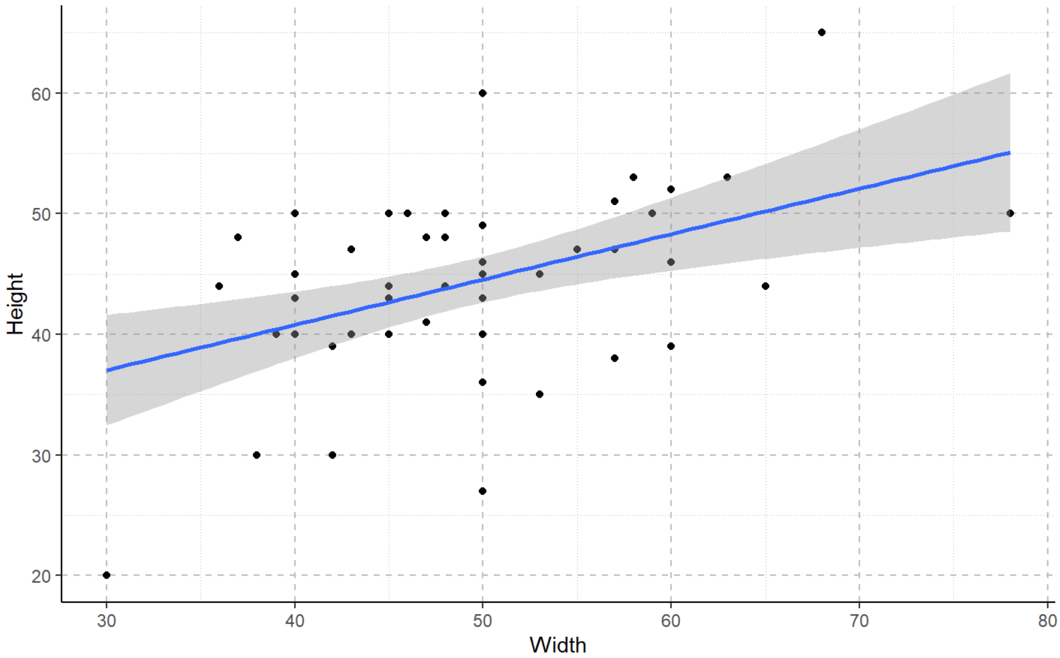


Figure A12 Bivariate scatter plot of height and width (cm) with best fit line for Cluster 1 burrows.

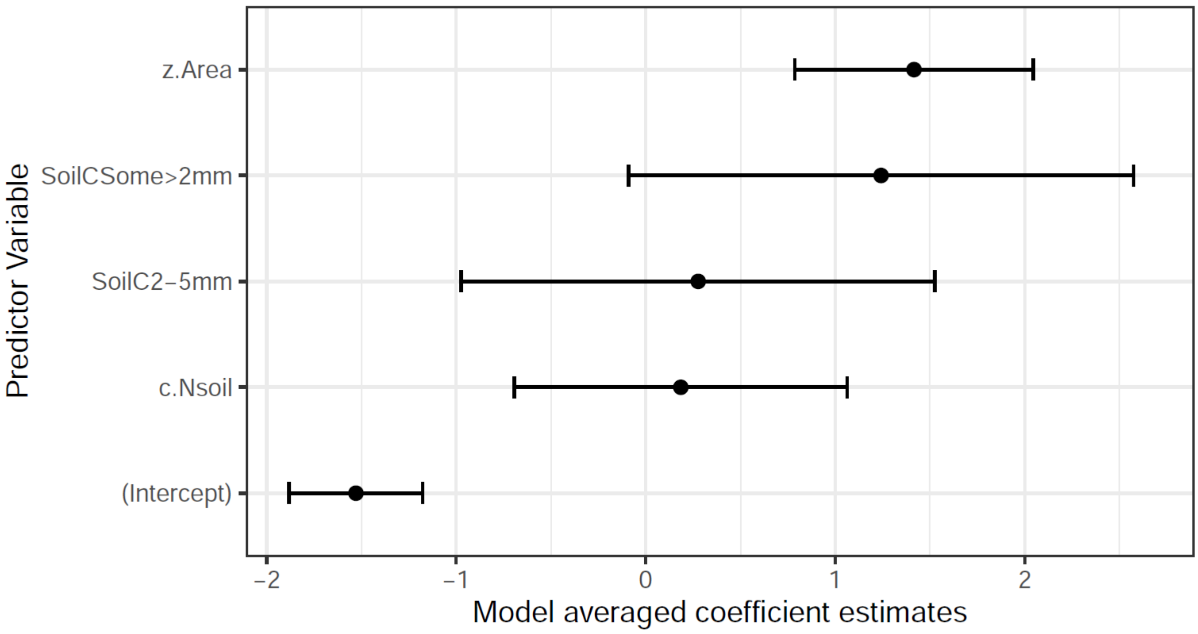


Figure A13 Confidence intervals of each burrow characteristic for the average top models, identified during model averaging of the Cluster 1 GLM. Points represent the standardised coefficient estimate from the averaged top models. Soilc refers to sail grain size, Nsoil refers to luvic phaeozem soil types. Area refers to CSA.

Table A5 Generalized variance inflation factor (VIF) scores calculated to test collinearity between the predictor variables of C1. Scores of >3 are considered collinear.

Collinearity Statistics		
	VIF	**Tolerance**
CSA	1.04	0.96
Soil type	1.03	0.973
Grain size	1.03	0.972
Termite	1.02	0.979
Aspect	1.01	0.988

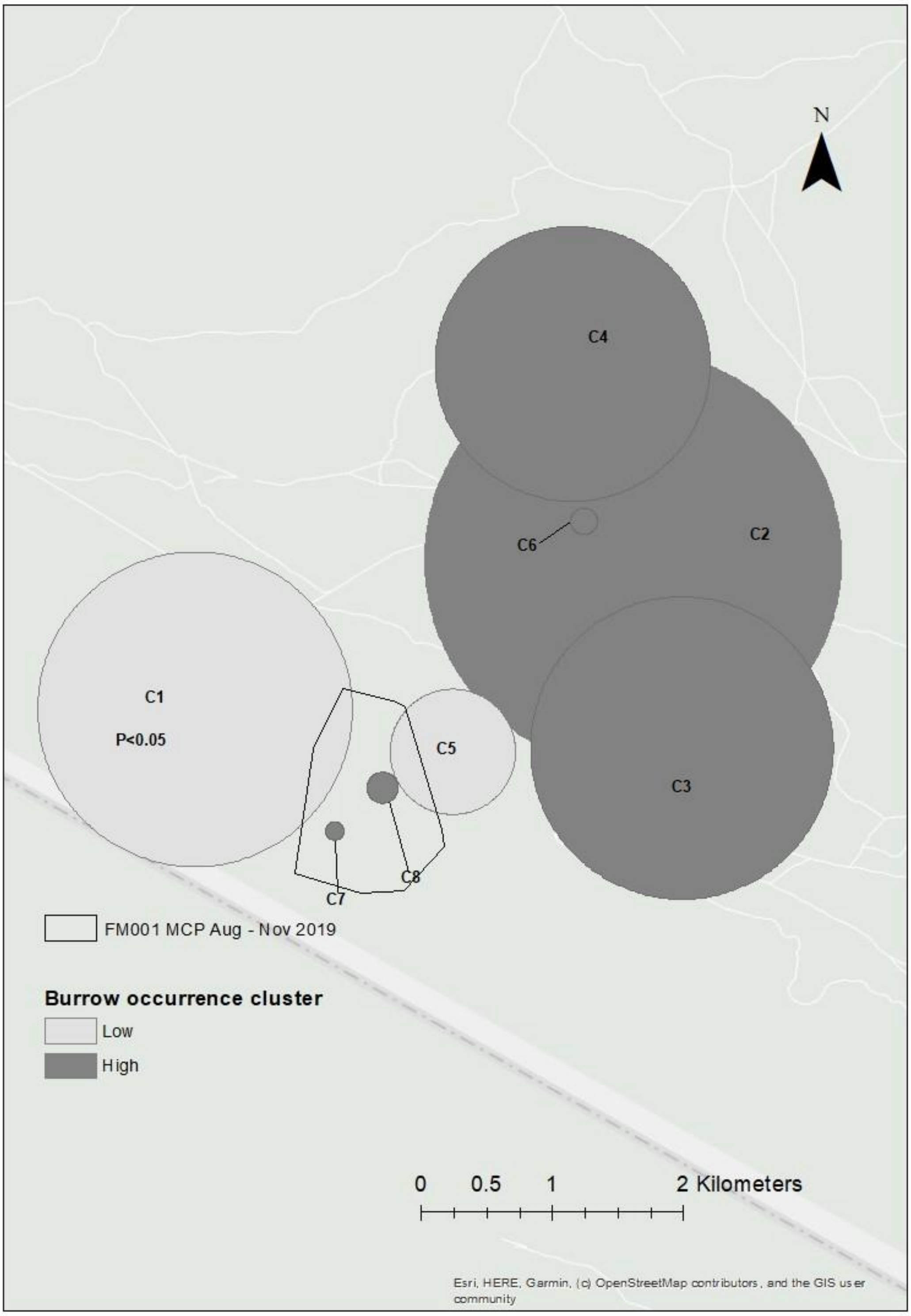


Figure A14 Minimum convex polygon area of FM001 satellite tag home range from August to November 2019. SatScan clusters displayed. Clusters with significantly high burrow use are denoted with a p-value.

