Connectivity at the Large Carnivore Scale:

The Kafue-Zambezi Interface

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Acronyms

AUC	Area Under Curve
DNPW	Department National Park and Wildlife
FR	Forest Reserve
GIS	Geographic Information System
GKS	Greater Kafue System
GMA	Game Management Area
HFP	Human footprint pressure
IUCN	International Union for Conservation of Nature
KAZA	Kavango-Zambezi
KNP	Kafue National Park
MaxEnt	Maximum Entropy
NGO	Non-Government Organisation
NP	National Park
TFCA	Transfrontier Conservation Area
WDC	Wildlife Dispersal Corridor
WMA	Wildlife Managed Area
ZAWA	Zambia Wildlife Authority

Abstract

The growth and expansion of human populations and resource demands is driving large scale fragmentation and loss of wildlife habitat, isolating wildlife populations and pushing many species towards extinction at local to global scales.

Attempts to promote connectivity between wildlife managed areas at transboundary scales has been proposed as a solution to negative effects associated with population isolation. Such approaches commonly require the maintenance of wildlife populations throughout human-dominated landscapes subject to various degrees of effective protection.

The aims of this study are to (1) assess the status of the large carnivore guild throughout ten wildlife managed areas comprising the Zambian component of Kavango-Zambezi Transfrontier Conservation Area between Kafue National Park and the Simalaha Wildlife Recovery Sanctuary on the Zambezi River; (2) model habitat suitability and connectivity in this landscape for Lion, Leopard and Spotted hyena; and (3) develop a site-specific map of human footprint pressure for the landscape and test if it can be used a proxy for determining the occurrence of these three species. And further, explore if there are thresholds in human footprint pressure beyond which species are likely extirpated from wildlife managed areas.

Methods included library studies to determine historical status of the large carnivore guild and twenty-six common prey species, spoor tracking in conjunction with qualitative surveys and supplemental data analysis to ascertain species current distribution, remote sensing with ground-truthing to build landcover maps, Maximum Entropy and Current Flow models, and extensive use of Geographic Information Systems.

The findings conclude that there have been large scale losses in species assemblages throughout majority of southern wildlife managed areas, including the Simalaha Wildlife Recovery Sanctuary. However, no detectable changes were evident in Kafue National Park and surrounding Game Management Areas. Human activities are limiting habitat suitability and scope for occurrence in central southern areas of the landscape, with the likelihood of a connectivity bottleneck occurring. There is significant overlap in habitat requirements and scope for species movement. Human footprint pressure models appear to demonstrate utility as a proxy measure for occurrence of our large carnivore subset, though require some refinements and supplemental data layers to increase predictive power. Human footprint pressure at the wildlife managed area scale indicates threshold levels at which target species occur or are locally extirpated.

Analyses have identified important additions to the existing wildlife managed area network in Open communal land that could provide valuable habitat and connectivity for target species given effective management and finance, including containment of negative human disturbance variables modelled (agro-pastoralist activities and infrastructure development). The effects of poaching are also hypothesized to be a significant driver limiting species persistence.

Continued expansion of human population, settlement and agro-pastoralist activities will limit scope for expansion of large carnivores and their principle prey throughout the Kafue-Zambezi interface, effectively severing connectivity and isolating the Greater Kafue System from adjacent wildlife managed areas in the Kavango-Zambezi Transfrontier Conservation Area.

Narratives surrounding the development of wildlife-based land uses and species-level connectivity benefit from the application of conservation science and generation of empirical data to guide management.

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Chapter 1: Introduction

1.1 Protected Areas and Protected Area Networks

Protected Areas encompassing IUCN Ia-VI categories remain for many the bedrock of biodiversity conservation. Management objectives are typically spilt between 1. Maintaining natural and cultural resources for local communities relying on natural capital within and surrounding Protected Areas, and 2. For the broader global community focused on wider cultural, economic, leisure, aesthetic and environmental well-being values (UNEP-WCMC, 2015; Barrett *et al.*, 2018). However Protected Areas are increasingly imperiled and failing to fulfil their broad mandates at multiple scales (Brandon *et al.*, 1998; Leverington *et al.*, 2010).

Evolving knowledge surrounding limitations of the existing Protected Area networks to fulfil broad ecological relevance, political resilience and social acceptance mandates has resulted in novel approaches to increase the effective spatial scale of Protected Areas, incorporating new and existing areas into larger Protected Area networks at both National and Transboundary scales (Suich *et al.*, 2012). Transfrontier Conservation Areas commonly seek to integrate wider ecosystem-scale landscapes incorporating complex and dynamic coupled socioecological management units subject to rising anthropogenic disturbance (Andersson *et al.*, 2017)

A major driver of biodiversity conservation is the establishment of many larger Protected Area networks is the promotion of functional ecological linkages between Protected Areas and the wildlife populations residing within them (Hanks, 2000; Cumming, 2008). This is especially relevant for wide-ranging low-density species of conservation concern such as the large carnivore guild requiring vast areas to secure viable populations (Woodroffe & Ginsberg, 1998; Crooks *et al.*, 2011).

The ecological effectiveness of linking and managing large-scale Protected Area networks largely concerns benefits surrounding the connection of wildlife populations and reduction of risks associated with isolation of core wildlife managed areas (Margules & Pressey, 2000; Newmark, 2008).

The effectiveness of expanding and linking Protected Areas into larger networks are multi-faceted and tempered by significant challenges. These include chronic underfunding for biodiversity conservation and management (Pringle, 2017), expanding human settlement and intensifying agropastoralist activities within and surrounding Protected Areas (Wittemyer *et al.*, 2008; Jones *et al.*, 2018), the widespread over-exploitation (legal and illegal) of wildlife and natural resources (Maxwell *et al.*, 2016), negative effects of veterinary fencing on wildlife movement (Ferguson & Hanks, 2012) and political struggle over control of key resources (Duffy, 2006).

In central Southern Africa there has been a proliferation of Transfrontier Conservation Areas (TFCAs) and 'Peace Parks' since the turn of the Millennium. While the 'Peace Park' inferences to ameliorate prospects for renewed regional conflict has perhaps reasonably been portrayed as 'palliative rhetoric' (Murphree, 2017), broader goals are likely worthy and justified. These include an antidote to the multifaceted problems of Colonial-era boundaries bisected ecosystems, wildlife populations and communities, and addressing socio-economic marginalization of people living on the boundaries of Protected Areas (Andersson *et al.*, 2017).

1.2 The Kavango-Zambezi Transfrontier Conservation Area and Greater Kafue System

The Kavango-Zambezi Transfrontier Conservation Area (KAZA TFCA) spans >500,000 km^2 at the interface of Angola, Botswana, Namibia, Zambia and Zimbabwe (KAZA, 2011a). The landscape broadly encompasses the basins of the region's two largest river systems, the Kavango and Zambezi, giving the KAZA TFCA its name.

Concurrent with many of the subcontinent's other TFCAs, KAZA's stated objectives focus on integrating conservation and development, promoting cooperation and facilitating connectivity of ecosystems and wildlife populations (KAZA, 2011a). And again, the challenges facing this complex, dynamic and coupled socio-ecological system are manifest, and broadly similar to other regional TFCAs - mounting anthropogenic pressure, poor land use planning, institutional conflicts and stakeholder disenfranchisement (Andersson *et al.*, 2017) are driving human encroachment and disturbance around and into former wildlife areas, resulting in habitat loss and fragmentation (Watson *et al.,* 2015; Newmark, 2008; Simukonda, 2008). Unsustainable harvesting of wildlife threatens many of the Kavango-Zambezi TFCA's iconic natural assets critical to the development of wildlife-based land uses options and natural economies (Funston *et al.,* 2013).

With the region's human population expected to double by 2050 (UN, 2019), and likely impacts of climate change exacerbating socioeconomic development challenges (Pachauri *et al.,* 2014; Bellard *et al.,* 2012), even moderately optimistic scenarios imply regional biodiversity loss will accelerate significantly this century without drastic increases in funding and political support (Biggs *et al.,* 2008).

Collectively these challenges raise important questions surrounding the scope, scale and ambition of narratives promoting landscape-level linkages, the interventions required to maintain or expand connectivity, and what purposes these proposed linkages may serve in the long term (Cumming, 2008). A clear imperative thus exists to promote evidence-based socioeconomic and environmental policies and interventions built around the application of conservation science (Sutherland *et al.*, 2004), including research and monitoring of changes to site and system states and their response to factors driving connectivity at the scale of interest. But the process of informed decision-making is data hungry. Local, regional and transboundary data sources are disparate and inconsistent, undermining attempts to understand complex socioecological systems such as the Kavango-Zambezi TFCA (Cumming, 2008). Data deficiencies ultimately constrain effective decision making and appropriate interventions to promote biodiversity conservation and development.

The Kavango-Zambezi TFCA's boundaries are imprecise. However, Cumming (2008) characterizes the TFCA as comprising a matrix of >70 wildlife managed areas in eleven IUCN Categories covering strict National Parks under State control with no (legal) human settlement, through various designated hunting area categories (some unsettled and others under Communal tenure and subject to extensive subsistence agriculture), through to multiple use Communal Conservancies under Customary management of local Traditional Authorities in their respective Chiefdoms. In total some 76% of the KAZA TFCA is categorized as wildlife managed areas, 22% of which falls within Protected Areas with no human settlement (fully protected), 54% falls within settled hunting areas and Community Conservancies (partially protected), and the remaining 34% is covered by Communal areas (nominally protected), including small portions of urban and extra-urban development.

Collectively these wildlife managed areas fall into three main clusters centered on the region's major National Parks – Kafue, Chobe and Hwange (Figure 1.1), and five peripheral sub-clusters, with Kafue National Park and surrounding wildlife managed areas constituting the major northern cluster and focus of my study.

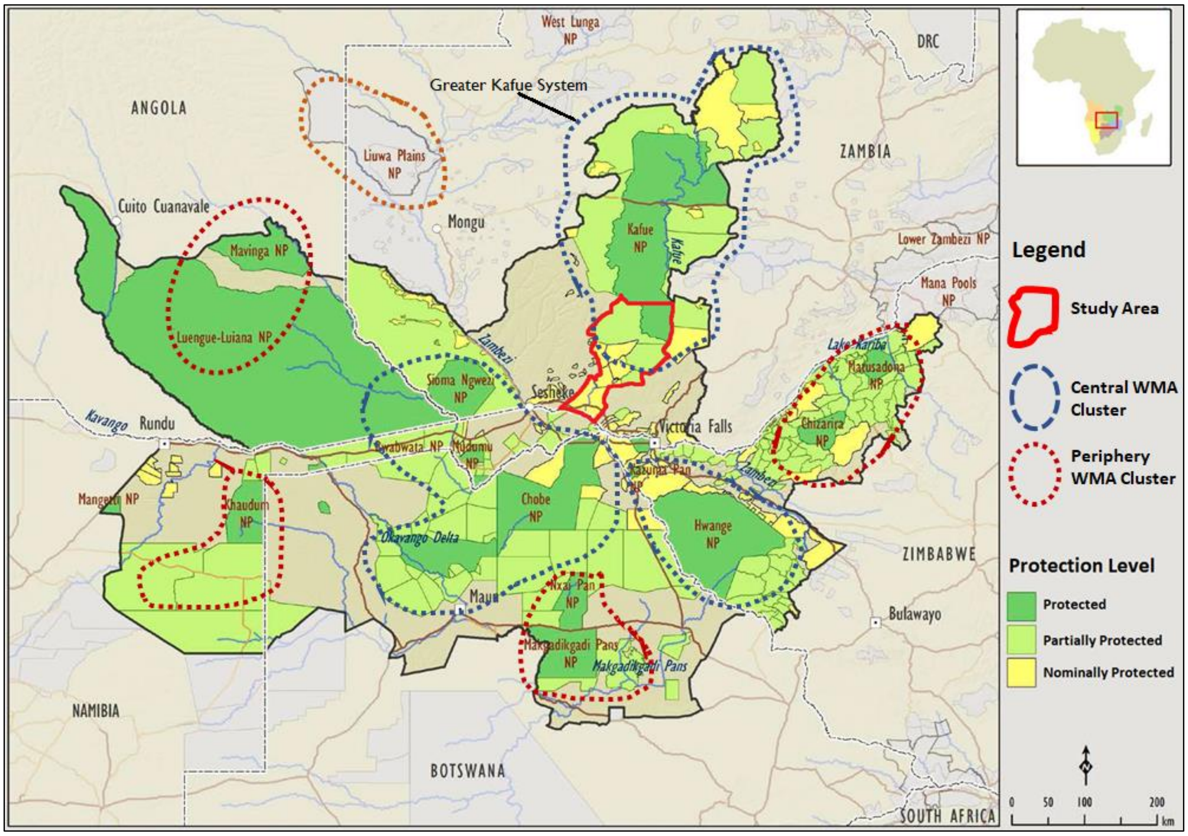

Figure 1.1. The Kavango-Zambezi Transfrontier Conservation Area landscape, indicating study area, clusters of wildlife managed areas (WMAs) and their degrees of protection. Protected = National Parks IUCN II; Partially Protected = IUCN III-VI; Nominally Protected = IUCN *Not Reported* (*adapted* from PPF, 2011a).

While at a Regional scale Southern Africa scores fairly well against a global index of megafauna conservation, conservation effectiveness throughout major wildlife managed areas across the KAZA TFCA is broadly considered weak and underfunded, with data showing five major Protected Areas receiving between 9-39% of estimated budgets required for their effective operation (Lindsey *et al*., 2017). Given limits to information systems and data access, even for key species of conservation concern, combined with heavily constrained State funding for core National Parks, it is clear budgets and resources for broader wildlife managed areas under Communal and Customary tenure are woefully inadequate (Cumming, 2008).