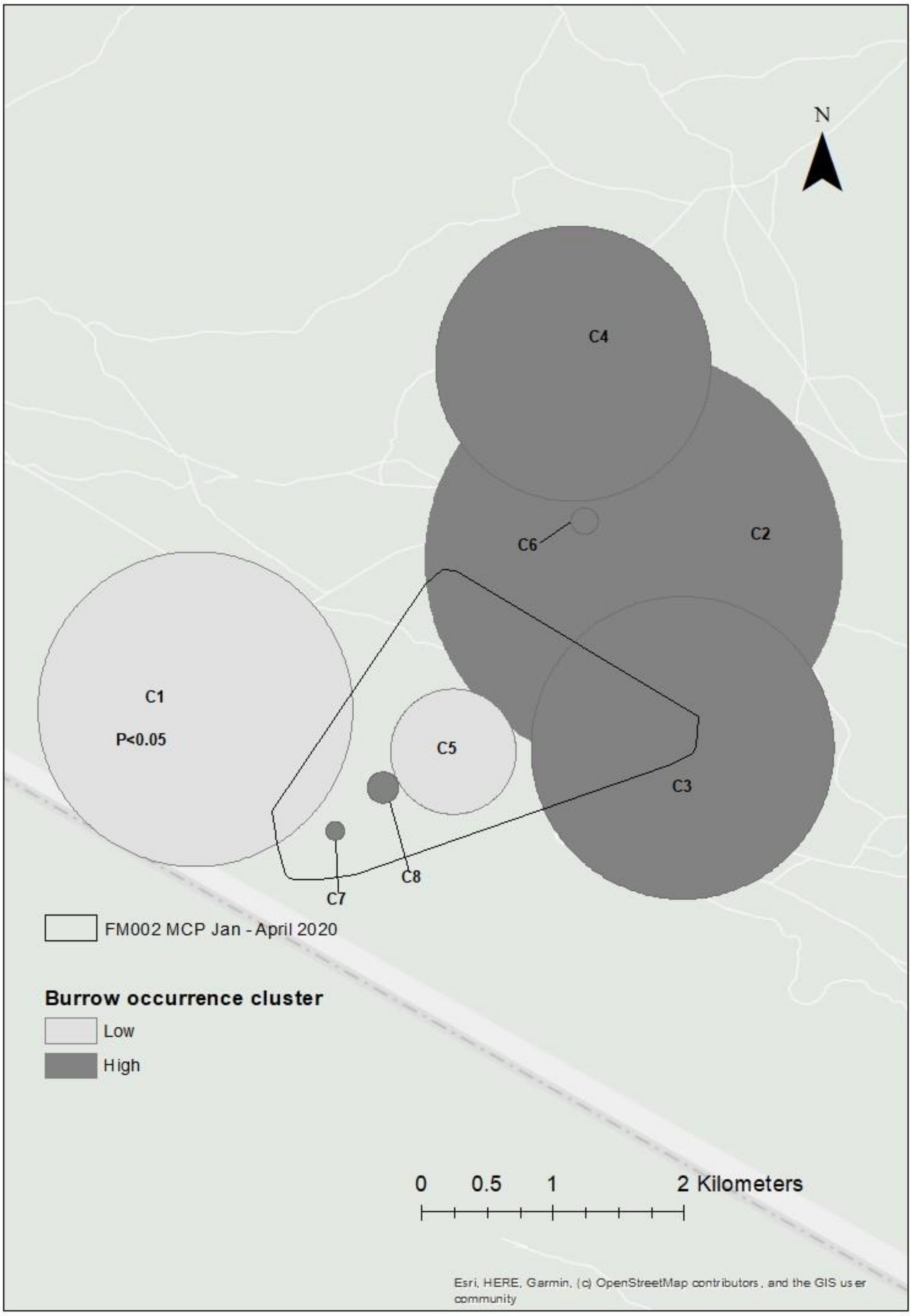


Figure A15 Minimum convex polygon area of FM002 satellite tag home range from January – April 2020. SatScan clusters displayed. Clusters with significantly high burrow use are denoted with a p-value.

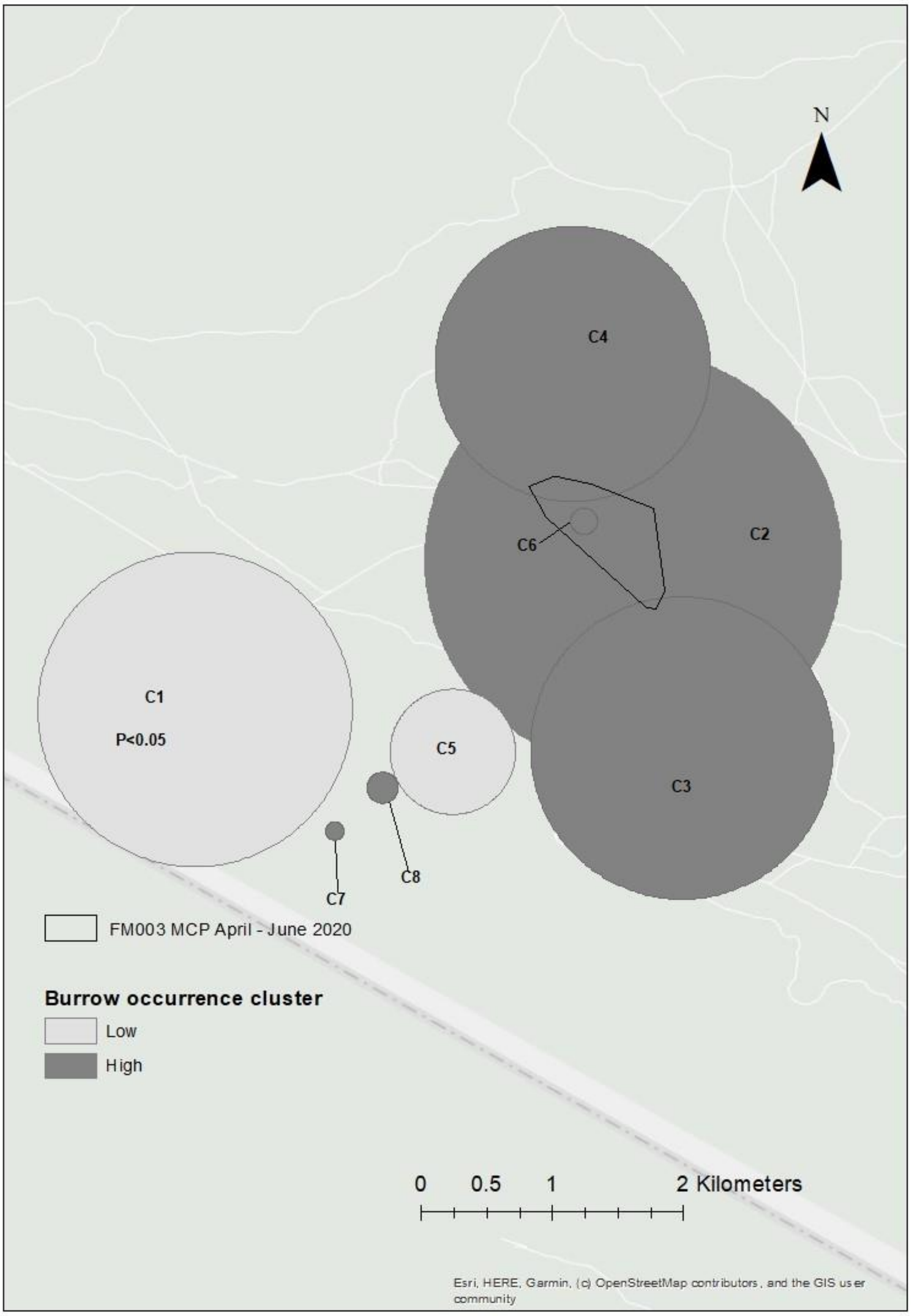


Figure A16 Minimum convex polygon area of FM003 satellite tag home range from April to June 2020. SatScan clusters displayed. Clusters with significantly high burrow use are denoted with a p-value.

Appendix 3 – Chapter 3: Burrow subset analyses (four characteristics measured)

The binomial logistic regression with four subset variables revealed no important predictor variables for pangolin burrow occurrence (Table A1). No variables were considered collinear because all VIF scores were < 3 (Table A2). Model averaging and selection revealed four models within AICc < 2 of each other. These were 1) soil type only, 2) soil type and CSA, 3) null model, and 4) CSA only (Table A3). No variable had a positive or negative association with pangolin burrow occurrence. All confidence intervals overlapped with zero indicating there were no influential variables (Table A4 and Figure A1). N = 281 for this model.

Table A1 Binomial logistic regression of burrow use characteristics broken down by variable. Residual deviance: 250.08 on 270 degrees of freedom. AIC: 272.08. Number of Fisher Scoring iterations: 4. N = 281. Note. Estimates represent the log odds of "Pangolin = Presence" vs. "Pangolin = Absence".

Model Coefficients - Pangolin			
Predictor	**Estimate**	**SE**	**Z**
Intercept	-1.393	0.549	-2.533
CSA	-2.721e-4	2.17e-4	-1.257
Termite: (Yes versus)			
No	0.002	0.343	0.008
Aspect: (South West versus)			
South	0.634	0.517	1.227
Southeast	0.254	0.667	-0.382
West	-0.629	0.620	-1.014
Northeast	0.624	0.627	0.995
East	0.533	0.566	0.940
North	0.188	0.757	0.249
Northwest	-0.179	0.694	-0.259
Soil: (Eutric planosols versus)			
Luvic phaeozems	0.915	0.416	2.199

Table A2 General linear models in AICc < 2 (top models) used for model averaging to describe the relationship between pangolin burrow use and burrow characteristics. logL = log-likelihood values; k = number of parameters per model; AICc = Akaike information criteria corrected value for the sample size between a model and the best fitting model; w = Akaike weight; R^2m = marginal R^2 (variance explained by the fixed factors); R^2c = conditional R^2 (variance explained by the fixed factors).

Model	**logL**	**k**	**AICc**	**∆AICc**	**w**	**R^2m**	**R^2c**
Soil only	-129.81	2	263.66	0.00	0.36	0.02131605	0.02131605
Soil and CSA	-128.94	3	263.97	0.31	0.31	0.03587660	0.03587660
Null	-131.58	1	265.17	1.51	0.17	0	0
CSA only	-130.64	2	265.32	1.66	0.16	0.015212305	0.015212305

Table A3 Confidence intervals of each burrow characteristics of the subset for the average top models identified during model averaging.

Parameter	**Estimate**	**Lower**	**Upper**
Intercept	-1.5534	-1.86743	-1.23934
Soil type (Luvic phaeozems)	0.4992	-0.01543	1.501350
CSA	-0.2083	-1.11838	0.228672

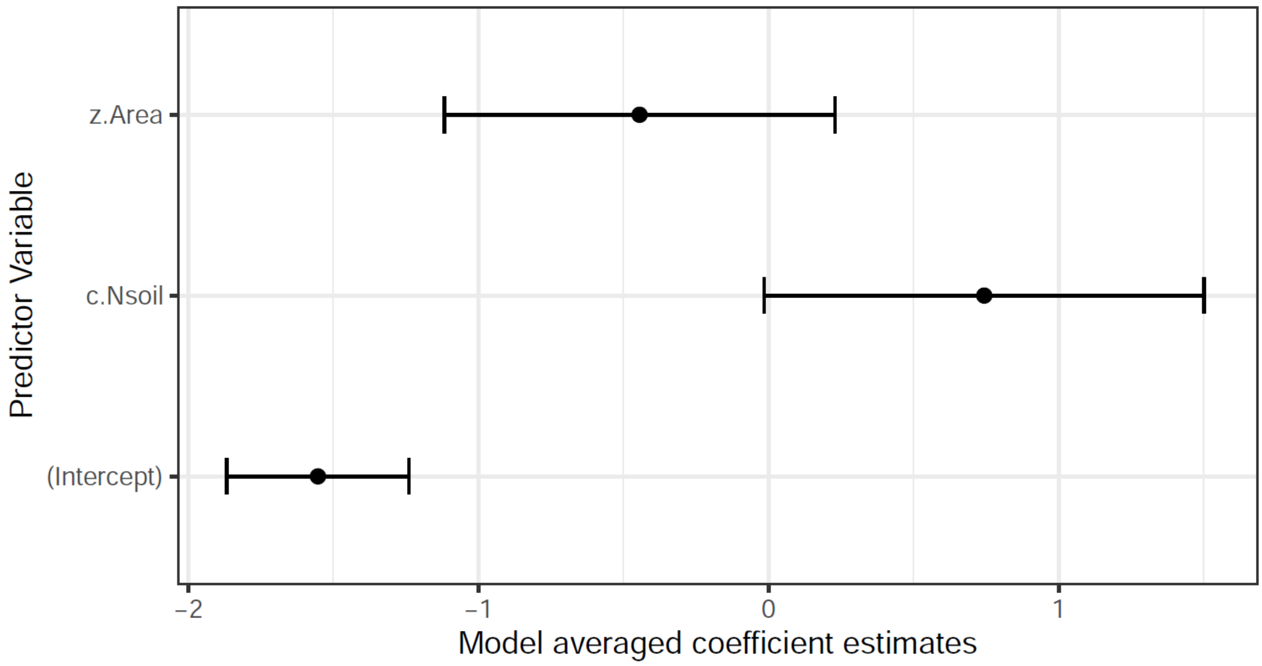


Figure A1 Confidence intervals of each burrow characteristic for the average top models, identified during model averaging of the four variable subset GLM. Points represent the standardised coefficient estimate from the averaged top models. Area represents CSA and c.NSoil represents luvic phaeozems.

Table A4 Generalized variance inflation factor (VIF) scores calculated to test collinearity between the predictor variables for the four variable burrow subset. Scores of >3 are considered collinear.

Collinearity Statistics		
	VIF	**Tolerance**
CSA	1	0.995
Aspect	1.01	0.992
Termite	1.04	0.966
Soil type	1.06	0.944

Appendix 4 – Chapter 4: Ambassador and pangolin sightings forms

<u>Pangolin Ambassador Activity Form</u>

1. What county was the activity?
    a. Narok
    b. West Pokot
    c. Taita-Taveta

2. Pangolin Ambassador details: ______________________________

3. Ambassador's name:____________________________

4. Conservancy/Reserve representing (The name of the conservancy or area you are representing as an ambassador)
    a. Lemek Conservancy
    b. Pardamat Conservation Area
    c. Mara North Conservancy
    d. Pololeti plains
    e. Ol Derkesi Conservancy
    f. Pellow Conservancy

5. Activities carried out: ______________________________

6. Date of activity:

Delivered key messages?

a. Yes
b. No

7. Community or area visit (Name the area, village, market, etc that you visited. Name it as is commonly called): ______________________________

8. How many people did you speak to? (The number of people spoken to when delivering key messages in the community you visited)______________________

9. GPS point where the key messages were delivered (latitude, longitude, altitude, accuracy)______________

First Responder Activity?

a. Yes
b. No

10. Which first responder activity?
    a. Live pangolin sighted
    b. Pangolin carcass sighted
    c. Pangolin scales sighted
    d. Pangolin held/kept by a community member

11. If scales found, location and number?___________________________

12. Community or area visit (Name the area, village, market, etc that you visited. Name it as is commonly called): _______________________________

13. GPS point where the key messages were delivered (latitude, longitude, altitude, accuracy)______________

14. Brief summary of events (list the issues that you responded to)_____________________________________

15. Did you notify TPP? (Did you tell TPP of the incident or report?)
    a. Yes
    b. No
    c. If not, why?_________________

16. Did you notify KWS?
    d. Yes
    e. No
    f. If not, why?_________________

17. Did you notify the conservancy?
    g. Yes
    h. No
    i. If not, why?_________________

18. Distance covered? (km)______________

Recording sightings? This is when you get information of someone who has seen a pangolin and you record all the details required in the sightings data form.

a. Yes

b. No

19. Community or area visit (Name the area, village, market, etc that you visited. Name it as is commonly called): ______________________________

20. GPS point where the key messages were delivered (latitude, longitude, altitude, accuracy)______________

21. How many sightings questionnaire form filled? The number of sightings recorded.__________

22. Distance covered? (km)______________________

Answering questions from the community? This is when you answer questions from the community. This can be questions asked during any of the other activities or when they just come to you with questions concerning pangolins.

a. Yes
b. No

23. Community or area visit (Name the area, village, market, etc that you visited. Name it as is commonly called): ______________________________

24. Distance covered? (km)___________________________

25. GPS point where the key messages were delivered (latitude, longitude, altitude, accuracy)______________

26. What questions were asked? List the questions asked by the community., separating each with a comma, (e.g. what do pangolins eat?, do pangolins have teeth?)____

Team meeting? This is when you attend team or project activity.

a. Yes
b. No

27. Where was the meeting or activity? This is where the activity was held eg Virtual (over the internet), Aitong, Cottars camp, etc. ____

Any other activity that is not listed above? Was any other activity undertaken or carried out that is not in the previous list?

a. Yes
b. No

28. List any other activity undertaken_____________________________

29. Community or area visit (Name the area, village, market, etc that you visited. Name it as is commonly called): ________________________________

30. GPS point where the key messages were delivered (latitude, longitude, altitude, accuracy)______________

Challenges faced in the course of your work? If no challenges write NA.____

<u>Pangolin Sightings Form</u>

1. What county was the sighting?_________________
2. Details of staff entering the data:_______________________
   Staff post:______________________
   Staff name______________________

3. Pangolin ambassador details

4. Ambassador's name:______________________________

5. Conservancy/Reserve representing (The name of the conservancy or area you are representing as an ambassador)
   g. Lemek Conservancy
   h. Pardamat Conservation Area
   i. Mara North Conservancy
   j. Pololeti plains
   k. Ol Derkesi Conservancy
   l. Pellow Conservancy

6. Respondent details_____________________
   Name of respondent______________
   Age_______________
   Phone number_____________

Alternative phone number_________________

Sightings information

7. Sightings within the last 10 years ______________________

8. Date of sighting:

9. Location of sighting_______________________

10. GPS point where the key messages were delivered (latitude, longitude, altitude, accuracy)______________

11. Timing of sighting?
    a. Morning
    b. Afternoon
    c. Evening
    d. Night-time
    e. Don't know

12. Weather at time of sighting
    a. Overcast
    b. Sunny
    c. Rainy
    d. Don't know
13. Distance to nearest water source

14. Activity of pangolin when first sighted
    a. Moving
    b. Other__________

15. Activity of respondent at the time of sighting
    a. Other_________________

16. What did the respondent do when they saw the pangolin?
    a. Try to pick it
    b. Harm it (hit it)

c. Picked it and sold it
d. Picked it and killed it
e. Ran away from it
f. Informed someone (ranger, tourguide, etc)
g. Ignored it and left it alone
h. Other____________

17. Do you have any photos of the sighted pangolin?
    a. Yes
    b. No
    c. If no, why?_______________

18. Any other relevant information?_______________________

Appendix 5 – Chapter 4: Raw data and exploratory graphs

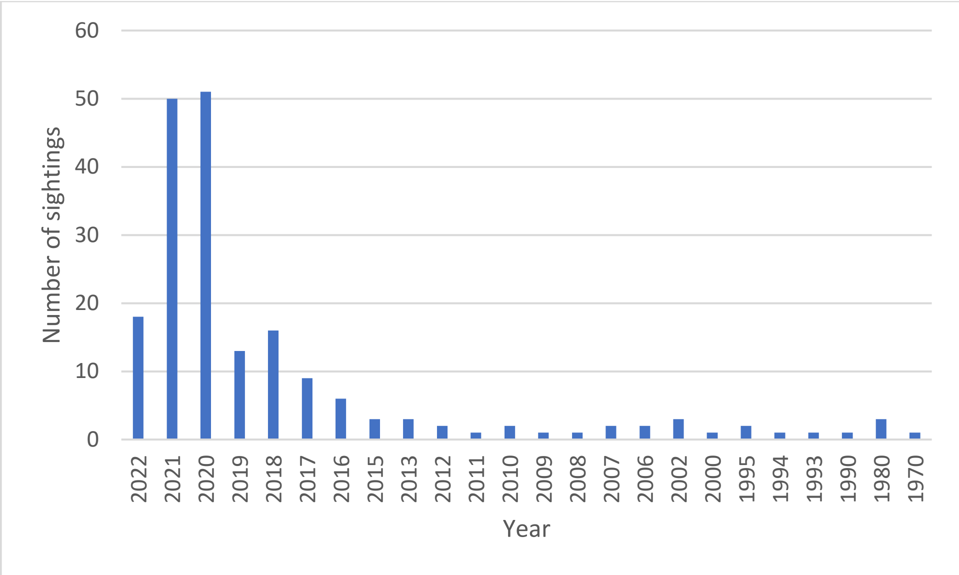


Figure A1 The number of pangolin sightings from the community reports, reported for each year with at least one record, from 1970 – 2022.

Table A1 Summary of the number of pangolin sightings reported for each year, dating back to 1970.

Year	**Sightings**	**Percentage**
2022	18	7.3
2021	50	20.2
2020	51	20.6
2019	13	5.2
2018	16	6.5
2017	9	3.6
2016	6	2.4
2015	3	1.2
2013	3	1.2
2012	2	0.8
2011	1	0.4
2010	2	0.8
2009	1	0.4
2008	1	0.4
2007	2	0.8
2006	2	0.8
2002	3	1.2
2000	1	0.4

1995	2	0.8
1994	1	0.4
1993	1	0.4
1990	1	0.4
1980	3	1.2
1970	1	0.4

Table A2 Summary of counties where Pangolin Ambassador activities took place.

County	Frequency	Percentage
Narok	622	99.5
West Pokot	3	0.5

Table A3 Summary of which activities were conducted. Multiple activities could be undertaken at one time.

Activity	Total frequency	Percentage of time undertaken
Delivered key messages	626	100
Answered community questions	434	69.3
Recorded sightings	87	13.9
Team meeting	41	6.5
First responder activity	11	1.7
Burrow investigation	1	0.15

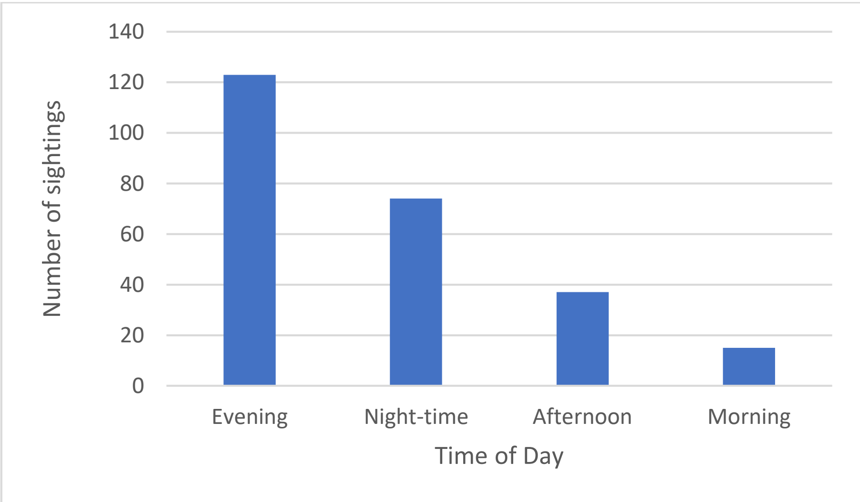


Figure A2 The frequency at which pangolins were sighted at different times of day.