1.3 Study Area - The Kafue-Zambezi Interface

Historical drivers impacting species distribution and connectivity:

In developing a holistic understanding of landscape connectivity in the Kafue-Zambezi interface my research sought to identify significant historical events that have shaped the contemporary landscape. This provides a foundation for interpreting current drivers impacting resource demands, land use and development pathways that will shape longer term prospects for large carnivore conservation and connectivity throughout this study area and the wider KAZA TFCA.

The mosaic of land uses and ownership at the Kafue-Zambezi interface represent a complex, dynamic, coupled human-nature system with a written history covering a mere 160 years, though oral history predates this to c.1700 at the arrival of the Bantu people from the Congo-basin region (Gann, 1969). The Bantu migration largely displaced resident San Bushmen around the late Nineteenth Century after occupying the broader landscape for at least 20,000 (and possibly over 70,000 years), leaving only remnants of their rock art as sole evidence of their historical relationship with the landscape and its natural resources (Suzman, 2001). Following the Bantu migration into Zambia I have relied on historical texts from early explorers, hunters, traders and missionaries that have left a trail of grey literature and few formal texts on the areas' history, wildlife, people, commerce and politics to frame the study area (e.g. Martelli, 1970; Sampson, 1972; Ansell, 1978; MacKenzie, 1997, Calvert, 2005; Macmillan & Hugh, 2005).

Major events shaping wildlife diversity and distribution in the Kafue-Zambezi interface can broadly be broken down into the effects of commercial hunting, especially ivory and rhino horn, in the late Nineteenth Century (e.g. Sampson, 1972), followed by the Rinderpest Panzootic of the early 19th century that decimated game and livestock populations (Roeder *et al.,* 2006). These events were followed in the early 20th century by increased pressures on habitat and wildlife associated with the development of the Zambezi Sawmills, the Livingstone-Mulobezi railways and additional transport and settlement infrastructure (Calvert, 2005). Zambian Independence in 1964 saw the deprioritizing of wildlife conservation versus other development priorities (Gibson, 1999) at around the time the Angolan Bush War (1966-1989) expanded into southwestern Zambia. During this conflict foreign combatants set up encampments in the broader Simalaha area and used it as a base to exploit local wildlife for rations and profit. Following cessation of hostilities small arms proliferated, and in conjunction with expanding human population and limited funding for law enforcement and natural resource management, ongoing unsustainable harvesting of wildlife continued (Inyambo-Yeta, *pers comms*).

Based primarily on the research of Ansell (1978), and notwithstanding likelihood of non-detection error, we can be confident that prior to the Angolan Bush War focal species existed throughout the Kafue-Zambezi interface, and the landscape should thus be considered connected at the large carnivore scale.

Contemporary drivers impacting species distribution and connectivity:

Kafue National Park is Zambia's oldest and largest Protected Area at 22,480 km^2, the largest IUCN Category II National Park in the Kavango-Zambezi TFCA and second largest throughout Africa (UNEP-WCMC, 2015). Kafue National Park is surrounded by nine IUCN category VI Game Management Areas and multiple Forest Reserves with no bordering fences inhibiting wildlife movement, creating a single effective wildlife managed area, variously termed the Greater Kafue Ecosystem or System covering c.68,000 km^2, marginally smaller than Scotland, or about half the area of England or Greece (Fig 1.2).

Formally unsettled (fully) Protected Areas cover 33% of this landscape, with the remaining 67% under Customary tenure of local Chiefdoms. Of this 35% is settled (partially protected) Game Management Areas, 3% is registered Communal Conservancies and 10% State Forest Reserves, all of which are considered potentially partially protected in light of significant funding and management constraints over the long term. The remaining 19% encompasses further Open Communal area and heavily settled former wildlife managed areas, now converted to agro-pastoralism and degazetted from the Zambia's formal wildlife estate.

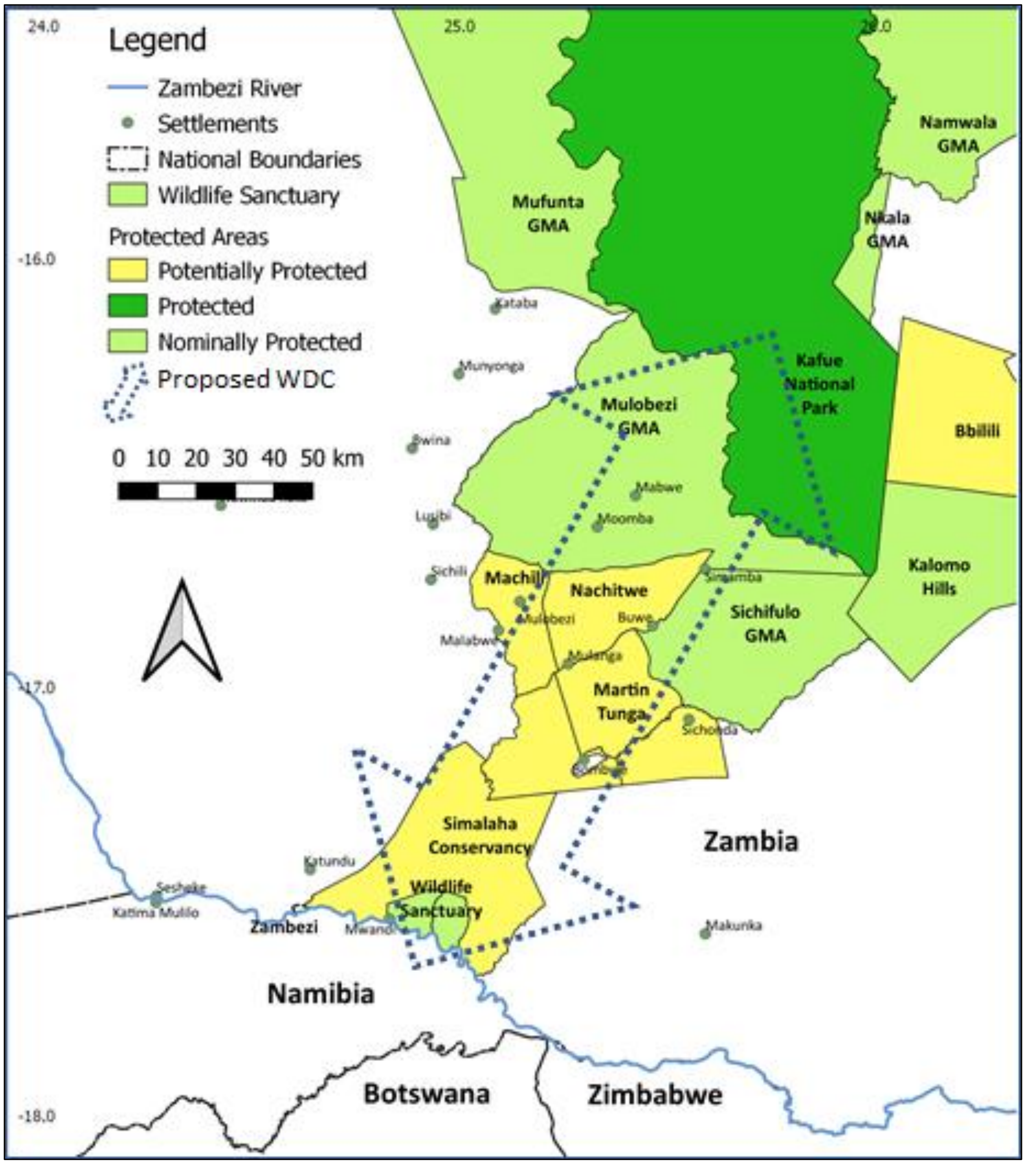

Figure 1.2. Protected Areas, Kafue-Zambezi Interface, indicating proposed Wildlife Dispersal Corridor (WDC).

Broadly, according to Lindsey *et al.* (2014), Kafue National Park and surrounding Game Management Areas are under-performing in socioecological and economic perspectives due to effects related to a rapidly expanding human populations, stubborn poverty levels and *de facto* open-access systems in Game Management Areas. This results in widespread bushmeat poaching and habitat encroachment which underfunded and under-resourced

State Authorities struggle to manage. State Authorities also extract revenues from Game Management Areas to cover shortfalls in operational costs, limiting sufficient devolution of user-rights over wildlife to communities, marginalizing their legal benefits from wildlife and disincentivizing wildlife conservation over other land uses and livelihood opportunities. Additionally, the photo-tourism industry is under-developed, and unfavorable terms combined with corruption discourage investment and good practice by hunting operators. Finally, blurred responsibilities surrounding anti-poaching in Game Management Areas drives under-investment by all stakeholders. In combination these challenges have resulted in major wildlife reductions in Kafue National Park and surrounding Game Management Areas, and a loss of wildlife habitat in the Game Management Areas.

Most of the Greater Kafue System lies between 900-1100 m above sea level. Rainfall averages 650 mm in the south and 1,050 mm in the north, falling predominantly from November to April. Vegetation is characterized by the Zambezian Miombo woodland Ecoregion, typical of large areas throughout southern and eastern Africa, dominated by *Brachystegia* spp., *Combretum* spp., *Mopane* spp., *Terminalia* spp. and *Baikaea* spp. characteristic of substrate and precipitation. Woodlands are interspersed by open floodplain grasslands and drainage lines (ZAWA, 2010). Species records include 158 mammals, 481 birds, 69 reptiles, 35 amphibians and 58 fish, with the greatest antelope diversity of any African National Park (21 species), an intact carnivore guild and a full complement of Zambia’s large mammals with exception of Giraffe (*Giraffa giraffa*), Black Rhinoceros (*Diceros bicornis*) and Tsessebe (*Damaliscus lunatus*) (Ansell, 1978; Moss, 2012).

The Greater Kafue System has been included as Zambia's majority component within Kavango-Zambezi TFCA (KAZA, 2014). Proposed connectivity to the broader Kavango-Zambezi landscape is contingent on development or maintenance of a landscape level linkage routing south-southwest from the Kafue National Park border through a mosaic of nominally, potentially and possibly protected wildlife managed areas including Mulobezi and Sichifulo Game Management Areas, Nachitwe, Martin and Machili Forest Reserves, the Nyawa communal areas, and the recently proclaimed Simalaha Communal Conservancy including the fenced Simalaha Wildlife Recovery Sanctuary. In concert these wildlife managed areas extend the Greater Kafue System to around 7.3m ha.

A secondary (south-westerly) linkage passing through Mulobezi to Sioma National Park (bordering Namibia and Angola) has been proposed, though our focus remains the linkage broadly following the Machili stream catchment basin from the southern Kafue National Park border (S16.1380, E25.3650) to the northern bank of the Zambezi River in the Simalaha Wildlife Recovery Sanctuary, bordering Botswana and Namibia (S17.5550, E24.9770) (KAZA, 2014).

The proposed landscape linkage varies in length from 140-170 km. The human population is around 110,000 and growing at 2.5% pa, with a population density ≈4.0/km^2 (CSO, 2019). Communities are centered on a few larger settlements of 5,000-10,000 residents, and otherwise in clusters of scattered villages typically concentrated along water courses, seasonal waterholes, and few majority hand-pumped ground water supplies. Subsistence agro-pastoralists dominate this landscape, with residents largely dependent on exploiting a wide range of the area's natural resources in support of basic livelihood needs (Musgrave, 2016). Formal employment opportunities beyond the distant urban settlements of Sesheke and Livingstone are negligible. Customary law within the Lozi, Nkoya, and Tonga ethnolinguistic groups represent the *de facto* regional governance system under Chiefdoms (Brelsford, 1965; Musgrave, 2016).

Biodiversity conservation funding varies widely around a low mean throughout this landscape, as with the broader KAZA TFCA. While precise figures are unavailable, Lindsey *et al.* (2017) suggests Kafue National Park operates with 10-15% of recommended budgets for large African Protected Areas yet has the highest funding for biodiversity conservation throughout our study area. This is followed by Mulobezi then Sichifulo Game Management Areas which receive minor budget allocations from the Department of National Parks and Wildlife, augmented by finance and in-kind operational support from resident safari hunting operators and other conservation actors, including local and international NGO's. Nachitwe, Martin and Machili Forest Reserves have intermittently received minor budgets from the Provincial Forestry Offices (ZAWA, 2010; Chifunte, *pers comms*). The recently proclaimed Simalaha Communal Conservancy only started receiving any formal wildlife resource protection as recently as 2013 following no formal biodiversity conservation budgets since the Angolan Bush/South African Border War spilled over into Zambia in the early 1970's (Inyambo-Yeta, *pers comms*). As part of the Simalaha Communal Conservancy initiative a 240 km^2 fenced Wildlife Recovery Sanctuary stocked with >600 head of game has been built, funded by an international NGO. This significant investment is being promoted as part of a programme for developing wildlife-based land uses throughout the broader Simalaha Communal Conservancy (PPF, 2019). It is unclear if the Nyawa Communal areas receives any formal wildlife management budget or support.

1.4 Connectivity and Large Carnivores in the KAZA TFCA

Fragmentation and loss and wildlife habitat has direct effects on landscape structure by isolating habitat patches and restricting or severing organism-scale movements between patches (Taylor *et al.,* 1993). As habitat fragmentation and loss expands any remaining natural areas are partitioned into ever smaller, more isolated patches within an expanding human-modified matrix, creating increased barriers to movement (Crooks *et al.,* 2011). These barriers limit resource access for wildlife, including seasonal water sources, hunting and foraging areas, refugia and breeding sites (Crooks & Sanjayan, 2006). At larger spatio-temporal scales barriers can impact adaptive responses to broader drivers including climate change (Heller & Zavalenta, 2009). Barriers limiting ecological processes surrounding immigration, emigration and dispersal, constrains gene flow and genetic health within and between populations (Brook *et al.,* 2002).