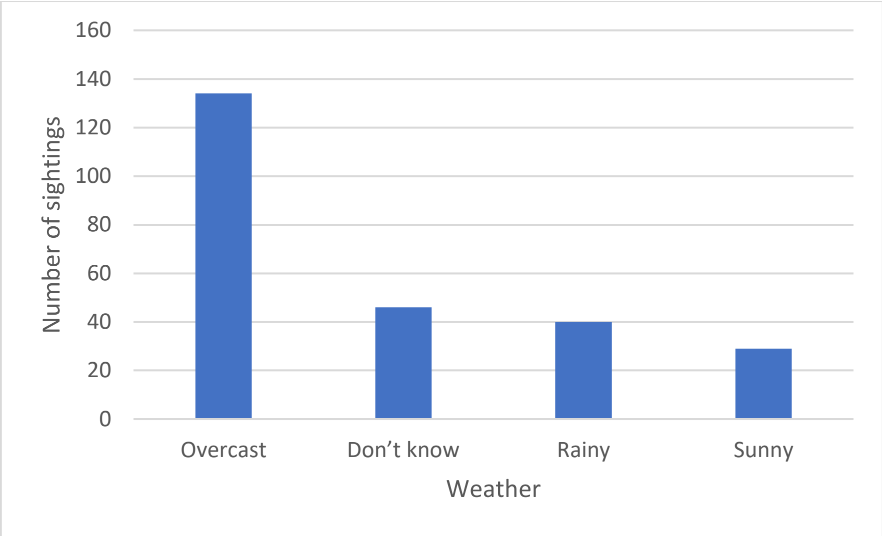


Figure A3 The frequency each weather type was reported when a pangolin was sighted during the citizen science reports.

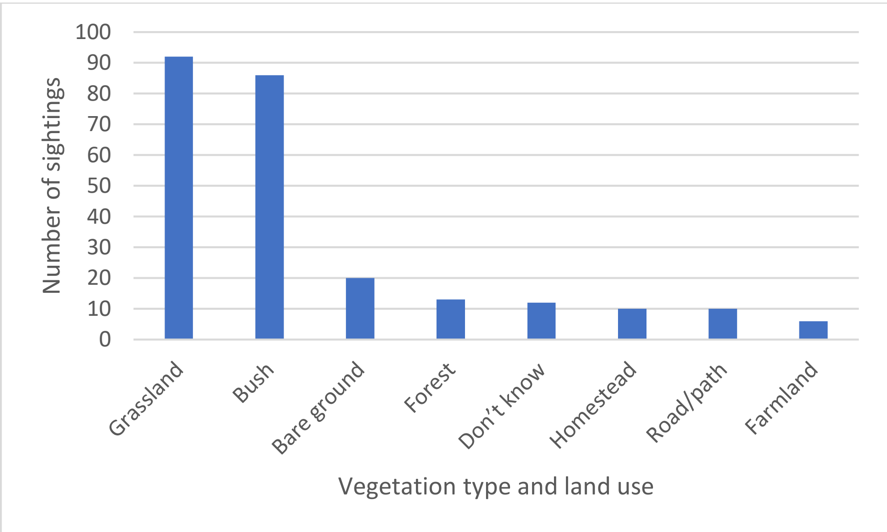


Figure A4 The vegetation type or land type where pangolins were reported, during the citizen science reports.

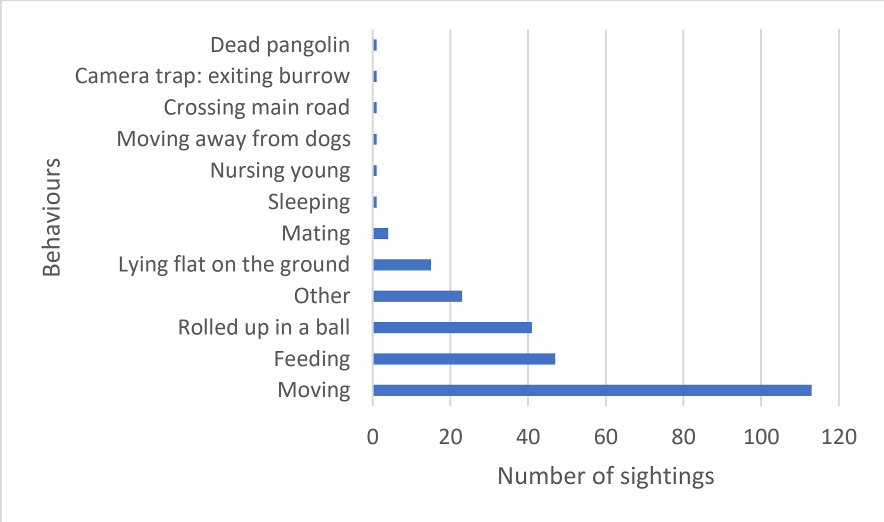


Figure A5 The frequency at which each pangolin behaviour was observed by the citizen science reporters.

Table A4 Summary of the predictor variables recorded during pangolin sightings, including time of day, weather conditions, and vegetation/land use.

Time of day	**Frequency**	**Percentage**
Evening	123	49.4
Night-time	74	29.7
Afternoon	37	14.9
Morning	15	6
Weather conditions		
Overcast	134	53.8
Don't know	46	18.5
Rainy	40	16.1
Sunny	29	11.6
Vegetation type and land use		
Grassland	92	36.9
Bush	86	34.5
Bare ground	20	8
Forest	13	5.2
Don't know	12	4.8
Homestead	10	4
Road/path	10	4
Farmland	6	2.4

Table A5 Response variable breakdown of the different behaviours or states witnessed by participants during a sighting.

Behaviour	**Frequency**	**Percentage**
Moving	113	45.4
Feeding	47	18.9
Rolled up in a ball	41	16.4
Other	23	9.2
Lying flat on the ground	15	6
Mating	4	1.6
Sleeping	1	0.4
Nursing young	1	0.4
Moving away from dogs	1	0.4
Crossing main road	1	0.4
Camera trap: exiting burrow	1	0.4
Dead pangolin	1	0.4

Table A6 Soil type codes and types for the Narok site.

Soil code	**Abbreviation**	**Soil type**
0		Unknown
1	Ntu	Humic nitisols
2	Anm	Mollic andosols
3	FRr	Rhodic ferralsols
4	PHl	Luvic phaeozems
5	Ple	Eutric planosols
6	LVv	Vertic luvisols
7	Ach	Haplic acrisols
8	Cmu	Humic cambisols
9	PHh	Haplic phaeozems
10	RGc	Calcaric regosols
11	Lpu	Umbric leptosols
12	GRh	Haplic greyzems
13	Acu	Humic acrisols
14	Vre	Eutric vertsols
15	Cme	Eutric cambisols
16	Rge	Eutric regosols
17	SNg	Gleyic solonetz
18	NTr	Rhodic nitisols
19	Fle	Eutric fluvisols
20	SCh	Haplic solonchaks
21	LVh	Haplic luvisols

22	nd	no data
23	SCg	Gleyic solonchaks
24	LXh	Haplic lixisols
25	SNk	Calcic solonetz

Table A7 Soil type codes and types for all of Kenya.

Soil code	**Abbreviation**	**Soil type**
0		Unknown
1	SNk	Calcic solonetz
2	Arb	Cambic arenosol
3	Fle	Eutric fluvisols
4	CMc	Calceric cambisol
5	RGc	Calceric regosol
6	Ple	Eutric planosols
7	FLc	Calceric fluvisols
8	SCk	Calcic solonchaks
9	nd	no data
10	LXh	Haplic lixisols
11	LVx	Chromic luvisols
12	FLt	Fluvisols
13	LPq	Lithic leptosols
14	LVk	Calcic luvisols
15	CLh	Haplic calcisols
16	Cme	Eutric cambisols
17	FRr	Rhodic ferralsols
18	LVf	Ferric luvisols
19	RGd	Dysteric regosols
20	Rge	Eutric regosols
21	SNm	Mollic solonetz
22	LVh	Haplic luvisols
23	CMx	Chromic cambisols
24	LPe	Eutric leptosols
25	SCn	Sodic solonchaks
26	Vre	Eutric vertsols
27	PHl	Luvic phaeozems
28	SCh	Haplic solonchaks
29	LVv	Vertic luvisols

30	LPk	Plintic leptosols
31	SNh	Haplic solonetz
32	Gle	Eutric gleysols
33	NTh	Haplic nitosols
34	CMd	Dystric cambisols
35	Cmu	Humic cambisols
36	Aro	Ferralic arenosols
37	SNg	Gleyic solonetz
38	Ach	Haplic acrisols
39	GLk	Calcic gleysols
40	Acu	Humic acrisols
41	Fru	Humic ferralsols
42	NTr	Rhodic nitisols
43	Ntu	Humic nitisols
44	Hss	Terric histosols
45	GLm	Mollic gleysols
46	FRh	Haplic ferralsols
47	LXf	Ferric lixisols
48	CHk	Calcic chernozem
49	Acp	Plinthic acrisols
50	Acf	Ferric acrisols
51	CLp	Petric calcisols
52	PLd	Dystric planosols
53	Anu	Umbric andosols
54	Anh	Haplic andosols
55	SNj	Stagnic solonetz
56	Plu	Humic planosols
57	Anm	Mollic andosols
58	LXp	Plintic lixosols
59	PHh	Haplic phaeozems
60	Cmo	Ferralic cambisols
61	Glu	Umbric gleysols
62	CMg	Gleyic cambisols
63	Lpu	Umbric leptosols
64	GRh	Haplic greyzems
65	PHg	Gleyic phaeozems
66	nd	No data
67	LVg	Gleyic luvisols
68	Arl	Luvic arenosols
69	FRx	Xanthic ferralsols
70	Arh	Haplic arenosols

71	Ara	Albic arenosols
72	Alh	Haplic alisols

Appendix 6 – Chapter 5: Questionnaire and survey cover page

Animal Electrocution Questionnaire Cover Page

Thank you for your interest in completing this survey.

This research project aims to investigate if fences have an impact on animal behaviour and movement with a focus on Temminck's ground pangolins. This questionnaire aims to determine how often pangolins are killed (electrocuted) on fence wires. This will help improve conservation management for this important and vulnerable species.

You are invited to participate if you:

- Are based or have ever been based within African ground (Temminck's) pangolin range (This includes: Angola; Botswana; Burundi; Central African Republic; Chad; Ethiopia; Kenya; Malawi; Mozambique; Namibia; Rwanda; South Africa; Sudan; South Sudan; Tanzania; Uganda; Zambia; Zimbabwe)

Participants from all of the above countries are welcome and we are especially interested in responses from those in South Africa due to the high presence of electric fences.

And **any** of the following apply:

- You are a landowner or manager
- You are a game ranger
- You are a conservationist
- You work or have worked on a game reserve, ranch, or farm
- You have ever worked with wildlife
- You have witnessed wildlife electrocutions on fences

There are two parts to this survey. You are asked to please complete Part One. This is short and will take 10-15 minutes.

You will then have the option to complete Part Two, these are follow-up questions to gather more information. This will take an additional 10-15 minutes.

Before you complete the survey please ensure you have read the following frequently asked questions:

Do I have to take part? Participation is completely voluntary and you may refuse to participate at any time, and you may decline to answer any questions that you are not comfortable with.

What do I have to do? Please answer the questions in the questionnaire to the best of your ability. If you are unsure of how to answer feel free to ask someone (e.g. a colleague or manager) who may know the answer.

What are the possible disadvantages and risks of taking part? There are no risks associated with participating in this study.

What are the possible benefits of taking part? By participating in this study, you will help contribute to Temminck's ground pangolin conservation. Additionally, if you are based in South Africa, there is also an option to enter a prize draw to win 1 of 10 R200 digital gift vouchers as a thank you for your participation. Winners can choose from PickNPay, Netflix, Uber, the App Store, or Play Store. South Africa is the primary target location of this study due to the high use of electric fencing.

Each part you complete will equal one entry into a prize draw, if you wish to enter. Completing both parts mean you will be entered twice.

What if something goes wrong? If you have any complaints about the project you can contact any member of the research team or the University of Brighton Ethics Committee. University of Brighton Life, Health and Physical Sciences Research Ethics Committee l.redhead@brighton.ac.uk

Will my taking part in this project be kept confidential? All the information that we collect about you during the course of the research will be kept strictly confidential. You will not be able to be identified or identifiable in any reports or publications. Any data collected about you in the online questionnaire will be stored online in a form protected by passwords consistent with data protection regulations. Any responses you provide will be generated into a unique ID number that will ensure you and your land are anonymous. Only locational data on municipality will be retained and only a limited number of the research team will have access to this information. You do not need to provide your name or contact details unless you wish to enter the prize draw.

What type of information will be sought from me and why is the collection of this information relevant for achieving the research project's objectives? You will be asked about your fences and if you have ever witnessed animals electrocuted on fencing. The most common animals electrocuted on fences are tortoises, pangolins, reptiles, antelopes, and birds. Even if you have not witnessed any electrocutions your responses are still important to us. You will not get into trouble in any way for having electrocutions happen on your land or for reporting them to us.

What will happen to the results of the research project? Results of the research will contribute to a PhD thesis and may be academically published. If you wish to be kept up to date on the research findings you can opt in to updates at the end of the questionnaire.

Who is organising and funding the research? The project is a partnership involving Lea Stracquadanio (PhD candidate), Dr Bryony Tolhurst, Dr Sam Penny and Dr Niall Burnside at the University of Brighton (UK), and Prof Andre Ganswindt at the University of Pretoria Mammal Research Institute (South Africa).

Who has ethically reviewed the project? This project has been ethically approved by the University of Brighton Life, Health and Physical Sciences Research Ethics Committee.

Contact information: Lea Stracquadanio, School of Pharmacy and Biomolecular Sciences, University of Brighton, UK l.stracquadanio@brighton.ac.uk

Please share this questionnaire with anyone who you think would be interested.

By clicking next you confirm that you have read and understood the above and give your consent for your responses to be collected and used in the study.

Animal Electrocution Questionnaire Part One

1. Are you a landowner or land manager? Please answer for the primary land you own/work on. If you work across multiple sites you can record this in Part Two.

    a. Yes, landowner

    b. Yes, land manager

    c. Yes, both landowner and land manager

    d. No

If you selected No, please specify profession (e.g. tour guide, farmer, conservation professional, student, game rancher, professional hunter, or any other profession):

2. Please state the name and location of this land (e.g. reserve or farm name and province). Answer the sections you are comfortable with. Why am I being asked this? We wish to gather information on where electrocutions occur and where pangolins are present. This information will also give us habitat information.

    a. Prefer not to say

Land name:

Province:

Postcode:

Country:

3. Please state the name and location of the land you work/have worked on (e.g. reserve or farm name and province). Answer the sections you are comfortable with. Why am I being asked this? We wish to gather information on where electrocutions occur and where pangolins are present. This information will also give us habitat information.

    a. Prefer not to say

Land name:

Province:

Postcode:

Country:

4. How long have you worked in this role?

    a. Less than 1 year

    b. 1-5 years

    c. 5+ years

5. Where does the majority of the land's income come from? Select all that apply.

    a. Tourism

    b. Trophy hunting

    c. Meat/livestock production

    d. Agriculture/farming

    e. Prefer not to say

    f. Other (please specify):______

6. Is there fencing on or around the land?

   a. Yes

   b. No

7. Approximately how long is the fence in total?

   a. Prefer not to say

   b. Don't know

   c. Kilometres: _______

8. What is the purpose of the fence? Please select all that apply.

   a. To mark a land boundary

   b. Security (keep people out)

   c. To keep animals in

   d. Prefer not to say

   e. Other (please specify):_______

9. How often are the fences monitored? Please fill in whichever box is most appropriate, you do not need to respond in every box. Why am I being asked this? This will help us understand how frequently electrocutions occur. The number of electrocutions reported may be influenced by how often the fence is observed. This question is not intended to gather information on fence security.

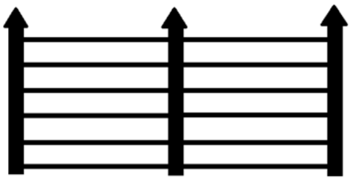
   a. Times per day_________

   b. Times per week_______

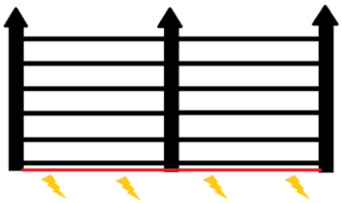
   c. Times per month ______

   d. Other (please specify):_______

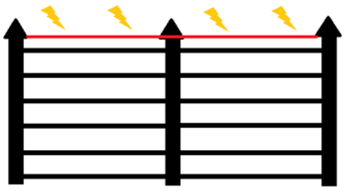
10. What type of fence(s) is present? Please select all that apply. Why am I being asked this? We Would like to determine how prevalent electric fences are and if a particular fence type is more prime to electrocutions. This question is not intended to gather information on fence security.



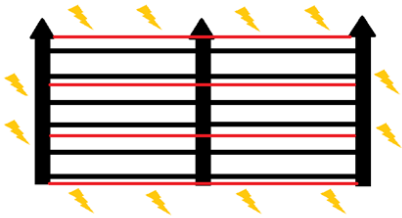
No electric wires present



Electric wires present at ground level (under 20cm approx.)



Electric wires present on top of fence



Electric wires present at multiple heights including ground level (under 20cm approx.)

a. No electric wires present

b. Electric wires present at ground level (under 20cm approximately)

c. Electric wires present on top of fence

d. Electric wires present at multiple heights including ground level (under 20cm approx.)

e. Other

f. Don’t know

g. Prefer not to say

For electric wires present at ground level (under 20cm approximately) please indicate the approximate total length (km) of this fence type: _____________

For electric wires present on top of fence please indicate the approximate total length (km) of this fence type: _____________

For electric wires present at multiple heights including ground level (under 20cm approximately) please indicate the approximate total length (km) of this fence type: _____________

If you selected Other, please describe the fence type(s) and indicate total fence length(s) (km) of these fences: __________

11. If electric wires are present what voltage(s) is the fence?

    a. No electric wires present

    b. Don't know

    c. Prefer not to say

    d. If known, please list any/all voltages used:____________

12. How high are the electric wires off the ground? Please select all that apply.

    a. 0-5cm

    b. 5-20cm

    c. 20-40cm

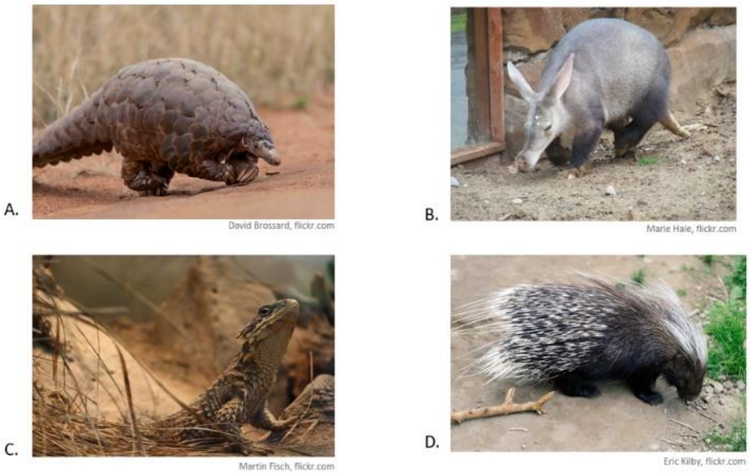
    d. 60-100cm

    e. 100cm+

    f. Don't know

    g. Prefer not to say

13. Which of these photos represents a pangolin?



(A: Brossard, 2012; B: Hale, 2011; C: Fisch, 2007; D: Kilbry, 2014)

a. A

b. B

c. C

d. D

e. None of these

f. Don’t know

14. Have you or anyone else seen a pangolin or signs of pangolins on this land? Please select all that apply.

    a. No

    b. Don’t know

    c. Yes, live animal

    d. Yes, burrow, tracks, or other field signs

    e. Yes, dead pangolin carcass

    f. Other (e.g. records from wildlife surveys, etc.) Please specify _____________

15. Have you or someone else ever seen any dead or electrocuted animals of any species on or near the fences (within approximately 10m)?

    a. No fences present

    b. Yes

    c. No

16. If yes, which animal(s)? Please select all that apply.

    a. Tortoise

    b. Pangolin

    c. Snake

    d. Lizard

    e. Antelope

    f. Bird

    g. Other

If known, please specify which species: _______________

17. Do you currently use any fence modifications or other methods to prevent animal electrocutions?

    a. Yes

    b. No

If you selected Yes, please give details____________

18. How many times have pangolin deaths or electrocutions occurred on this land?

    a. Don't know

b. None to my knowledge

c. Number of times within the last month_________

d. Number of times within the last 6 months________

e. Number of times within 6 months – 1 year ________

f. Number of times within the last 1-5 years________

19. How long have you (or the person providing this information) worked/lived on/managed this land? Please fill in whichever box is most appropriate, you do not need to respond in both boxes.

    a. Don't know

    b. Months______

    c. Years _______

20. Please enter any additional comments or relevant information below:

21. Optional: Please select any of the following if you would like to be:

    a. Entered in a prize draw (voucher will be emailed to you) – South Africa participants only

    b. Involved in a follow-up survey

    c. Updated with the research findings

Name:

Email address:

Phone number:

Address:

22. Do you wish to continue to Part Two?

a. Yes

b. No

Animal Electrocution Questionnaire Part Two

23. What is the purpose of this land? Please select all that apply.

    a. Farmland

    b. Game ranch/reserve

    c. Residential

    d. Other (please specify)______

24. What habitats exist on this land? Select all that apply.

    a. Nama-Karoo

    b. Savannah

    c. Succulent karoo

    d. Fynbos

    e. Grassland

    f. Desert

    g. Albany thicket

    h. Indian ocean coastal belt

    i. Forest

    j. Don't know

    k. Other (please specify)________

25. What is the size of the land? Please indicate whether this is in kilometres squared or hectares (you only need to answer one of these).