Large carnivores are especially vulnerable to habitat loss and fragmentation due to intrinsic biological traits - large body size and extensive home range requirements, low densities and slow population growth rates (Cardillo *et al.,* 2005), combined with external anthropogenic threats including effects of legal and illegal persecution (Balme *et al.,* 2009) and prey depletion (Wolf & Ripple, 2016). Together these drivers create edge effects (Woodroffe & Ginsberg, 1998) and ecological traps limiting effective refugia from direct and indirect human disturbance (Pitman *et al.,* 2015) and constraining species ability to persist in landscapes without functional linkages or a permeable matrix between suitable habitat (Crooks *et al.,* 2011).

Consequently, connectivity between wildlife managed areas is widely considered fundamental to the long-term survival of majority large carnivore populations beyond the very largest or intensively managed Protected Areas (Woodroffe & Ginsberg, 1998; Bauer *et al.*, 2015). Promoting landscape-level connectivity has been identified as a key management objective for wildlife managed area networks, including dominant narratives behind the development of the KAZA TFCA Programme (Van der Meer *et al.*, 2016; KAZA, 2018).

A core objective of the KAZA TFCA is to:

"…*ensure connectivity between key wildlife areas, where necessary, join fragmented wildlife habitats in order to form an interconnected mosaic of Protected Areas, as well as restore transboundary wildlife migratory corridors between wildlife dispersal areas. These corridors re-establish and conserve large-scale ecological processes that extend beyond the boundaries of Protected Areas*" (KAZA, 2014).

And in the Zambian component of the KAZA TFCA similar explicit connectivity objectives are identified:

"*to join fragmented wildlife habitats into an interconnected mosaic of Protected Areas and transboundary wildlife corridors, which will facilitate and enhance the free movement of animals across international boundaries*." (ZAWA, 2008)

Empirical movement and connectivity studies are a relatively novel addition to our understanding of natural resource management in the KAZA TFCA, and mainly limited to elephant and large herbivore movements (e.g. Naidoo *et al.*, 2012 & 2018; Metcalfe & Kepe, 2008; Gerhardt-Weber & Katharina, 2011). While much anecdotal evidence and grey literature supports transboundary movement of large carnivore throughout the KAZA TFCA (KAZA, 2018), published literature is scarce. The work of Elliot *et al.* (2014) and

Cushman *et al.* (2016 & 2018) provide a substantive body of work surrounding lion movement and connectivity models at the broader KAZA TFCA scale based on intensive studies from one population. In reality few data support broader connectivity and directed movements maps for large carnivores across much of the KAZA TFCA landscape beyond aspirational maps (Figure 1.3). The Kafue–Chobe Wildlife Dispersal Corridor is a case in point with no existing evidence of wildlife movement, or species-level studies from this landscape.

Figure 1.3. KAZA TFCA Wildlife Dispersal Corridors (KAZA 2014).

1.5 Focal Species: Large Carnivores

The large carnivore guild are an iconic group of apex predators (Wallach *et al.,* 2015) and an integral component of complex food webs, driving ecosystem function, structure and resilience by exerting top-down regulatory pressures on prey and their habitats (Estes *et al.,* 2011; Ripple *et al.,* 2014). They also represent a pivotal resource in the promotion of wildlife-based land uses, including tourism (Funston *et al.,* 2013), thus serving a multitude of ecological, socio-economic and political functions (Chapron & Lopez-Bao, 2014).

As apex predators at the top of the food chain large carnivores exist at low densities, even in ideal conditions (Gittleman & Harvey, 1982). Their wide-ranging behaviour and feeding habits commonly bring them into conflict with human due largely to real or perceived threats to human lives and their livelihoods, and broader competition over shared resources (Treves & Karanth, 2003). Direct and indirect human disturbance pressures on the large carnivore guild is driving loss and fragmentation of habitat (Crooks, 2002), reduction of wild prey base (Wolf & Ripple, 2016) and widespread persecution (Woodroffe, 2000). In concert, intrinsic biological traits and exposure to external human pressures is driving dramatic declines in range and population for the majority of species and increasing extinction risk, even within and surrounding formally Protected Areas designated to conserve them in the long term (Cardillo *et al.,* 2004; Woodroffe & Ginsberg, 1998).

The Kafue-Zambezi landscape is known from historical (Ansell, 1978) and contemporary records (Lines *et al.,* 2018) to maintain an intact large carnivore guild, incorporation Lion (*Panthera leo*), Leopard (*Panthera pardus*), Cheetah (*Acinonyx jubatus*), African wild dog (*Lycaon pictus*) and Spotted Hyena (C*rocuta crocuta*). Initially we attempted to model habitat suitability and connectivity for all five species known from the landscape based on a pilot study to determine optimal sampling effort to detect target species and cover the landscape in a single field season within an occupancy framework (Lines & MacKenzie, *unpublished data*), though detection probability for African wild dog and cheetah proved too small to generate sufficient data beyond occurrence, and we decided to omit these two species for further analyses.

1.5.1 African Lion (Fig 1.4) are amongst our most well-known and iconic large mammals, characteristic of Savanna and woodland biomes to which most populations are now restricted to (Riggio *et al.*, 2013). Lion are the most social of the felid family with related females forming the basis of prides and related and unrelated males, singularly or in coalitions, competing over pride tenure. Pride size averages four to six adults plus sub-adults and cubs (Schaller, 1976). While lions tend to live at higher densities than most other felids, the density of animals in resident populations varies dramatically from 0.5 adults/100 km^2 in the semi-desert of northwest Namibia to 55/100 km^2 in parts of the Serengeti (Sunquist & Sunquist 2017). Pride range varies from 266 km^2 to 4,532 km^2 (Bauer *et al.*, 2016). In the absence of significant human pressures both density and home range is heavily influenced by availability of preferred prey- medium to large bodied mammals (Hayward & Kerley, 2005).

Figure 1.4. Lions mating, Kafue National Park. *Credit R. Lines.*

Lions are one of few species known to prey on humans, though such events are rare (Packer *et al.,* 2007). Where lions and human coexist, interactions are typically characterized by conflict (Sillero-Zubiri & Laurenson, 2001; Thirgood *et al.,* 2005). Such conflict has resulted in large scale declines in lion population size and distribution, and the species are categorized as ‘Threatened/Vulnerable A2abcd’ and declining, numbering 23,000-39,000 adults and yearlings across Africa. This represents a 42% decline over 3 generations (22.3yrs) based on longitudinal data from 47 well-studied sub-populations (Bauer *et al.,* 2016). But course-scale analyses mask significant variation within and between countries and by sub-populations. The KAZA TFCA maintains 13 lion conservation units (Bauer *et al.,* 2016) and the Okavango-Hwange complex has one of Africa’s 10 remaining lion ‘strongholds’ (Riggio *et al.,* 2013). Data on lion in the Greater Kafue System is patchy, with studies restricted to northern sections of Kafue National Park (Midlane, 2014). This study represents the only systematic body of work for southern Kafue including the mosaic of land uses through to the Zambezi River.

1.5.2 *Leopard* (Fig 1.5) represents the smallest of four species in the *Panthera* genus. They are largely solitary and highly adaptable, with the widest range of all wild cats. Populations are found throughout sub-Saharan Africa, the Middle East, and South Asia to the Russian Far East (Stein & Hayssen, 2013). Leopard's behavioral plasticity allows them to exist across a wide variety of habitats including forest, woodland, mountain, savanna and semiarid environments, with some the highest densities recorded in suburban and extra-urban areas (Jacobson *et al.,* 2016). Diet reflects the species behavioral plasticity with a preference for small to medium sized ungulates, though leopard readily eat fish, reptiles, insects and birds (Hayward *et al.,* 2006). In human dominated landscapes domestic animals, including dogs and livestock, can form a large part of leopard prey, causing much human-leopard conflict (Mukherjee *et al.,* 2001; Athreya *et al.,* 2014). Attacks on humans, provoked or otherwise, are considered rare in southern Africa (Dunham *et al.,* 2010), though extensive records of man-eaters and attacks on humans exist elsewhere (e.g. Corbett & Gobetti, 1946).

As with lion, leopard population density broadly tracks preferred prey biomass and habitat productivity (Hayward et al., 2007; Macdonald & Loveridge, 2010), varying 300-fold from 0.1 – 30.9 individuals/100 km^2 (Boast & Houser, 2012; Edgaonkar, 2008), complicating reliable estimation of global population numbers across their range (Jacobson *et al.,* 2016).

Despite leopard's wide distribution the IUCN lists them as "Vulnerable A2cd" and several Asian subspecies are listed as Endangered (Stein *et al.*, 2017), with many sub-species in decline throughout much of their range (Jacobson *et al.,* 2016). The causes of these declines are almost entirely anthropogenic: direct persecution (Thorn *et al.*, 2013), illegal wildlife trade including skins for cultural regalia (Datta *et al.*, 2008, Balme, *unpublished data*), poorly managed trophy hunting (Balme *et al.*, 2009), prey declines (e.g. Lindsey *et al.*, 2012; Selvan *et al.*, 2014) and habitat fragmentation (Gerland *et al.*, 2014).

Stein *et al.* (2016) estimates a >30% worldwide range loss for the species in the last three generations (22.3 years), and 21% range loss in southern Africa.

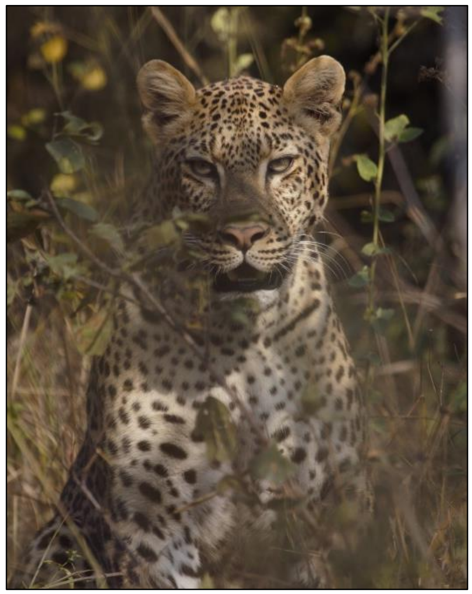

Figure 1.5. Male leopard, Kafue National Park. *Credit: R. Lines*

Knowledge of leopard in and around Kafue is limited to historical studies (Mitchelle, 1965; Ansell, 1979; Bertram, 1982), and in broader scale analyses studying the impact of the bushmeat poaching crisis (Lindsey *et al.*, 2013). While research suggests ungulate populations have perhaps increased by 24% across southern Africa as a whole (Craigie *et al.*, 2010), finer scale analyses in Zambia indicates severe reductions in Leopard’s principle prey inside and outside of Protected Areas (Lindsey *et al.*, 2014; Watson *et al.*, 2015). Zambian Game Management Areas and National Parks maintain large mammal populations at 93.7% and 74.1% below estimated carrying capacity (Lindsey *et al.*, 2014), with severe implications for all large carnivores.

1.5.3 The Spotted hyena (Fig 1.6) is a highly social and adaptable species, and the sole extant representative of the *Crocuta* genus. Spotted hyena live in matrilineal clans and are found in a wide range of habitats from desert, to mountain, savannah and woodland (East & Hofer, 2013). Sub-populations can be found in close proximity to human settlements, notably in Ethiopia where co-existence with humans has a strong cultural/spiritual association (Yirga *et al.*, 2016; Abay *et al.*, 2011). Early misconceptions surrounding their scavenging habits have long been dispelled, and Spotted hyena are now understood to be flexible and successful hunters, preying on a wide range of species, alongside their scavenging abilities (Kruuk, 1972; Höner *et al.*, 2005). As with leopard they can also prey on domestic animals, causing similar human-wildlife conflict, though attacks on humans are rare (Bohm & Höner, 2015; Butler *et al.*, 2013).

Clan size varies from 5-80 individuals with densities ranging from 0.6-240/100 km^2 – exhibiting even greater variability than leopard (Hofer & Mills 1998). Home ranges vary from 13 km^2 to 1,065 km^2 from high prey areas in productive habitat, to semi-desert (Holecamp & Dloniak, 2010). Clan size and density are considered related to food availability and primary production (Hayward *et al.,* 2006; Mills, 1990).

The IUCN provides a global population estimate of 27,000-47,000 adults, classifying the species as ‘Least Concern’, though there is much uncertainty in status within and between countries and sub-populations, and a reassessment is current underway incorporating data from this study (Weise, *pers comms*). Nonetheless the majority of southern Africa’s larger Protected Area populations, and several populations in eastern Africa, are considered stable

(Bohn & Honer, 2015). But beyond, and increasingly within Protected Areas, direct and indirect persecution is common. Spotted hyena are notable bycatch in snares set for ungulates, as with other large carnivores (Lindsey *et al.*, 2013), and this can be the cause of majority adult mortality (Hofer *et al.*, 1996). Spotted Hyaenas are also susceptible to mass poisoning events as both target species and as bycatch (Holekamp *et al.*, 1993). While the numbers of hyena killed by sport hunting is low, impacts of legal off take can be drastic as hunters tend to target the largest individuals, commonly the alpha females, with severe implications for clan structure and breeding (Cozzi *et al.*, 2015). Hyena are also killed for food, medicine and witchcraft in many countries (Hofer & Mills 1998). As with most large carnivores hyenas are also threatened by prey reduction, habitat loss, overgrazing by livestock and game-meat hunting by humans (Bohn & Honer, 2015).

Figure 1.6. Spotted Hyena, Mulobezi Game Management Area, Zambia. *Credit: R. Lines.*

There have been few formal studies on Spotted hyena in Zambia (Berentsen *et al.*, 2012; M'soka *et al.*, 2016), and no formal research on Spotted hyena in the Greater Kafue System, though reports and sightings are widespread from studies on sympatric carnivore (e.g. Mitchelle, 1965; Midlane *et al.*, 2015) and via trophy hunting records (PHAZ, 2019).

1.6 *Thesis Structure*

Here, in Chapter 1, the Introduction, I have provided a general overview of Protected Areas and Protected Area Networks in context of the broader Kavango-Zambezi Transfrontier Conservation Area, the Greater Kafue Ecosystem and the Kafue-Zambezi Interface, including a summary outlining key social, economic, environmental and cultural drivers shaping the Kafue-Zambezi landscape. I then summarized connectivity considerations for this landscape, and within the broader KAZA TFCA, then reviewed the status, ecology and relevance of target species for connectivity and for broader conservation outcomes.

Chapter 2 presents an exhaustive historical analysis of wildlife in the Kafue-Zambezi interface, referencing data and anecdotal evidence from early hunters and missionaries through to grey literature and available published records, including oral records from meetings with Traditional Authorities. I identify key drivers of changes to species composition and distribution by wildlife managed area prior to contemporary fieldwork, generating a foundational understanding of the area's wildlife. I then integrate multiple datasets from Government anti-poaching operations, interviews with safari hunters and extensive spoor tracking to provide up to date analyses on the current status of 31 terrestrial mammals known from the landscape from our historical analyses. This chapter was published as Lines *et al.* (2018).

Chapter 3 delves into the argument for single and multi-species connectivity across this landscape using lion, leopard and spotted hyena as proxies for broader habitat suitability and connectivity analyses. I employ high resolution Sentinel imagery (Copernicus Sentinel data, 2018). and extensive ground truthing to generate a landcover map at 10m resolution for 38,000km^2 , achieving >91% classification accuracy. I then integrate empirical occurrence data from Chapter 1 with the landcover map to model habitat suitability for each species, then apply a further analytical step to model potential for single and multi-species corridors across this landscape, identifying a novel area for protection to increase scope and scale for connectivity. This chapter is in review with Oryx (Lines *et al.,* 2020).

Chapter 4 develops an innovative use of fine-scale, site-specific human footprint pressure mapping as a proxy for understanding species sensitivity to anthropogenic disturbance throughout the Kafue-Zambezi interface. Seven human impact layers are integrated from our landcover maps plus supplemental sources to generate a large-scale, fine resolution human footprint map covering c.4 m ha. I then use this map to model effects of derived Human footprint pressure on lion, leopard and spotted hyena occurrence. Finally, I undertake preliminary exploratory analysis to investigate if model and map outputs can determine mean human footprint pressure thresholds at which species occur at the wildlife managed areas scale.

In Chapter 5, the Discussion, I synthesize the three data chapters and contextualize with important supplemental information and insights. This provides a meaningful interpretation of scope and scale for single and multi-species connectivity given historical data, current analyses and prospects under various future management interventions. I identify gaps in knowledge and additional research priorities for our core study area and the broader KAZA TFCA landscape. This produces a holistic understanding of connectivity at the large carnivore scale for this dynamic, heterogenous landscape is thus presented.

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Chapter 2: Status of Terrestrial Mammals at the Kafue-Zambezi Interface: Implications for Transboundary Connectivity.

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Abstract

The Kavango-Zambezi Transfrontier Conservation Area Programme promotes landscape-level connectivity between clusters of wildlife managed areas in five neighboring countries. However, declining regional biodiversity can undermine efforts to maintain, expand and link wildlife populations. Narratives promoting species connectivity should thus be founded on studies of system and state changes in key resources.

By integrating and augmenting multiple data sources throughout eight wildlife managed areas covering 1.7 m ha, we report changes from 1978-2015 to the occurrence and distribution of 31 mammal species throughout a landscape linking the Greater Kafue System to adjacent wildlife managed areas in Namibia and Botswana. Results indicate species diversity was largely unchanged in Kafue National Park, Mulobezi and Sichifulo Game Management Areas. However, 100% of large carnivore and 64% of prey diversity have been lost in the Simalaha areas in Zambia. No evidence was found of migration behaviour or species recolonization from adjacent wildlife areas was established. While temporal sampling scales impacts the definition of species occupancy and distribution, and

data cannot elaborate on population size or trends, findings indicate an emerging connectivity bottleneck within Simalaha. At current disturbance levels, evidence suggests the Greater Kafue System, Zambia's majority component in the Kavango-Zambezi Transfrontier Conservation Area, is becoming increasingly isolated at the large mammal scale contrary to prevailing narratives.

Further investigations of the site-specific, interacting drivers impacting wildlife distribution and occurrence are required to provide management with appropriate conservation interventions aimed at wildlife recovery in key areas identified to promote transboundary connectivity in the Kavango-Zambezi Transfrontier Conservation Area.

Keywords: Kavango-Zambezi Transfrontier Area, Kafue, connectivity, mammal loss.

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2.1 Introduction

Wildlife managed areas are frequently clustered along international borders, with arbitrarily drawn political boundaries dividing ecosystems in which these areas occupy (Zbicz, 1999a; Hanks, 2000). Where fences and physical barriers combined with expanding human settlement and intensified agropastoralist activities, over-exploitation and extreme wildlife population decline can occur (Ogutu *et al.*, 2016). Additionally, invasion, disease, pollution and climate change (Maxwell *et al.*, 2016; Pachauri *et al*., 2014) interact with intrinsic species traits (Cardillo *et al.*, 2008) to inhibit or sever wildlife movement patterns, isolating core wildlife managed areas (Margules & Pressey, 2000; Newmark, 2008). In concert these drivers are exposing wildlife populations to escalating edge-effects and ecological traps, threatening species persistence within and outside protected areas (Woodroffe & Ginsberg, 1998; Battin, 2004).

Conversely, intact species assemblages have wide-ranging implications for sustainable and resilient social-ecological systems (Cummings, 2011). Heterogeneity and functional diversity drives system productivity and its capacity to absorb, resist and respond to shocks, perturbations and other stressors that negatively impact system structure and function (Fischer *et al.*, 2006). Cumulatively, threats to species persistence undermine habitat integrity, ecosystem services, food security, the development of sustainable wildlife-based land uses and human wellbeing (Lindsay *et al*., 2013; WHO/MEE, 2005).

Acknowledging the limitations imposed by these constraints, stakeholders in Southern Africa are increasingly embracing Transfrontier Conservation Areas (TFCAs) as a new conservation paradigm (Hanks, 2000), considered an evolution of previous Community Based Natural Resource Management (CBNRM) approaches that yielded mixed results

(Andersson, 2016). Enticing narratives include the integration of biodiversity conservation with the promotion of sustainable socioeconomic development and a culture of peace and cooperation at the ecosystem level, linked to the removal of fences and other barriers inhibiting the free movement of wildlife across vast interconnected landscapes (Linde *et al.*, 2002, Hanks, 2003).

The Kavango-Zambezi Transfrontier Conservation Area (KAZA TFCA) is working to capitalize on the regions' unique diversity and distribution of wildlife assets by advocating shared natural resource management and development goals across an immense network of protected areas spanning over 500,000 km^2 at the interface of Angola, Botswana, Namibia, Zambia and Zimbabwe (KAZA, 2011b; Hanks & Myburgh, 2015). Stated objectives to integrate conservation and development, promote peace and cooperation, and facilitate connectivity of wildlife populations between clusters of wildlife managed areas have become popular and compelling programme narratives driving north-south finance initiatives, non-government organisation engagement, and energizing State buy-in (KAZA, 2011a; PPF, 2008; WWF, 2011).

Notwithstanding evolving conservation and development narratives, the KAZA TFCA landscape faces many existing and emerging challenges constraining programme success. Mounting anthropogenic pressures combined with poor land use planning, institutional conflicts and stakeholder disenfranchisement (Andersson, 2016), are driving encroachment into wildlife areas, habitat loss and fragmentation (Watson *et al.*, 2015; Newmark, 2008; Simukonda, 2008), and unsustainable harvesting of wildlife, threatening many of the Kavango-Zambezi TFCA's iconic natural assets (Lindsay *et al.*, 2013). With the region's human population expected to double by 2050 (UN, 2015) and likely impacts of climate change exacerbating socioeconomic development challenges (Pachauri, *et al*., 2014; Bellard *et al.*, 2012), even moderately optimist scenarios imply regional biodiversity loss will accelerate significantly this century (Briggs *et al.*, 2008).

Collectively these challenges raise important questions surrounding the scope, scale and ambition of narratives promoting landscape-level linkages, the interventions required to maintain or expand connectivity, and what purposes these proposed linkages may serve in the long term (Cumming, 2008). A clear imperative thus exists to promote evidence-based socioeconomic and environmental policies and interventions built around the application of conservation science (Sutherland *et al.*, 2004), including research and monitoring of changes to site and system states, and their response to factors driving connectivity at the scale of interest. But the process of informed decision-making is data hungry. Local, regional and transboundary data sources are disparate and inconsistent, undermining attempts to understand complex social ecological systems such as the Kavango-Zambezi TFCA. Data deficiencies ultimately constrain effective decision making and appropriate interventions to promote biodiversity conservation and development.

In this paper we interrogate and synthesize existing data sources, and supplement with additional research to document the historical and contemporary status of the African Elephant (*Loxodonta africana*), five large carnivores, one mesopredator and twenty four prey species throughout eight wildlife managed areas between the Greater Kafue System and the Zambezi River. This landscape is promoted as a key linkage to the central cluster of wildlife managed areas in Namibia and Botswana, at the heart of the KAZA TFCA (KAZA, 2014).

Through integration, harmonization and triangulation of data we were able to determine changes to species occurrence and distribution by wildlife managed area and designation.

2.2 Methods

2.2.1 Study Area

The KAZA TFCA’s boundaries are imprecise (Andersson, 2016). However, Cummings (2008) characterizes the TFCA as comprising a matrix of over 70 wildlife managed areas from strict National Parks under State control to multiple use areas under Customary/communal management. These wildlife managed areas fall into three major clusters and five periphery sub-clusters, with Kafue National Park and surrounding wildlife managed areas constituting the major northern cluster (Fig. 2.1).

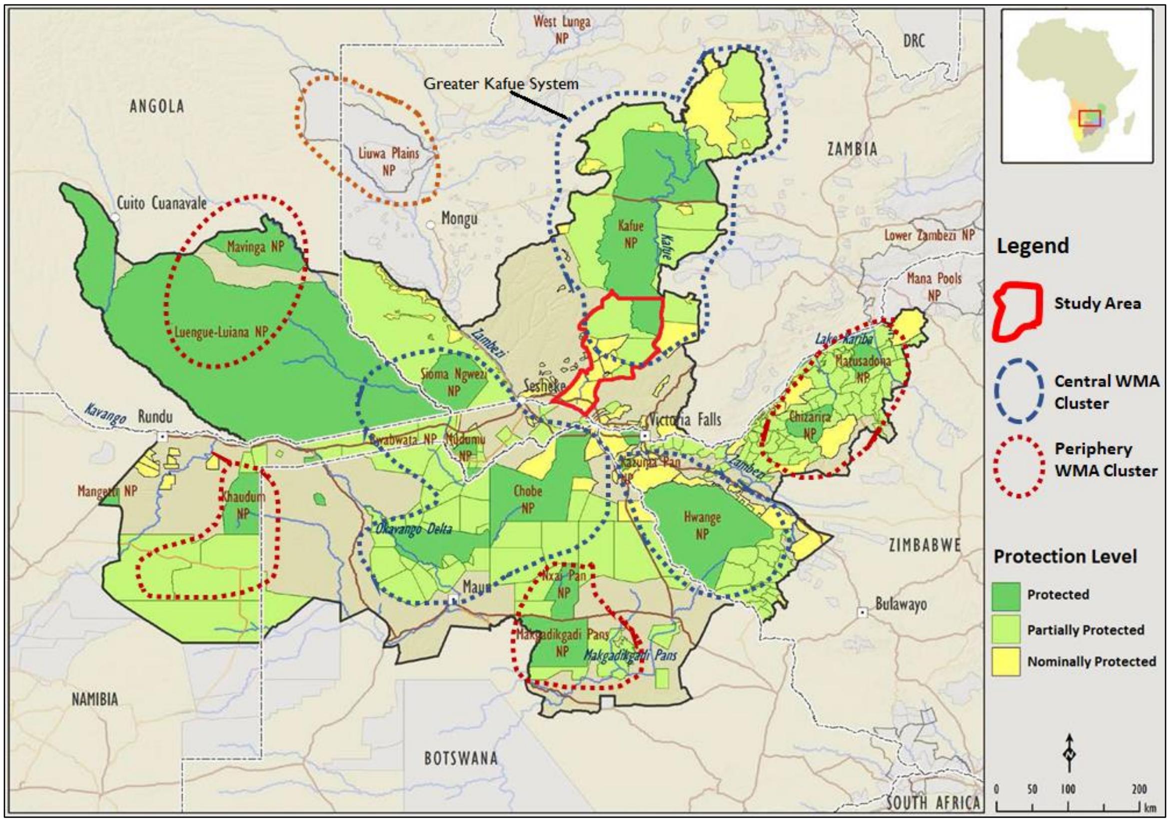

Figure 2.1. The Kavango-Zambezi Transfrontier Conservation Area landscape, indicating study area, clusters of wildlife managed areas (WMAs) and their degrees of protection. Protected = National Parks IUCN II; Partially Protected = IUCN III-VI; Nominally Protected = IUCN *Not Reported* (*adapted* from PPF, 2011a).

At 22,480 km^2 Kafue National Park is Zambia's oldest and largest protected area, the largest National Park in the Kavango-Zambezi TFCA and 2nd largest National Park in Africa (UNEP/WCMC, 2016). In concert with nine surrounding IUCN category VI Game Management Areas and multiple Forest Reserves, the effective unfenced wildlife managed area, termed variously as the Greater Kafue Landscape or System, covers 68,000 km^2 – a vast undeveloped area approximately half the size of England, and representing 9% of Zambia's land mass and over 13% of the KAZA TFCA estate.