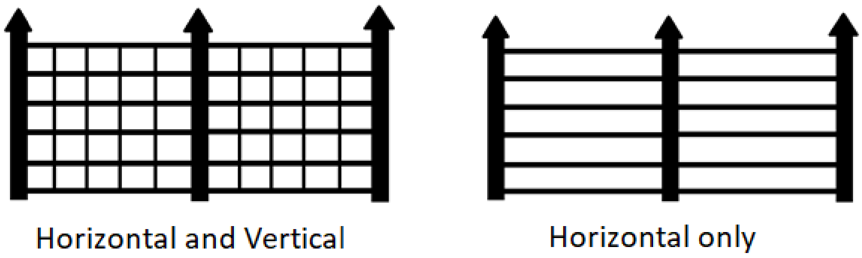
a. Prefer not to say

b. Don’t know

c. Km2_____

d. Hectares____

26. Does the fence have both horizontal and vertical wires, or only horizontal?



a. No fences present

b. Horizontal and vertical

c. Horizontal only

d. Don’t know

e. Prefer not to say

27. Are electrocutions damaging the fences?

a. Yes

b. No

c. Don’t know

28. If yes, is this a concern of yours?

a. Yes

b. No

29. Overall, how concerned are you about the number of animal electrocutions the land experiences?

    Concern level:

    1 (not concerned at all)

    2

    3

    4

    5

    6

    7

    8

    9

    10 (extremely concerned)

30. Why is this?

    a. I am not concerned.
    b. I am not currently concerned but may be if electrocutions increased.
    c. I am concerned for wildlife conservation reasons.
    d. I am concerned for reasons of animal suffering/welfare.
    e. I am concerned the fence is being damaged.
    f. Other (please specify)_________

31. Have you lived or worked in other areas that have pangolins?

a. Yes

b. No

c. Don't know

32. If yes, please list all these areas and give details of any electrocutions known to you. If possible, please be specific.

    a. Prefer not to say

Land name, province, postcode, country:_____________

If you have witnessed electrocutions of any species, including pangolins, please elaborate:____________

Land name, province, postcode, country:_____________

If you have witnessed electrocutions of any species, including pangolins, please elaborate:____________

Land name, province, postcode, country:_____________

If you have witnessed electrocutions of any species, including pangolins, please elaborate:____________

33. Would future methods to prevent electrocutions interest you? If you/your land are already using prevention methods answer if further methods would interest you.

    a. Yes

    b. No

34. Please enter any additional comments or relevant information below:

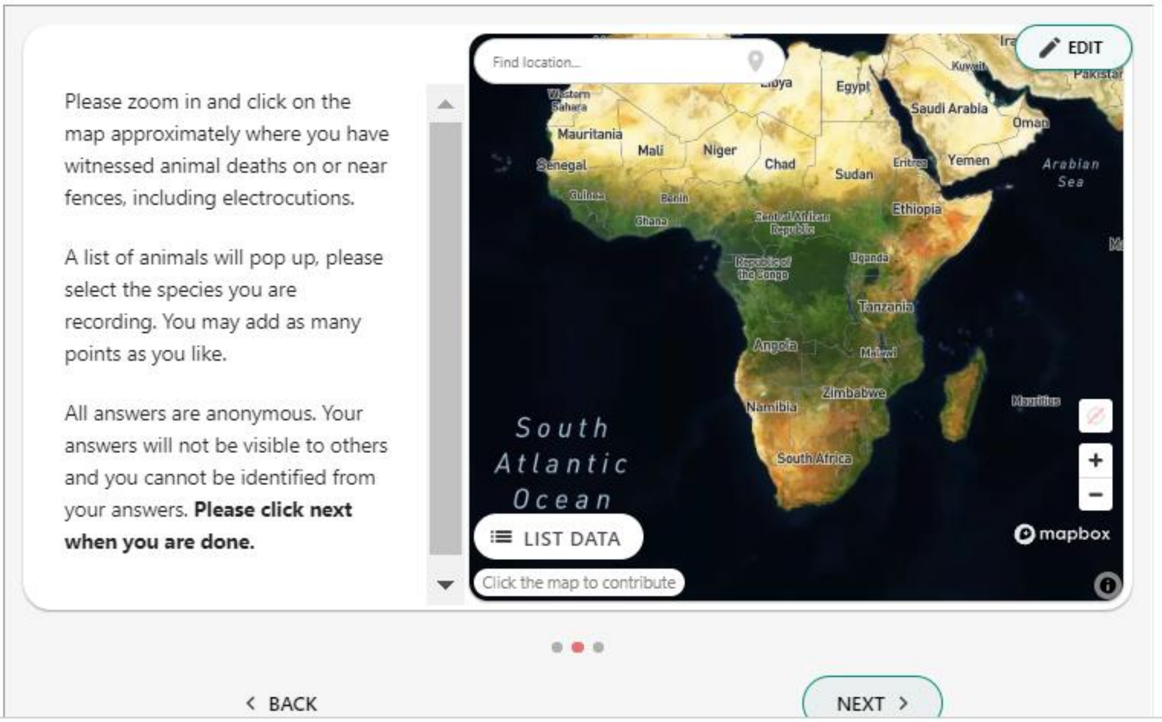
Final Question

Please use the interactive map below to mark where you have witnessed animal deaths on fences. Your responses cannot be linked to you and only the research team can see the responses.

This will take less than 5 minutes.

You may close the questionnaire when you are finished or if you have no deaths to record.

Please click next on the window below to view the map.



Appendix 7 – Chapter 5: Raw data and exploratory graphs

Table A1 Demographic information on 44 participants, including pangolin and fence use, based on an electronic questionnaire survey.

	Sample
N	73 (44 primary responses, 29 subsequent responses)
Profession Grouped when possible or removed from the analyses	Manager = 11; landowner and manager = 5; landowner = 5; conservationist = 5; guide = 4; researcher = 3; student = 2; tracker = 1; scientific director = 1; ranger = 1; ecologist = 1; biomonitoring manager = 1
Country	South Africa = 52; Botswana = 8; Tanzania = 5; Zimbabwe = 3; Mozambique = 1; Namibia = 1
Known pangolin presence	62 (85%)
Fence presence	64 (33 with electric wires)

Table A2 Responses from all countries and provinces reported by questionnaire participants.

Country	**Frequency**	**Proportion**
South Africa	52	74.3
Botswana	8	11.4
Tanzania	5	7.1
Zimbabwe	3	4.3
Namibia	1	1.4
Mozambique	1	1.4
Province		
Limpopo (SA)	22	40.74

North West (SA)	7	12.96
Northern Cape (SA)	5	9.26
Mpumalanga (SA)	4	7.41
Gauteng (SA)	3	5.56
KwaZulu-Natal (SA)	2	5.56
Bobirwa (Botswana)	1	1.85
Eastern/Western Cape (SA)	1	1.85
Matebeland South (Zimbabwe)	1	1.85
Maun (Botswana)	1	1.85
Ngamiland (Botswana)	1	1.85
North West-Mpumalanga-Limpopo (SA)	1	1.85
Tuliblock (Botswana)	1	1.85
Western Cape (SA)	1	1.85
Bulawayo (Zimbabwe)	1	1.85
Kweneng West (Botswana)	1	1.85

Table A3 Income source summary of all participants who reported this information, in South Africa.

Land Use	**Frequency**	**Proportion**
Tourism	11	45.8 %
Tourism, Meat/livestock production	2	8.3 %
Tourism, Trophy hunting	3	12.5 %
Management levies	1	4.2 %
Private funding	1	4.2 %
Meat/livestock production	1	4.2 %

Agriculture/farming	1	4.2 %
International students	1	4.2 %
Meat/livestock production, Agriculture/farming	1	4.2 %
Management levies and tourism	1	4.2 %
Tourism, Trophy hunting, Meat/livestock production	1	4.2 %

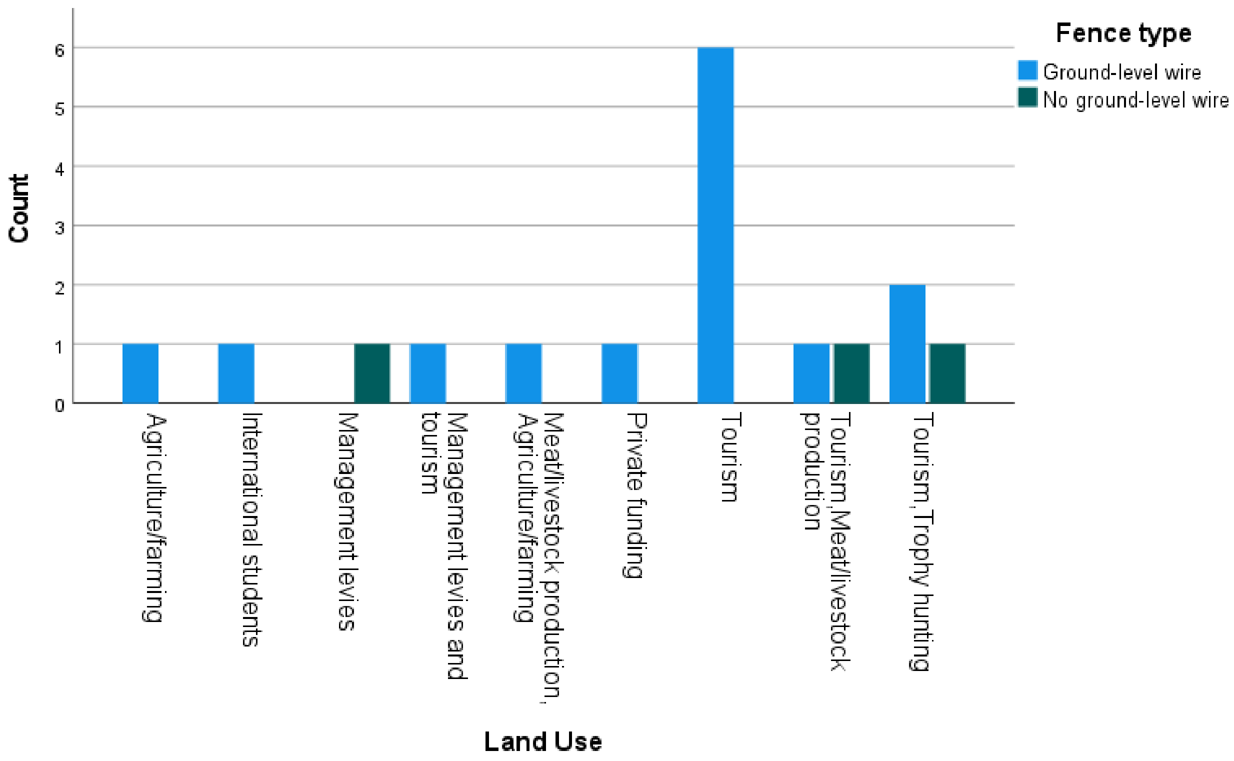


Figure A1 The number of each fence type used on land with different income sources, for all countries.

Table A4 Land purpose from responses within South Africa based on an electronic questionnaire survey.