Most of the Greater Kafue System lies between 900-1100 m above sea level. Rainfall averages 650 mm in the south and 1,050 mm in the north, falling predominantly from November to April. Vegetation is characterized by the Zambezian Miombo woodland Ecoregion, typical of large areas throughout southern and eastern Africa, dominated by *Brachystegia* spp., *Combretum* spp., *Mopane* spp., *Terminalia* spp. and *Baikaea* spp. Woodlands are interspersed by open floodplain grasslands and dambos (ZAWA, 2010). Species records include 158 mammals, 481 birds, 69 reptiles, 35 amphibians and 58 fish, with the greatest antelope diversity of any African National Park (21 species), an intact carnivore guild and a full complement of Zambia's large mammals with the exception of Giraffe (*Giraffa giraffa*) and Black Rhinoceros (*Diceros bicornis*), known historically from the reports, and Tsessebe (*Damaliscus lunatus*) which has not appeared in any historical records (Moss, 2012).

The Greater Kafue System has been included as Zambia's majority component within KAZA TFCA (KAZA, 2014), with connectivity to the broader KAZA landscape contingent on the maintenance of a landscape level linkage routing south-southwest through a mosaic of nominally, potentially and possibly protected wildlife managed areas including Mulobezi and Sichifulo Game Management Areas, Nachitwe, Martin and Machili Forest Reserves, the Nyawa communal areas, and the recently proclaimed Simalaha Communal Conservancy (Fig. 2.2). In concert these wildlife managed areas extend the Greater Kafue System to around 73,000 km^2.

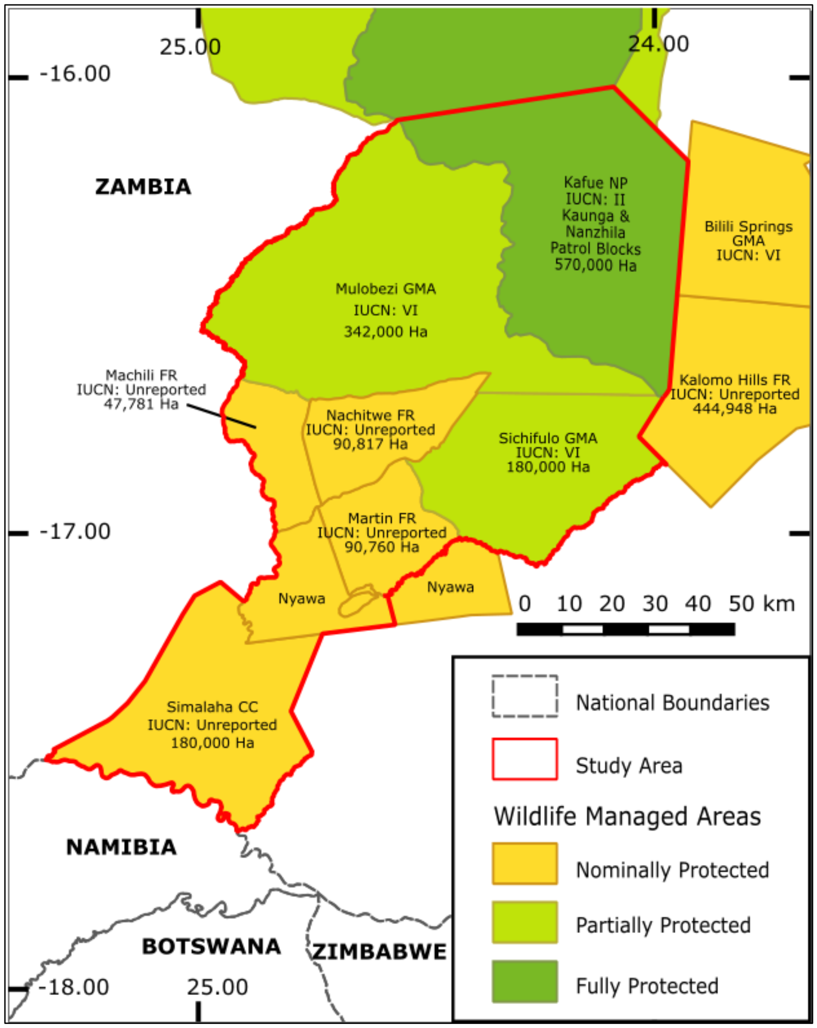

Figure 2.2 Wildlife Managed Areas within study area. CC=communal conservancy, FR=forest reserve, NP=National Park, GMA=Game Management Areas

A secondary (south-westerly) linkage passing through Mulobezi to Sioma National Park (bordering Namibia and Angola) has been proposed, though our focus remains the linkage broadly following the Machili stream catchment basin from the Kafue National Park border (S16.138^0, E25.365^0) to the northern bank of the Zambezi River (S17.555^0, E24.977^0), adjacent to Kasika and Salambala Communal Conservancies of East Zambezi Region in Namibia, and through to Chobe National Park in Botswana.

This proposed landscape linkage varies in length from 140-170 km and contains a human population of around 110,000, growing at 2.5% pa, with a population density ≈4.0/km^2 (CSO, 2010). Communities are centered on a few larger settlements of 5,000-10,000 residents, and otherwise in clusters of scattered villages typically concentrated along water courses, seasonal waterholes, and few pumped ground water supplies. Subsistence agro-pastoralists dominate this landscape, with residents largely dependent on exploiting a wide range of the area's natural resources in support of basic livelihood needs (Musgrave, 2016). Formal employment opportunities beyond few distant urban settlements are negligible. Customary law within the Lozi, Nkoya, and Tonga ethnolinguistic groups represent the *de facto* regional governance system (Brelsford, 1965; Musgrave, 2016).

Biodiversity conservation budgets have varied dramatically throughout this landscape, both spatially and temporally. While precise figures are unavailable, sources indicate that Kafue National Park (although operating with 10-15% of recommended protected area budgets) has received the greatest level of long-term biodiversity conservation support throughout the study area. This is followed by Mulobezi then Sichifulo Game Management Areas which receive minor budget allocations from the State Wildlife Authority, augmented by finance and in-kind operational support from resident safari hunting operators and conservation NGOs. Nachitwe, Martin and Machili Forest Reserves have intermittently received minor budgets from the State Wildlife Authority and Forestry Department (ZAWA, 2010; Chifunte, *pers comms*). The recently proclaimed Simalaha Communal Conservancy only started receiving any formal wildlife resource protection as recently as 2013 following no formal biodiversity conservation budgets since pre-1978 (Inyambo-Yeta, *pers comms*). We were unable to ascertain if the Nyawa Communal areas receives any formal wildlife management budget. In additional a 240 km^2 fenced Wildlife Recovery Sanctuary at the south of Simalaha, with an extensive open border against the Zambezi River, has received >600 head of game from eight species since 2013, representing a significant investment promoted as a justification for restocking the broader Simalaha Communal Conservancy (PPF, 2015). No formal monitoring of these species appears to have been undertaken since reintroductions.

2.2.2 Data Sources

The earliest records of terrestrial mammal occurrence and distribution in the vicinity of the proposed Kafue-Zambezi linkage are limited to disparate notes and reports in the grey literature from early explorers, hunters, traders and missionaries dating back to the late 19th century (e.g. Holub, 1975; Sampson, 1972), with approximate location data variously reported in relation to key landscape features. The first published checklists for Zambia (Pitman, 1934; Lancaster, 1953; Ansell, 1957/59/60) indicate no changes to the large mammal assemblage in and around Kafue National Park prior to the notable Black Rhinoceros extirpation in the mid-1980's, though unresolved questions surround anecdotal records of a relic Giraffe population (Moss & Fennessy, *pers comms*). Data for these checklists were ostensibly collected through *ad hoc* and opportunistic sightings from Government staff and 'expert' observers reporting from their travels throughout the country, augmented by trading records and hunting ledgers kept by District Commissioners.

The first systematic collation of species occurrence and distribution data was published by Ansell (1978), superseding previous literature. Amalgamated checklist data were mapped within ¼ degree grid squares, based on 1:50,000 Ordnance Survey map sheets. While data reflects minimum regional species range given the absence of reports from many inaccessible and largely unmapped periphery areas, much of this study area can be considered well mapped due to the established network of access routes developed alongside the nascent Teak logging and safari hunting industries (Musgrave, 2016).

While Ansell (1978) reports on 38 terrestrial mammals >10kg from 11 taxonomic families we restricted the contemporary list to 31 readily detected species from nine taxonomic families, omitting seven species considered either at the edge of known range and/or habitat specialists requiring species-specific survey techniques beyond the scope of this study.

Boundaries of contemporary land use classifications (UNEP-WCMC, 2016) were projected over Ansell's (1978) maps using QGIS (QGIS, 2017) (Fig 2.3) to allow for extraction of historical species distribution data at comparable spatial scales: Kafue National Park (Kaunga and Nanzilla management blocks at 5,700 km^2), Mulobezi Game Management Area (hereafter Mulobezi, at 3,420 km^2), Sichifulo Game Management Area including Nachitwe, Martin and Machili Forest Reserves (hereafter Sichifulo, at 4,090 km^2), and finally the Nyawa/Simalaha areas (2,800 km^2).

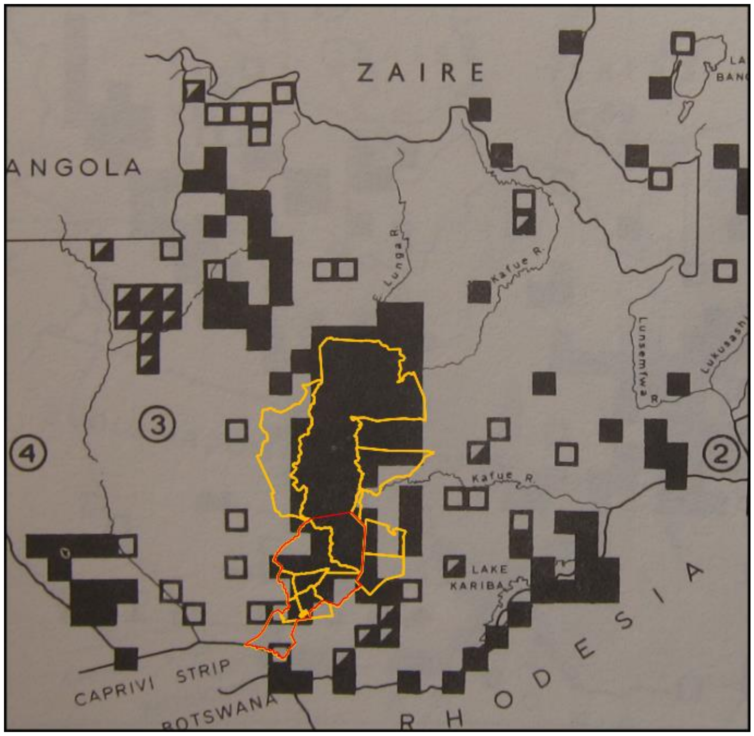

Figure 2.3. Historical Species Distribution from Ansell (1978) showing species known range (solid squares), possible range (hatched squares) and former range (unfilled squares), mapped here for Blue Wildebeest (*Connochaetes taurinus*). Boundary of contemporary wildlife managed areas in yellow, study area in red.

In compiling contemporary data sets (Fig 2.4) we constrained data gathering to three broadly comparable ground-based survey approaches. We omitted aerial survey data (e.g. DNPW, 2016) given limitations to detection rates for many species of primary interest in forested areas (Jachmann, 2002).

Firstly, the resident safari hunting operator, operational throughout Mulobezi and Sichifulo Game Management Areas during the preceding decade, was asked to provide sightings reports for 31 terrestrial mammals of interest through a questionnaire survey following the 2014 hunting season. Cumulatively, multiple groups of guides, hunters and skilled local trackers traversed both Mulobezi and Sichifulo Game Management Areas on and off road, by open vehicle and on foot, covering >10,000 km/dry season (Kraljik, *pers comms*). This was considered, in my expert opinion, to be sufficient survey effort and local expertise to provide a high probability of detecting target species.

Secondly, we collected patrol data from the local State and Community Wildlife Police Officers responsible for wildlife protection in southern Kafue National Park, Mulobezi and Sichifulo. We amalgamated data for the Kafue National Park patrol blocks adjacent to Mulobezi and Sichifulo Game Management Areas to provide a single area covering the border north of both Mulobezi and Sichifulo Game Management Areas. These data provided 1,920 georeferenced wildlife sighting reports during 2014/5 from 46,170 man-days of foot patrols (ZAWA, *unpublished data*).

Finally, in 2015, we undertook a systematic randomized spoor and sightings survey of large carnivores and their principle prey throughout 10 x 400 km^2 survey blocks in Mulobezi and Sichifulo Game Management Areas and the Nyawa/Simalaha areas (see Appendix 1). Detection probability and survey effort were optimized for large carnivores following Funston *et al.* (2010) and Thorn *et al.* (2010). In addition, a site-specific calibration process was undertaken from July to September 2014, conducted at varying spatiotemporal scales, to establish survey effort required to detect large carnivores and sample the landscape in a single season (MacKenzie & Royle, 2005, MacKenzie, *pers comms*). In total 102 x 4 km transects were walked three times by the principle investigator and two experienced local trackers from the safari hunting industry, cumulatively providing 1,224 km of spoor transects over six months fieldwork during the dry season from May and Oct 2015 (see Appendix 1 for further data and explanations on transect selection and criteria).

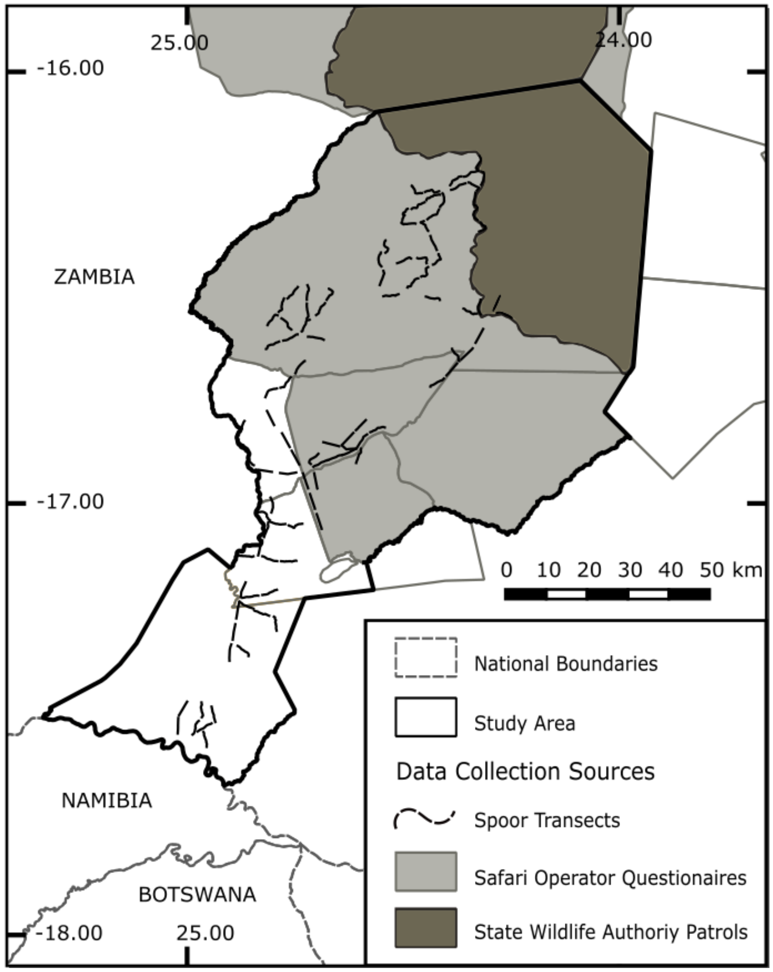

Figure 2.4: Contemporary Data Sources

2.2.3 Data Analysis

A confirmed sighting from any of the three expert contemporary sources was marked as a positive detection at the scale of interest. Given the atypical nature of ongoing ungulate reintroductions and management in the fenced Simalaha Wildlife Sanctuary, we restrict reporting to the detection of the carnivore guild for this subset of the Simalaha Communal Conservancy.

Data for each of the four composite wildlife management area blocks and three data sources were compiled against historical data to determine if any changes in species occurrence and distribution had been detected throughout the intervening years (1975-2014). Outputs reflected species persistence, loss or colonization at the composite wildlife management area scale.

Given survey methods were optimized for resident large carnivores and their principle prey species, elevated non-detection risks existed where species exhibited significant seasonal movement patterns (migration), non-resident movement patterns (emigration and immigration), or where surveys did not cover the restricted ranges of habitat specialists. Table 2.1 and subsequent analyses acknowledges these constraints.

Finally, an amalgamated distribution map was generated for the five extant large carnivores, indicating historical range within the survey area, and current known range within studied wildlife managed areas.

2.3 Results

2.3.1 Changes to Species Occurrence and Distribution

Table 2.1 indicates few non-detections recorded against any data sources since 1978 throughout southern Kafue National Park, Mulobezi or Sichifulo Game Management Areas. Notably Hippopotamus (*Hippopotamus amphibius*) appear no longer resident in any of the waterways along the Machili stream and catchment area. Klipspringer (*Oreotragus oreotragus*) appear absent from Mulobezi, though core habitat for this species went unsurveyed. Steenbok (*Raphicerus campestris*) are considered at the extent of their northeast range approaching Kafue National Park, with a single sighting recorded in Mulobezi.

Species binomial	Common Name	IUCN Status	Ansell 1978				Kraljik 2013/4		ZAWA 2014/5			Lines 2014/5			Distribution Change 1978-2014/5			
			KNP/S	Mulobezi	Sichifulo	Simalaha	Mulobezi	Sichifulo	KNP/S	Mulobezi	Sichifulo	Mulobezi	Sichifulo	Simalaha	KNP/S	Mulobezi	Sichifulo	Simalaha
Acinonyx jubatus	Cheetah	VU	✓	✓	✓	✓	✓	✓	✓	X	X	✓	✓	X	No	No	No	Yes
Panthera leo	Lion	VU	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes[1]
Panthera pardus	Leopard	VU	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	No	No	No	Yes[1]
Crocuta crocuta	Spotted Hyena	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes[1]
Canis adustus	Side-striped Jackal	LC	✓	✓	✓	✓	✓	✓	✓	X	X	✓	✓	✓	No	No	No	No
Lycaon pictus	African Wild Dog	EN	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes
Loxodonta africana	African Bush Elephant	VU	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes[1]
Equus quagga	Burchell's Zebra	NT	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes[2]
Phacochoerus africanus	Warthog	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes
Potamochoerus larvatus	Bushpig	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes
Hippopotamus amphibius	Hippopotamus	VU	✓	✓	✓	✓	X	X	✓	X	X	X	X	X	No	Yes[1]	Yes[1]	Yes[1]
Alcelaphus lichtensteiniix	Hartebeest	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes
Connochaetes taurinus	Blue Wildebeest	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes[2]
Oreotragus oreotragus	Klipspringer	LC	✓	X	✓	X	✓	✓	✓	X	X	X	X	X	No	No	No	No
Ourebia ourebi	Oribi	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	No	No	No	No
Raphicerus campestris	Steenbok	LC	✓	✓	✓	✓	X	X	X	X	X	✓	X	X	UK[3]	No	Yes	Yes
Raphicerus sharpei	Sharpe's Grysbok	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	No	No	No	No
Syncerus caffer	African Buffalo	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes
Tragelaphus oryx	Common Eland	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	X	No	No	No	Yes
Tragelaphus scriptus	Bushbuck	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes
Tragelaphus spekii	Sitatunga	LC	✓	X	X	X	X	X	X	X	X	X	X	X	Yes	No	No	No
Tragelaphus strepsiceros	Greater Kudu	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	No	No	No	No
Sylvicapra grimmia	Common Duiker	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	No	No	No	No
Hippotragus equinus	Roan Antelope	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes
Hippotragus niger	Sable Antelope	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes
Aepyceros melampus	Impala	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes[2]
Kobus ellipsiprymnus defassa	Defassa Waterbuck	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	No	No	No	Yes[2]
Kobus leche	Lechwe	LC	X	X	X	✓	X	X	X	X	X	X	X	X	No	No	No	Yes[2]
Kobus vardonii	Puku	NT	✓	X	X	X	X	X	✓	X	X	X	X	X	No	No	No	No[2]
Redunca arundinum	Southern Reedbuck	LC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	No	No	No	No
Hystrix africaeaustralis	Cape porcupine	LC	✓	✓	✓	✓	✓	✓	X	X	X	✓	✓	✓	No	No	No	No

[1] Non-resident individuals periodically reported by local community moving through the area
[3] Extent on known range
[2] Reintroduced in fenced 24,000ha breeding camp 2013-5

Table 2.1. Summary results of species detection by source and area, with distribution change, 1978-2014/5.

The absence of confirmed Caracal (*Caracal caracal*) and Serval (*Leptailurus serval*) sightings by Wildlife Police Office patrols in southern Kafue National Park appears an anomaly given detection from adjacent Game Management Areas. While I hypothesize these anomalies represents non-detection error versus absence, I nonetheless omitted these species from the final check list.

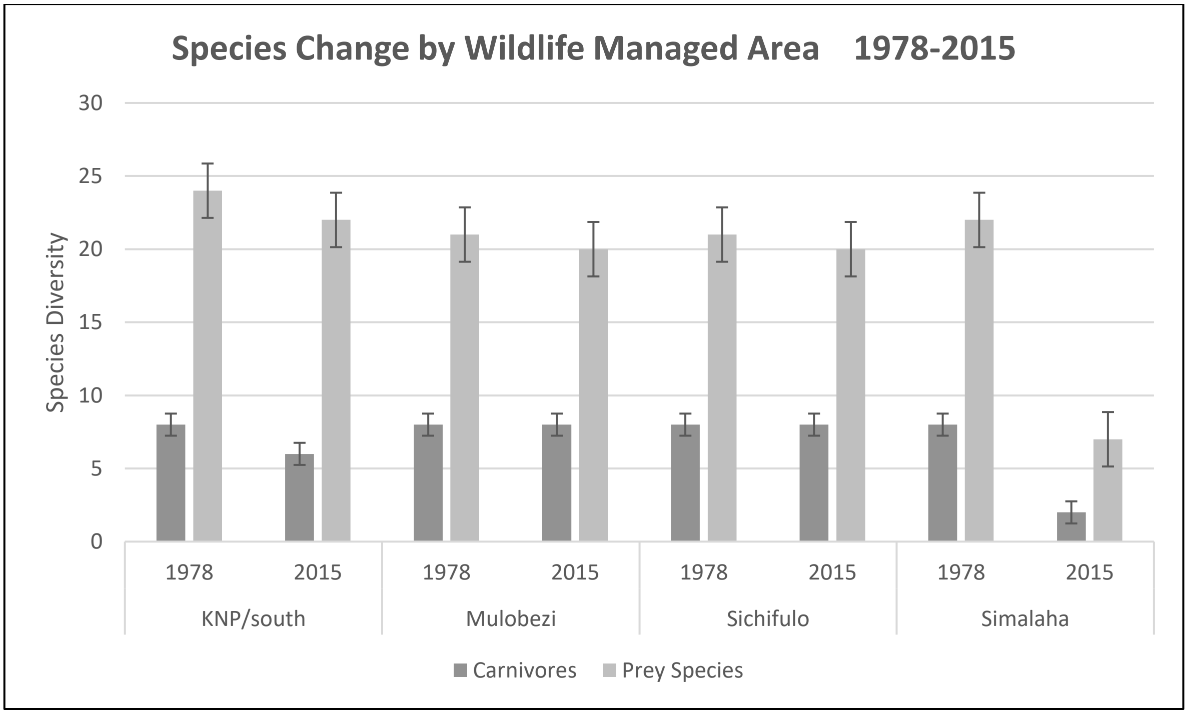

Figure 2.5. Changes to carnivore and herbivore composition by area, 1978-2014/15.

Major losses have occurred in the newly registered Simalaha Communal Conservancy, whereby 21/31 terrestrial mammals went undetected (Fig 2.5). Side-striped Jackal (*Canis adustus*) remained the only widespread carnivore detected in Simalaha. Both Spotted hyaena (*Crocuta crocuta*) and Leopard (*Panthera pardus*) were the only large carnivores detected within 60km of the Zambezi River in the Nyawa Communal area (Fig 2.6). The remaining large carnivore guild appears extirpated from the Simalaha/Nyawa area along with all ungulates >20kg, excluding the Southern Reedbuck (*Redunca arundinum*) and Greater Kudu (*Tragelaphus strepsiceros*). Kudu were also the only herding ungulate to be detected in Simalaha, through no aggregations over three animals were detected. Notably both Warthog (*Phacochoerus africanus*) and Bush pig (*Potamochoerus larvatus*), habitat and feeding generalists with high reproductive rates, went undetected in Simalaha. While

>600 head of game comprising seven species have been introduced into the 240 km^2 Simalaha Wildlife Recovery Sanctuary since 2013, only Side-Striped jackal were detected inside the (non-predator proof) area. There was no evidence of any species range extension or recolonization throughout any of the sampled areas.

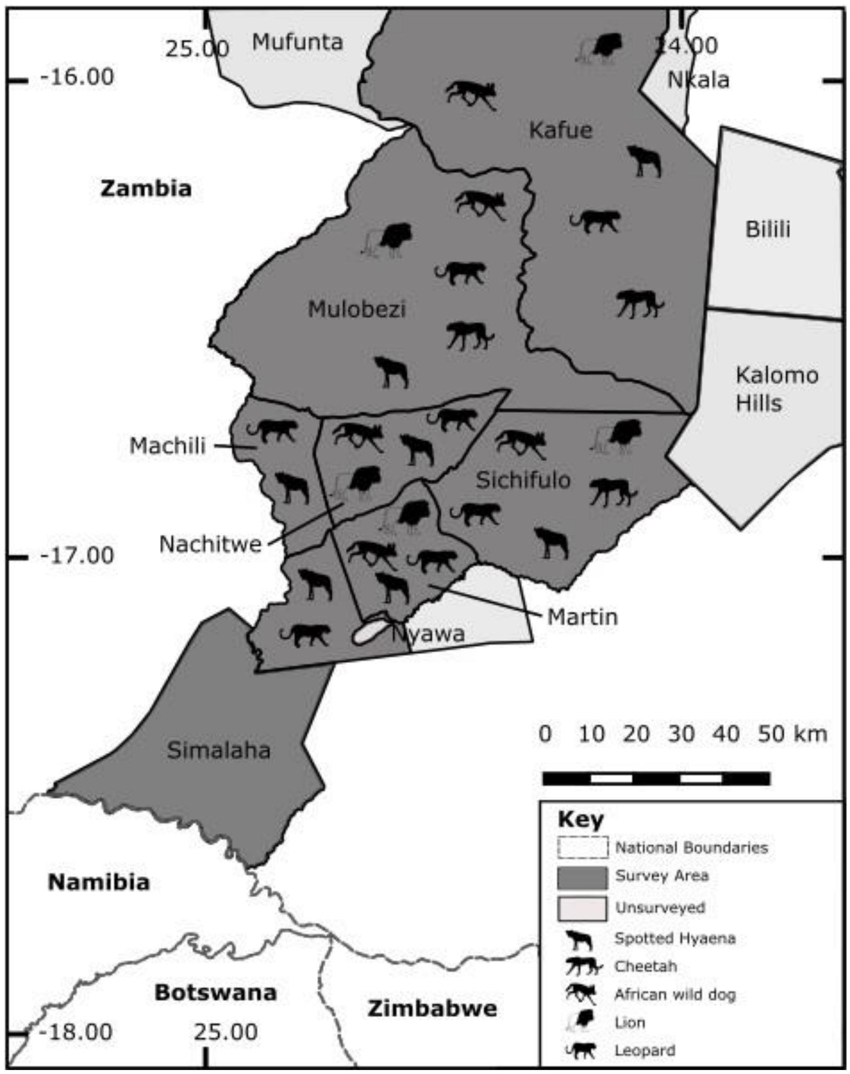

Figure 2.6. Distribution of large carnivores at Kafue-Zambezi Interface, 2014/5.