Land purpose	Frequency	Proportion
Game ranch/reserve	21	77.8 %
Farmland	1	3.7 %
Farmland, Residential	2	7.4 %

Conservation	1	3.7 %
Wildlife rehabilitation	2	7.4 %

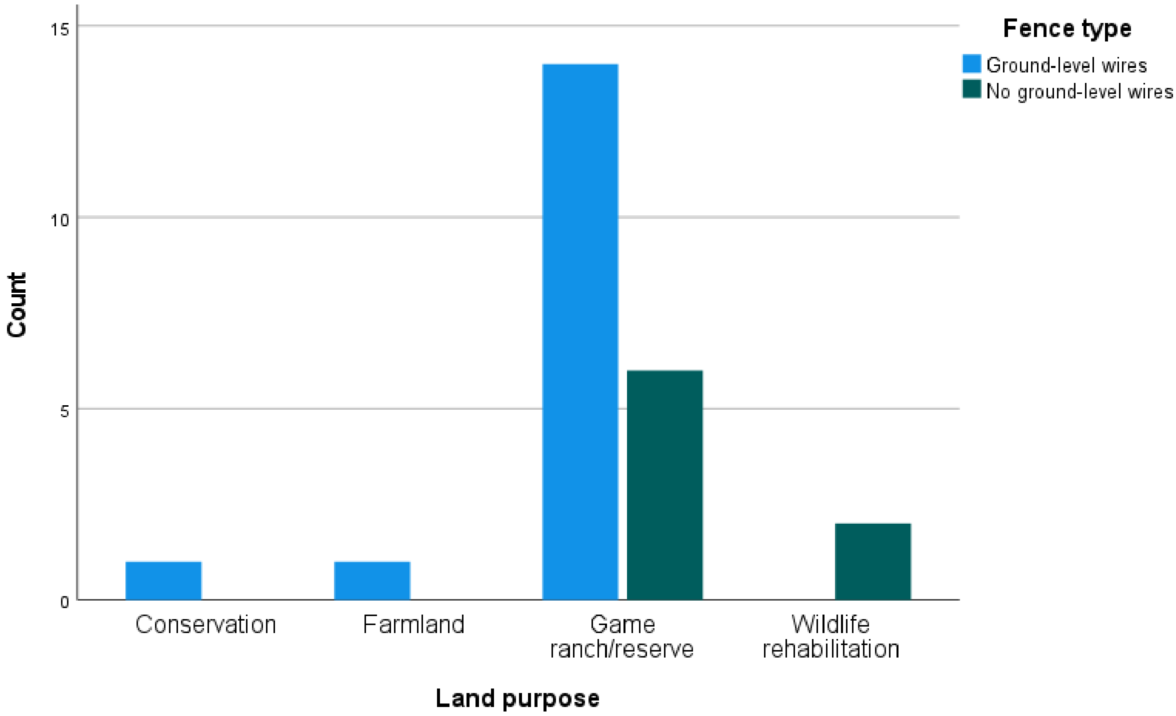


Figure A2 The number of each fence type used across different land uses for all countries.

Table A5 Summary of the reason participants utilise fences on their land in South Africa.

Fence purpose	Frequency	Proportion
To mark a land boundary, Security (keep people out),To keep animals in	13	46.4 %
To keep animals in	3	10.7 %
To mark a land boundary, Security (keep people out),To keep animals in, To keep animals out	1	3.6 %
To mark a land boundary, To keep animals in	4	14.3 %
Security (keep people out),To keep animals in	4	14.3 %
Security (keep people out)	1	3.6 %

Prevent further fence damage	1	3.6 %
Camp fence	1	3.6 %

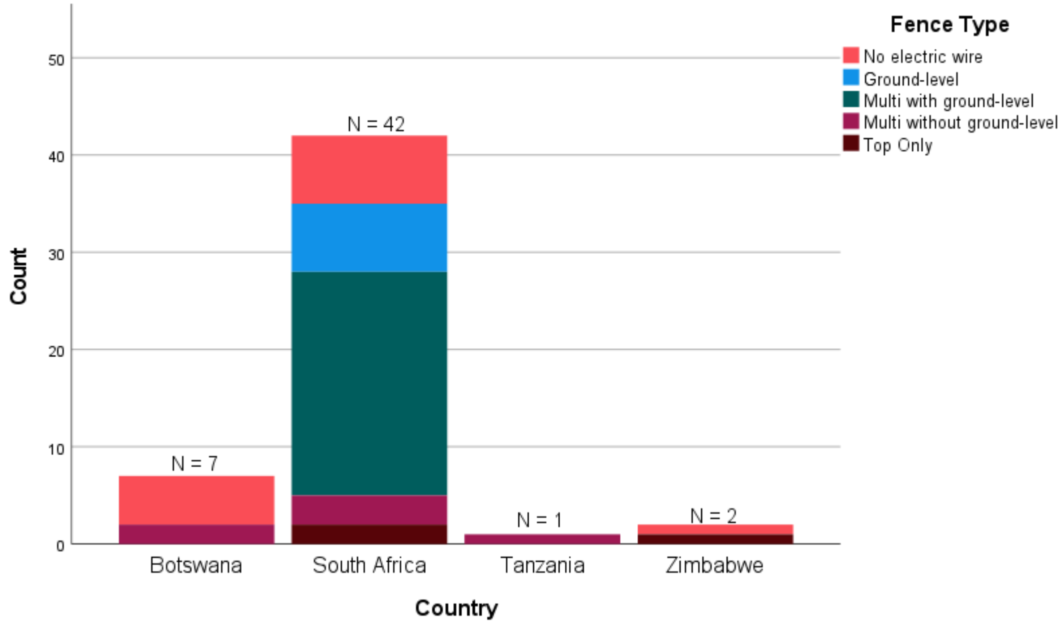


Figure A3 Frequency each fence types were used by participants from different countries. If a participant listed more than one fence type these were included separately.

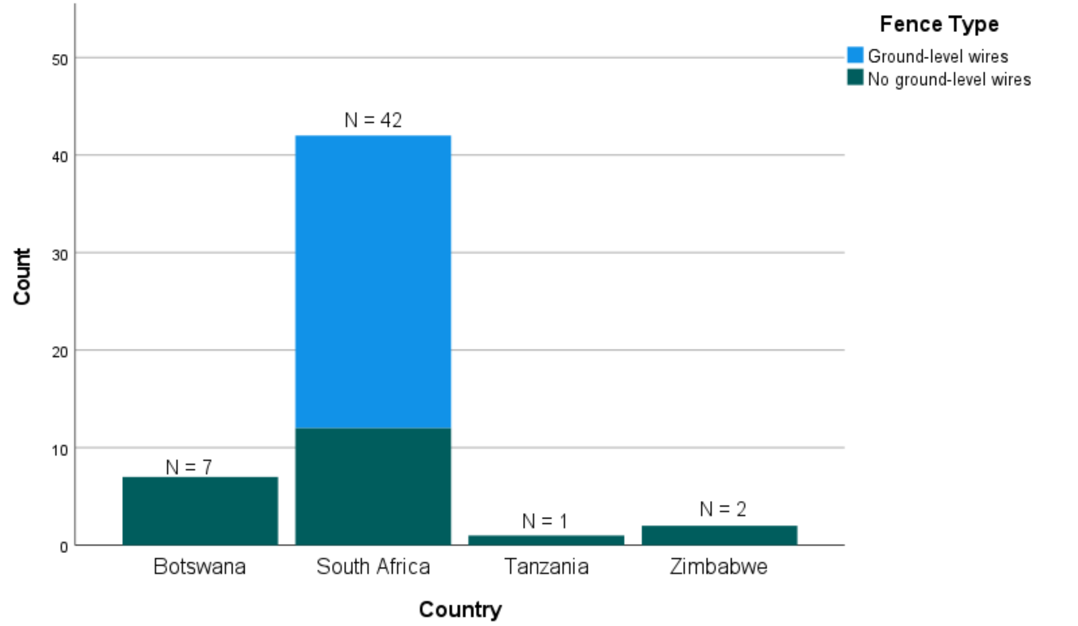


Figure A4 Frequency of each fence type used by participants from different countries. If a participant listed more than one fence type these were included separately.

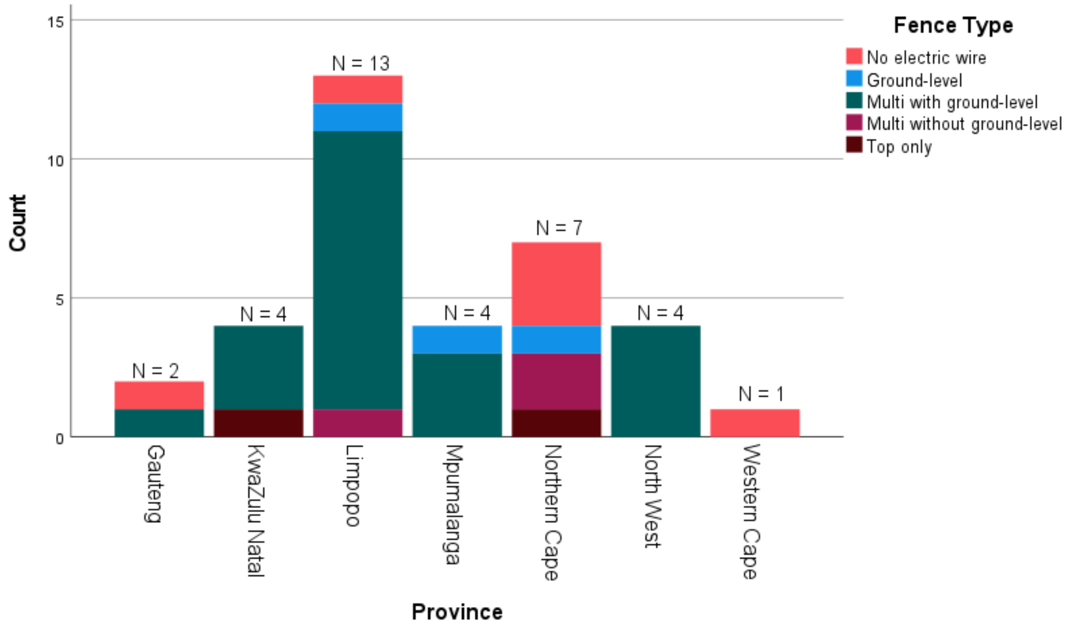


Figure A5 Fence types used by participants from different provinces in South Africa. If a participant listed more than one fence type these were included separately. All properties included, including those without pangolins.

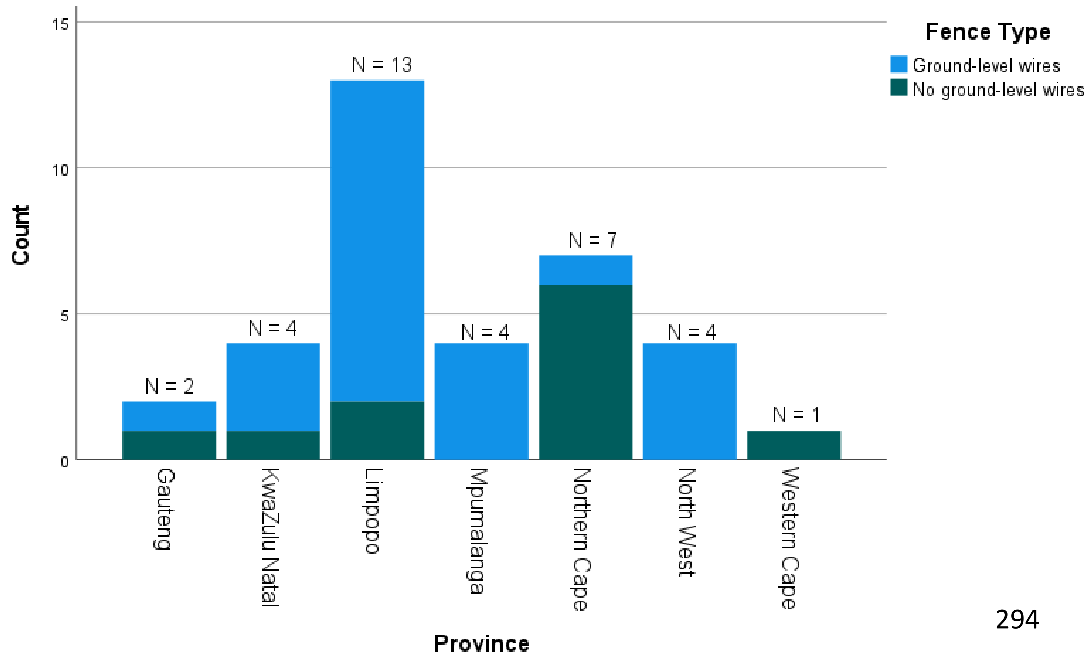


Figure A6 Frequency of fence types used by participants from different provinces in South Africa. If participant listed more than one fence type these were included separately. All properties included, including those without pangolins.

Table A6 Summary of habitat types found on participant's land in South Africa.

Habitat type	Frequency	Proportion
Savannah	22	45.8 %
Grassland	12	25.0 %
Forest	4	8.3 %
Nama-Karoo	2	4.2 %
Desert	2	4.2 %
Albany Thicket	2	4.2 %
Kalahari Thornveld	1	2.1 %
Semi-arid Savannah	1	2.1 %
Succulent Karoo	1	2.1 %
Fynbos	1	2.1 %

Table A7 Habitat types with the number of fence deaths recorded in each. Table also shows the count for each habitat type.

Habitat type	N	Mean number of killed species
Albany thicket	2	4
Forest	3	2.33
Grassland	10	3
Nama-karoo	2	3
Savannah	18	2.8

Table A8 Number of times each fence category was reported in South Africa based on an electronic questionnaire survey; this includes participants who reported more than one fence type.

Fence Type	Frequency	Proportion
No electric wires	7	16.66
Ground-level only	7	16.66
Multiple heights with ground-level wires	23	54.76%
Multiple heights excluding ground-level wires	3	7.14%
Top wires only	2	4.76%
Other	0	0

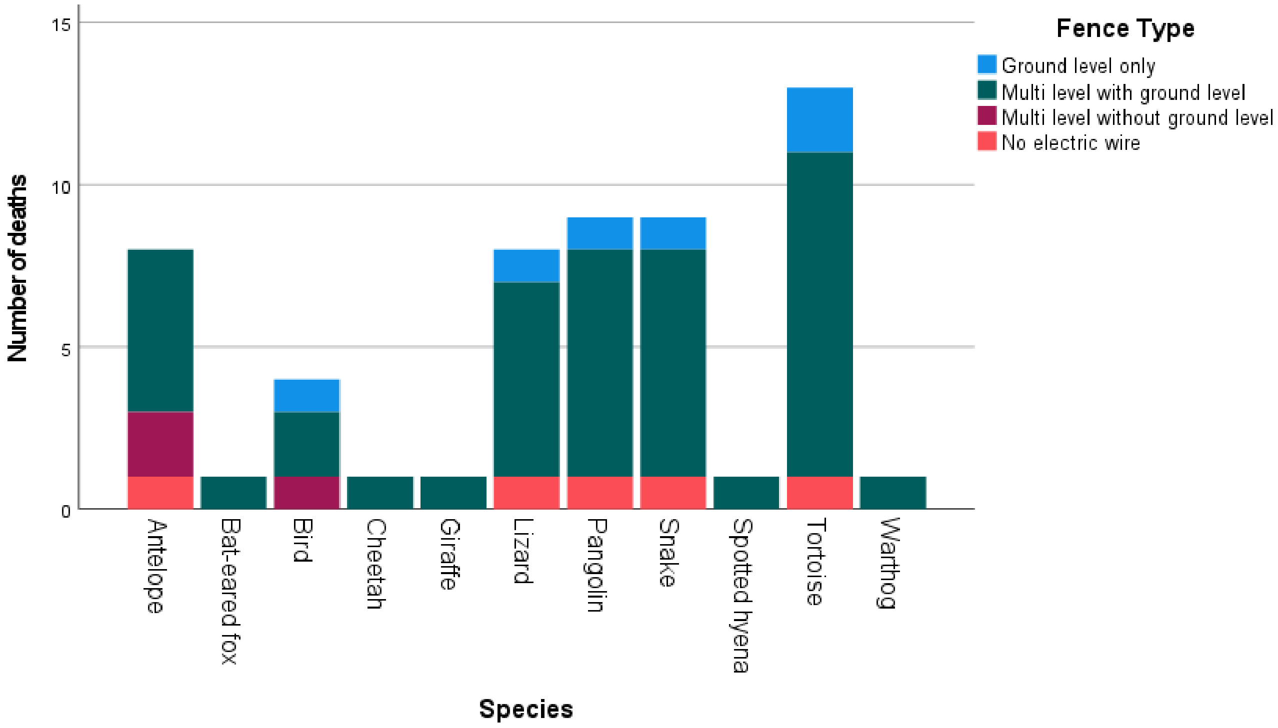


Figure A7 The number of times each species was reported as killed on each fence type. Data was filtered for fence presence. Those with more than one fence type were removed. Those without species records or with no killed species were removed. For all countries reported.

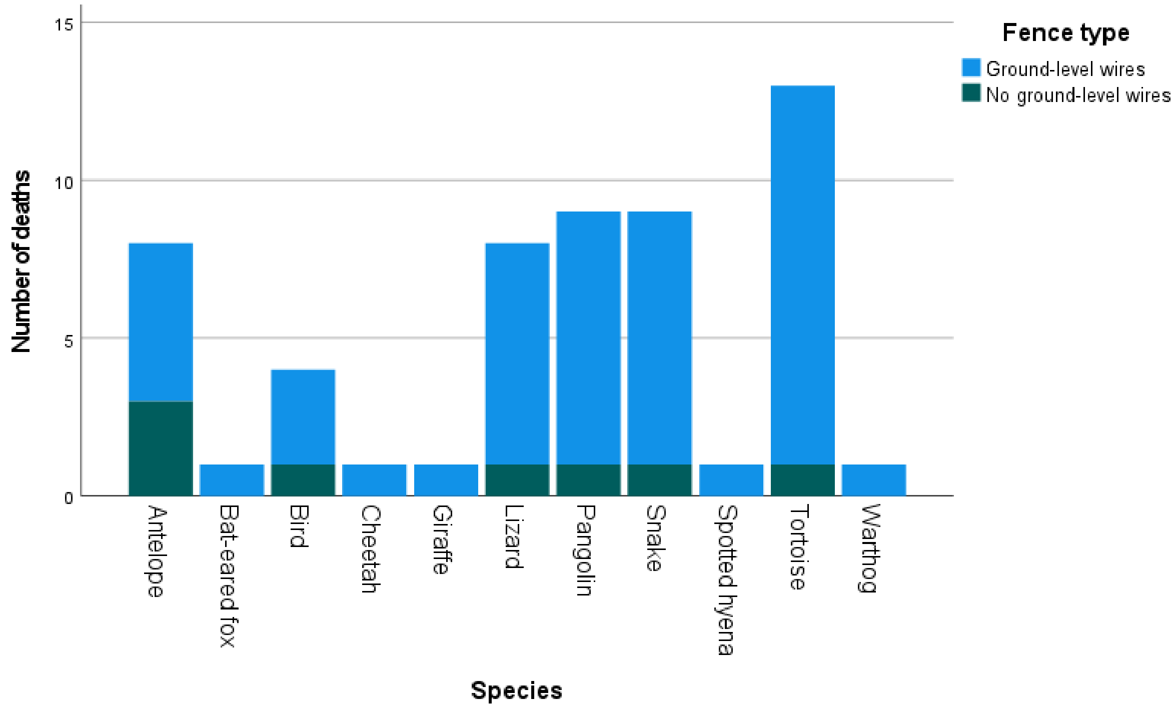


Figure A8 The number of times each species was reported as killed on fences with and without ground level electrified wires. Data was filtered for fence presence. Those with more than one fence type were removed. Those without species records or with no killed species were removed. For all countries reported.

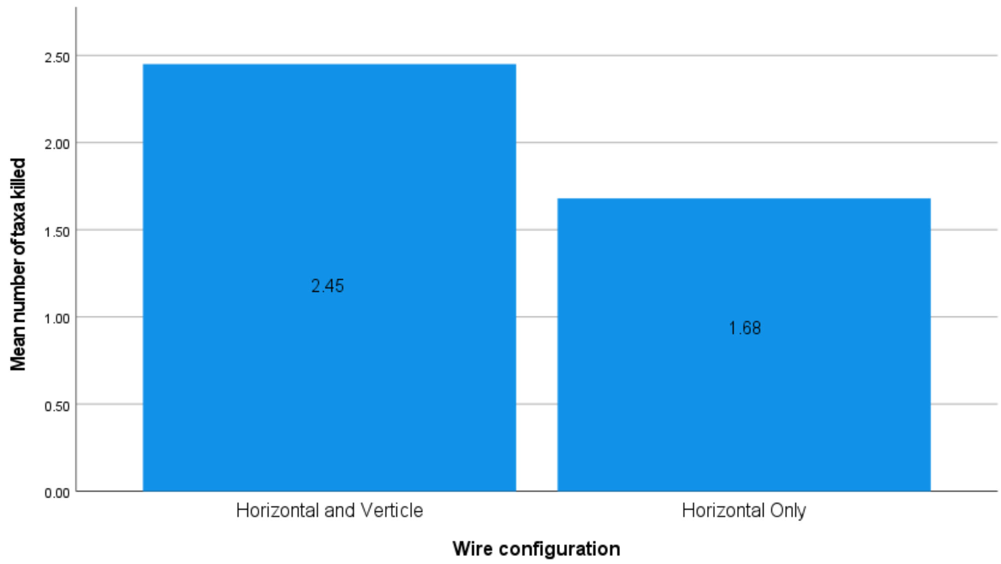


Figure A9 Histogram graph showing mean number of species killed on fences with each wire configuration in South Africa.

Table A9 Breakdown of fence modifications used by participants to reduce fence deaths in South Africa.

Mitigation	Frequency
Wire removed	3
Wire raised	2
Barrier near fence	2
No low wire	1
Earth wire	1
Low voltage on ground wire	1
Tunnel under fence	1
Wire lowered	1

Table A10 Likert concern level responses from participants who also reported the number of fence-associated mortalities that they have witnessed in South Africa.

Likert score	1	2	3	4	5	6	7	8	9	10
Count	4	3	2	2	5	1	2	0	1	6
Percentage	15.4	11.5	7.7	7.7	19.2	3.8	7.7	0	3.8	23.1