Although no long term, comparable, or landscape-level survey programme is in place to systematically monitor changes in species occurrence, distribution or abundance, much existing expertise and anecdotal evidence implies large scale population declines throughout the Greater Kafue System and beyond since 1978 (Chifunte, Daka, Hanks, Moomba, Moss & Inyambo-Yeta, *pers comms*). Contemporary data indicates Kafue National Park, the regions' prime wildlife area, is maintaining the majority of terrestrial mammals significantly below carrying capacity (Simukonda, 2008). Nonetheless, with few historical survey data available for direct comparison, we restricted our analyses to species diversity at the scale of interest, versus any interpretation of spatiotemporal changes to community structure and abundance, which is beyond the scope of this paper.

2.4 Discussion

Formal historical records explaining species loss in Simalaha and Nyawa areas are unavailable, though local Traditional Authorities (Chiefs Inyambo-Yeta, Moomba, *pers comms*) emphasized the impact of the Angolan Bush War (1966-1989) as a key driver, describing the activities of foreign combatant encampments in Simalaha being used as a base to exploit the areas' wildlife for rations and profit. Following cessation of hostilities much small arms proliferation occurred, and in conjunction with expanding human population and limited funding for law enforcement and natural resource management, ongoing unsustainable harvesting of wildlife continued. Given these circumstances the authors hypothesize that wildlife managed areas closer to Kafue National Park were spared much of these pressures, having also received elevated political and revenue support for wildlife management in the long term (Daka, *pers comms*).

Existing surveys at the Kafue-Zambezi interface have employed a range of *ad hoc* methodological approaches that failed to detect the majority of resident species throughout this landscape. The absence of a reliable baseline undermines efforts at evaluating the effectiveness of large-scale conservation interventions required to deliver key programme objectives within and between clusters of wildlife management areas.

Acknowledging non-detection error, we confirm that the terrestrial mammal (>10 kg) richness in southern Kafue National Park remains unchanged since 1978. Mulobezi and Sichifulo retain largely intact mammalian diversity, with the notable exception of resident Hippopotamus. No new data could be provided for the existence of free-ranging Giraffe in any of these wildlife managed areas.

While a single season survey design increases non-detection error associated with species dispersal or seasonal wildlife movement patterns, widespread losses, including three of six carnivore species and 16 of 25 prey species, were detected in the Simalaha Communal Conservancy / Nyawa areas, collectively key linking wildlife managed areas at the interface of the Greater Kafue System and adjacent wildlife managed areas in Namibia and Botswana.

These data emphasize the challenges surrounding scope and scale of conservation interventions required to limit factors driving species loss from seven of nine taxonomic families, representing a wide range of species traits. Significantly, if drivers of species loss continue to limit population recovery in Simalaha/Nyawa areas then source-sink dynamics and edge effects can negatively impact population viability of vulnerable species in periphery wildlife managed areas at local and transboundary scales.

Wide-ranging species are particularly susceptible to source-sink dynamics and edge effects, so the absence of large carnivores from the Simalaha and the Simalaha Wildlife Recovery Sanctuary indicates the need for additional research to understand the status and drivers of wildlife occurrence and distribution south of the Zambezi River throughout the wildlife managed areas of eastern Zambezi Region in Namibia, and the effects that ecological traps/attractive sinks might pose at transboundary scales on wildlife management interventions in Simalaha and other neighboring wildlife managed areas of Zambia.

Broader scale implications of species loss and ecological traps within the Kavango-Zambezi TFCA relate to dominant narratives surrounding wildlife managed area connectivity. The extent to which existing and emerging drivers of species loss are severing biological linkages between the Greater Kafue System and adjacent wildlife managed areas in the Kavango-Zambezi TFCA remain unquantified and subject to speculation. However, data suggests a connectivity bottleneck at the large mammal level in the Simalaha Communal Conservancy, with only 10 of 31 species known from historical records detected throughout this area in 2014/5.

While the long distance dispersal capabilities of large carnivores implies scope for gene flow between the Greater Kafue System and adjacent wildlife managed areas in the Kavango-Zambezi TFCA, the extent to which connectivity bottlenecks impact processes of immigration and emigration in highly mobile species is an important area of priority research for regional connectivity conservation management.

2.5 Conclusions

The study focused on ascertaining changes to the occurrence and distribution of 38 terrestrial mammals >10 kg known from four composite wildlife managed areas between the Greater Kafue System and central cluster of wildlife managed areas in the KAZA TFCA, and the methodological approach was successful for 31 species at the scale of interest.

While these data cannot elaborate on population numbers and trends, it is apparent that ongoing attempts to maintain population viability of vulnerable species, wildlife connectivity between clusters of wildlife managed areas, and the promotion of wildlife-based land uses, will depend on diagnosing and treating the interacting ecological, socio-economic and political drivers of species loss within and between clusters of wildlife managed areas utilizing comparative studies at appropriate temporal and spatial scales.

The limits to which sufficient political and economic capital can be leveraged to bridge these knowledge gaps, act accordingly on the findings, and be subject to monitoring, evaluation and feedback, will likely determine future connectivity for Zambia's majority component within the KAZA TFCA.

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Chapter 3: Modelling multi-species connectivity at the Kafue-Zambezi Interface: Implications for Transboundary Carnivore Conservation

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Abstract

Linking wildlife areas with corridors facilitating species dispersal between core habitats is a key intervention to reduce deleterious effects of population isolation. Large heterogeneous networks of areas managed for wildlife protection present site- and species-scale complexity underpinning the scope and performance of proposed corridors. In Southern Africa, the Kavango-Zambezi Transfrontier Conservation Area seeks to link Kafue National Park to a cluster of wildlife area centered on Namibia and Botswana. To assess and identify potential linkages on the Zambian side we generated a high-resolution land cover map and combined empirical occurrence data for lion (*Panthera leo*), leopard (*Panthera pardus*) and Spotted hyena (*Crocuta crocuta*) to build habitat suitability maps. We then developed four connectivity models to map potential single and multi-species corridors between Kafue and the Zambezi River border with Namibia. Single and multi-species connectivity models selected corridors follow broadly similar pathways narrowing significantly in central-southern areas of the Kafue-Zambezi interface, indicating a potential connectivity bottleneck.

Capturing the full extent of human disturbance and barriers to connectivity remains challenging, suggesting increased risk to corridor integrity than modelled here. Notwithstanding model limitations, these data provide important results for land use planners at the Kafue-Zambezi Interface, removing much speculations from existing connectivity narratives. Failure to control human disturbance and secure corridors will leave Kafue National Park, Zambia's majority component in the Kavango-Zambezi Transfrontier Conservation Area, isolated.

Keywords: Connectivity; Carnivores; KAZA; Transfrontier Conservation Area; Kafue; Zambia; Sentinel; Landcover; MaxEnt; Linkage Mapper.

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3.1 Introduction

Expanding human pressures on natural resources are driving rapid fragmentation and conversion of wildlife habitat to farmlands and rangelands, isolating wildlife populations, and driving widespread declines in wildlife (Maxwell *et al.*, 2016; Marco *et al.*, 2014). The large carnivore guild is notable in its sensitivity to anthropogenic pressures and exhibits elevated extinction risk with population isolation (Purvis *et al.,* 2000; Cardillo *el al.,* 2005). Ripple *et al.* (2014) calculated some 77% of terrestrial large carnivore species are now experiencing declines in population size and range due to anthropogenic pressures related to habitat fragmentation and loss. Maintaining free-ranging large carnivore populations is contingent on provision of sufficient habitat and prey species and limiting deleterious effects of human disturbances (Wolf & Ripple, 2017).

Given the importance of maintaining structural and functional connectivity between wildlife managed areas, large scale conservation networks, including Transfrontier Conservation Areas, are being developed to address issues surrounding fragmentation and isolation of wildlife populations (Farhig, 2003; Cushman *et al.*, 2013). These initiatives have important implications for many large carnivore populations (Crooks *et al.,* 2011), the ecological functionality of the landscapes within which they reside (Ripple *et al.,* 2014), and the development of wildlife-based land uses and economies (Funston *et al.*, 2013).

Understanding and promoting species-level connectivity between wildlife managed areas is a key objective of the Kavango-Zambezi Transfrontier Conservation Area (hereafter KAZA TFCA) Programme that spans five neighboring countries and ~70 wildlife managed areas across ~520,00 km^2 of central southern Africa (KAZA, 2011a). The KAZA TFCA represents the largest and arguably most important and ambitious conservation initiative in

Africa, covering a wide range of threatened species, habitats and ecosystem services that provide critical resources and natural wealth to the region's people. But much success with key objectives in this programme is dependent on maintaining and expanding landscape connectivity.

Yet few of the proposed wildlife managed area linkages in the KAZA TFCA Programme have been sufficiently studied at the species and scale of interest to provide planners and managers with the empirical evidence necessary for the informed decision making. This is critical to effective natural resource management and the development of wildlife-based land uses (Cumming, 2008; KAZA, 2014).

Connectivity between Kafue National Park in central western Zambia and the core cluster of wildlife managed areas centered on Chobe National Park in Botswana represents one of the largest questions (and challenges) surrounding natural resource management in the KAZA TFCA Programme. If connectivity cannot be established or developed, Zambia's majority component in the programme will effectively be isolated from the broader landscape, with significant implications for low density, wide-ranging species in Kafue National Park, and the potential and promise of the KAZA TFCA Programme as a whole.

But promoting connectivity and species-level movement at large spatial scales in heterogenous landscapes is dependent on high quality data of system states and species level response to key drivers (Worboys *et al.*, 2010). The main aim of this study is to assess landscape connectivity at the large carnivore scale at the interface of Kafue National Park and adjacent wildlife managed areas, through the Kafue-Simalaha Wildlife Dispersal Corridor and surrounds. Specifically, the objectives of this study are: a) to investigate and model the effect of environmental and anthropogenic factors on the occurrence three large carnivores between Kafue National Park and the Simalaha Wildlife Recovery Sanctuary; and b) to assess the potential of the proposed Kafue-Simalaha Wildlife Dispersal Corridor for single and multi-species landscape-level connectivity planning.

In order to achieve these objectives, we generated high resolution landcover imagery for 3.8m ha using the latest high resolution satellite imagery combined with ground truth data, then incorporated empirical occurrence data for lion (*Panthera leo*), leopard (*Panthera pardus*) and Spotted hyena (*Crocuta crocuta*) throughout ten wildlife managed area covering ~10,000 km^2 to produce species-level habitat suitability maps. Finally, we constructed connectivity models to investigate potential for single and multi-species corridors in support of conservation and land use planning for this vast, heterogenous and increasingly human-impacted landscape.

Our final output has broad applied value for corridor planning and the development of wildlife-based land uses throughout the Kavango-Zambezi Transfrontier Conservation Area and beyond, supporting the knowledge base for long term persistence of large carnivores, the ecological integrity of systems in which they reside and the promotion of sustainable wildlife-based land uses for the landscapes' rural poor.

3.2 Methods

3.2.1 Study Area

The KAZA TFCA encompasses a matrix of over 70 wildlife managed areas in IUCN I-VI and Not Reported categories (UNEP-WCMC, 2015), spanning the borders of Angola, Botswana, Namibia, Zambia and Zimbabwe in central southern Africa, extending over c.520,000 km^2 (KAZA, 2014). Spatially, these wildlife managed areas fall into three major clusters and five periphery clusters, with Kafue National Park and surrounding wildlife managed areas representing the major northern cluster (Fig. 3.1).

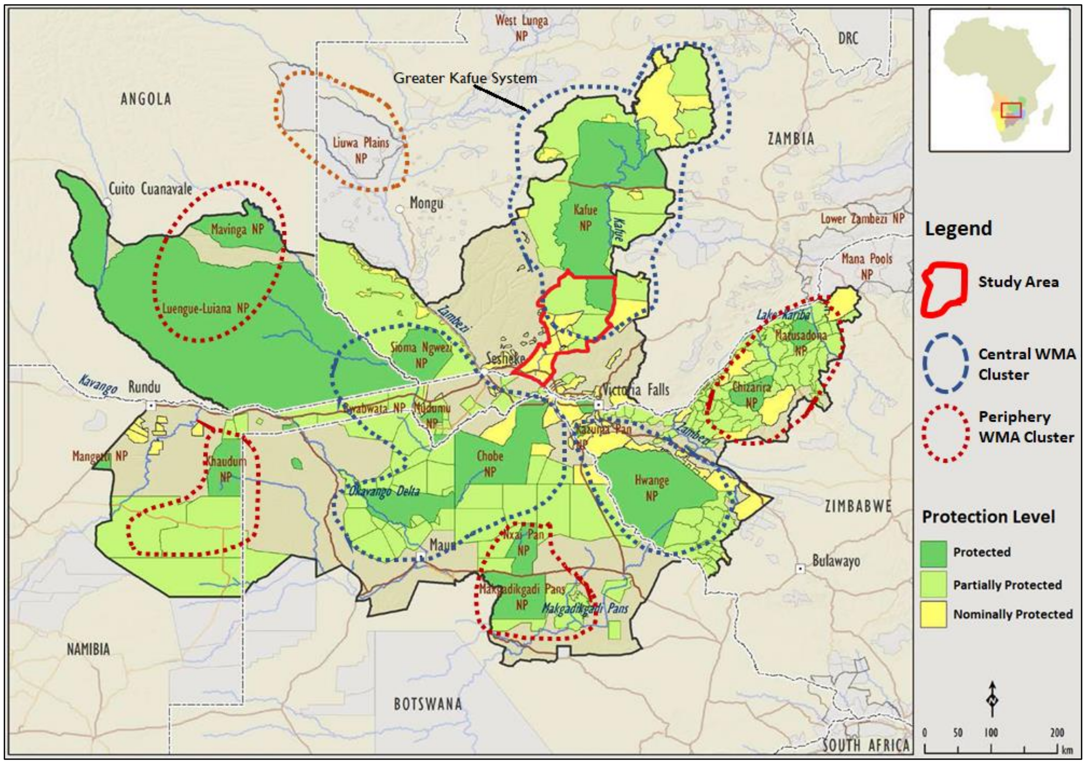

Figure 3.1. The Kavango-Zambezi Transfrontier Conservation Area landscape, indicating study area, clusters of wildlife managed areas (WMAs) and their degrees of protection. Protected = National Parks IUCN II; Partially Protected = IUCN III-VI; Nominally Protected = IUCN *Not Reported* (*adapted* from PPF, 2011a).

Kafue National Park is Zambia's oldest and largest protected area, the largest National Park in the KAZA TFCA and the 2nd largest National Park in Africa at 22,480 km^2 (UNEP/WCMC, 2015). In concert with nine surrounding IUCN category VI Game Management Areas, the effective unfenced area known as the Greater Kafue System covers c.68,000 km^2 – a vast undeveloped area approximately half the size of England, representing 9% of Zambia's land area (ZAWA, 2010).

The Greater Kafue System has been included as Zambia's majority component in the KAZA TFCA programme, encompassing c.25% of the Programme's wildlife estate (KAZA, 2014). Terrestrial connectivity to adjacent clusters of wildlife managed areas comprises a minor potential linkage routing west-southwest to Sioma National Park, spanning ≥210 km, and a major potential linkage routing south-southwest towards Chobe National Park, at the heart of the KAZA TFCA – the focus of this study. This linkage, termed the Kafue-Simalaha Wildlife Dispersal Corridor (KAZA, 2014), passes through a mosaic of nominally, potentially and possibly protected wildlife managed areas including Mulobezi and Sichifulo Game Management Areas, Nachitwe, Martin and Machili Forest Reserves, the Nyawa communal areas, and Simalaha Communal Conservancy (Fig. 3.2). In concert these wildlife managed areas extend the Greater Kafue System to around 7.3 m ha and provide a contiguous matrix of wildlife managed areas spanning 140-170 km from the Kafue National Park border south-southwest towards the Zambezi River at the confluence of Zambia, Namibia and Botswana, broadly following the Machili watershed (Lines *et al.*, 2018). Peripheral areas, considered outside of any formal wildlife protection category, are known as 'Open' Communal Areas, and fall under statutory land tenure authority of the local Chiefdom (Machina, 2005).

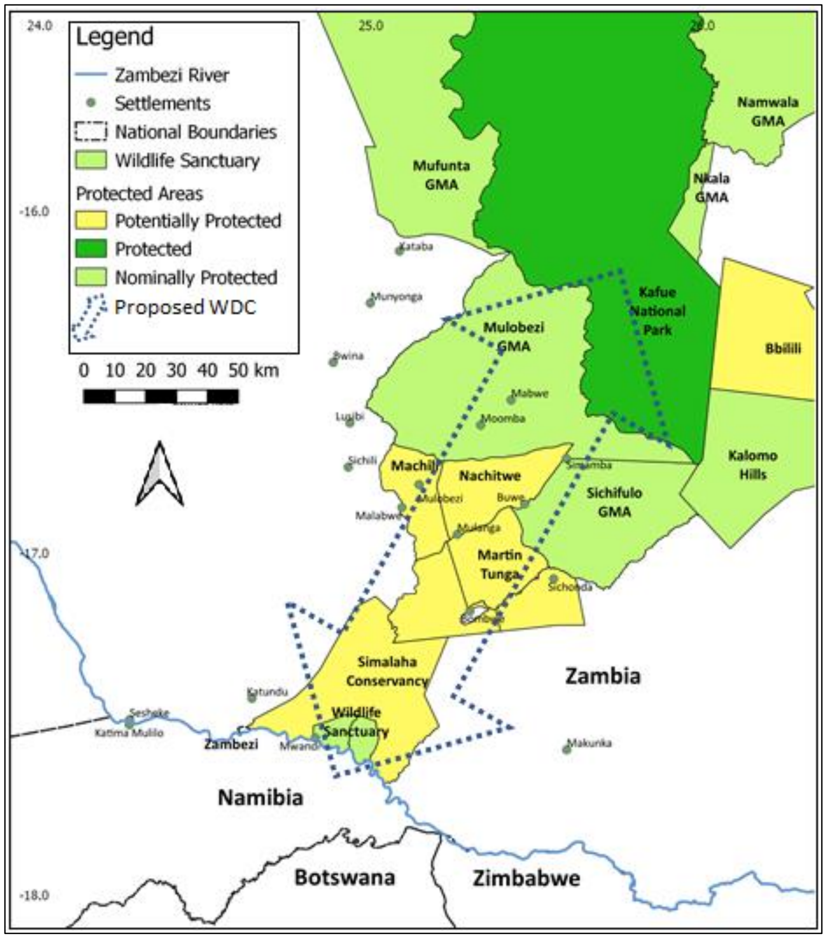

Figure 3.2 Wildlife managed areas within study area, indicating proposed Simalaha-Kafue Wildlife Dispersal Corridor.

3.2.2 Landcover Mapping

A landcover map of the study area was produced using a time-series of Sentinel 2 images in an object-oriented image analysis (OBIA) environment using the software eCognition (eCognition Developer, T, 2014). Sentinel 2 (Copernicus Sentinel data, 2018) is a constellation of two polar-orbiting satellites launched by ESA under the program Copernicus (formerly known as GMES; Drusch *et al.*, 2012). Due to the large size of the study area (32,812 km^2), and the fact that it fell within two paths of the Sentinel 2

(Copernicus Sentinel data, 2018) orbit, the study area was split in two parts and analyzed separately.

The eastern part was mapped using a time series of three images acquired in January, April and August 2016 while the western part was mapped using a time series of three images acquired in May, September and December 2016. The images were geometrically and atmospherically corrected prior to segmentation and classification. During the classification process various spectral ratios were calculated including Normalized Difference Vegetation Index (NDVI;), Normalized Difference Wetness Index (NDWI), Normalized Difference Moisture Index (NDMI), Near InfraRed/Red (NIR).

The first step in any image analysis using the OBIA approach (eCognition Developer, T, 2014) is the creation of meaningful image objects by using segmentation algorithms that group neighboring pixels according to certain criteria of homogeneity. The size and shape of the objects depend primarily on the selected scale parameter (which determines the degree of homogeneity in the resulted objects) as well as by the shape and compactness criterion. Various scale parameters were tested, with the aim of generating objects that have low internal variation and low spatial autocorrelation, and the results were visually inspected. The adopted scale parameter was set at 100 while the colour and homogeneity criterion were set at 0.3 and 0.5, respectively. Minimum mapping unit was set at 0.25 ha.

The training data set for the semi-automatic image classification was provided by *in-situ* observations. Six classes were identified in the field resulting in a training data set consisting of 172 *in-situ* observations made by the lead researcher while active in the field. The identified classes were Arable land, Kalahari, Mopane and Teak woodland, Seasonally flooded grasslands and permanent water. A vector dataset containing the settlements (comprising areas encompassing borders of housing aggregations), which were digitized manually using Google Earth, was integrated in the final classification product in a GIS environment (ESRI, 2012).

Random Forests was the classifier which was found to perform better in this study area and with the data used, compared to Classification Trees, Support Vector Machines and K Nearest Neighbor (see Appendix 2 for further explanations).

The two land cover maps that resulted from the classification of the two separate parts of the study area were then merged in eCognition and the accuracy assessment was performed for the entire land cover map. The method proposed by Congalton (1991) was employed for the accuracy assessment which uses an error matrix based on a TTA mask (see Appendix 2 for further explanations).

3.2.3 Habitat Suitability Modelling

The habitat suitability maps for lion, leopard and Spotted hyaena were generated using MaxEnt (Phillips *et al.*, 2008), as this software has been found to perform well compared to other modelling techniques that use presence only data (Elith *et al.*, 2006), and has been repeatedly used to model the distribution of large carnivores in diverse geographical contexts (e.g. Jackson *et al.*, 2016; Di Minin *et al.*, 2013; Angelieri *et al.*, 2016; Ahmadi *et al.*, 2017).

We incorporated empirically generated occurrence data from on-going research and monitoring in the area, from Lines *et al*. (2018). In total, 102 x 4 km transects, optimized for site conditions, were surveyed on foot three times by the author and two experienced local trackers from the safari hunting industry, amounting to 1,224 km of spoor transects during the dry season of May–October 2015 (see Appendix 2 for further explanations). To account for sampling bias problems relevant to prediction accuracy and model fitting, we spatially filtered occurrence records for all species by thinning records within 500 m of each other (incorporating a 500 x 500 m pixel-size grid of the area) using spThin package in R (Aiello-Lammens *et al.*, 2015). In total, 43 occurrence records were used for lions, 84 for leopards and 78 for spotted hyenas. While we sought to incorporate occurrence data for the entire extant large carnivore guild known from the Greater Kafue System, sample sizes were too small for cheetah (*Acinonyx jubatus*) and African wild dog (*Lycaon pictus*) to include in final analyses. For cheetah and African wild dog occurrence records see Lines *et al.* (2018).

The full set of predictor variables utilized is presented in Table 3.1. All vegetation-related variables (except Enhanced Vegetation Index), as well as proportion of arable land, distance to and proportion of settlements, and distance to water were derived from the land cover map generated using the Sentinel imagery described above. Roads layers, provided by Peace Parks Foundation, were modified where inaccurate using ground truthing via 4x4 vehicle during fieldwork planning, and distances to roads calculated in QGIS (2016). Bioclimatic parameters exhibit little spatial variability across the study area, so we did not use them as predictor variables (Fitzpatrick *et al.*, 2013). To account for collinearity, we retained all uncorrelated variables (using r, < 0.7), indicating weak relationships. In our case, only variables related to anthropogenic pressures and elevation were correlated (Table 3.2).

In terms of variable selection, to keep models as simple as possible to aid in the interpretation of the species' distribution and its environment drivers, we strived for “parsimonious and interpretable models” (Merow *et al.*, 2013). In all models, through a backwards stepwise process, we excluded all variables that when added in the models did not produce any increase in Area Under Curve, a measure of model fit. For the same reasons (parsimony and interpretability), we ran models using only linear and quadratic features (as suggested by Merow *et al.*, 2013). 30% of the occurrence data was left out as a testing set, and the models were trained with the remaining 70%. Fifty model iterations were ran, with 10,000 background points and default pseudoabsence generation. The resulting habitat suitability map provides a habitat suitability value between 0 and 1 for each grid cell/pixel.

Table 3.1. Predictor variables used in the model building process.
Source key: **[1]**Peace Parks Foundation (2016), **[2]**Expert knowledge/ground truthing, **[3]**Landcover map (this paper), **[4]**ASTER Global DEM, **[5]**MODIS Vegetation Index Products

Predictor Variables			
1	Proportion of arable land [3]	10	Distance to minor roads (unpaved) [1,2]
2	Proportion of Kalahari woodland [3]	11	Distance to major and minor roads, combined [1,2]
3	Proportion of Mopane woodland [3]	12	Distance to major, minor roads & rail, combined [1,2]
4	Proportion of Teak woodland [3]	13	Distance to train tracks [1]
5	Proportion of grassland [3]	14	Altitude (Digital elevation model) [4]
6	Proportion of settlements (at 1, 2 and 3 km radius) [3]	15	Topographic Position Index [4]
7	Distance to water [4]	16	Slope [5]
8	Distance to settlements [4]	17	Enhanced Vegetation Index [5]
9	Distance to major roads (paved)* [2]		

3.2.4 Connectivity Modelling

To provide insights into scope, scale and any species-level overlap of potential ecological flows in the Kafue-Simalaha Wildlife Dispersal Corridor we developed three individual species, and one multi-species model using Linkage Mapper (McRea & Kavanagh, 2011), as this software provides robust estimates of connectivity for large carnivores in heterogenous landscapes (Wolf & Ripple, 2018; Castilho *et al.*, 2015; Carroll *et al.*, 2012). The Pathway Tool was chosen to identify and model potential linkages between core areas, graphically displaying a least-cost corridor where species would encounter more features facilitating, and less features impeding movement between core areas based on predetermined site and species-specific resistance layers - the inversed habitat suitability maps generated by MaxEnt (McRae & Kavanagh, 2011). Parameterizing Linkage Mapper requires the identification of paired nodes between which patch-based graphic analyses of connectivity can be undertaken. Given Kafue National Park represents a single source population of all three target species, with a border extending c.120 km within the study area, we tested the effect of multiple source nodes along the Kafue border on least-cost path outcomes, finally settling on 3 roughly equidistant nodes at the northwest, central and southwestern points bordering a representative cross-section of adjacent Game Management Areas, implying target species could move between any of these nodes to the southern node at the Simalaha Wildlife Recovery Sanctuary.

3.3 Results

3.3.1 Landcover Mapping

The final landcover map (Fig. 3) had an overall classification accuracy of 91.6% and a Kappa Statistic of 0.88, indicating an excellent classification performance identifying our seven landcover variables. The dominant land cover is Kalahari woodland (56.2%), followed by Mopane woodland (15.6%) characteristic of south-central floodplains. Seasonally flooded grassland (13.0%) dominate the floodplains and drainage lines and are closely associated with water (0.2% and arable land (4.6%). Teak woodland (10.3%), formerly representing extensive closed-canopy forest tracts, has been heavily denuded by extractive activities, and further suppressed by fire (Musgrave, 2016). Settlements (0.1%) are closely associated with drainage lines (available surface water), grasslands and agricultural areas. Surface water is depicted here for dry season (May-Nov). After heavy rains most all grassland areas are commonly inundated for many months.

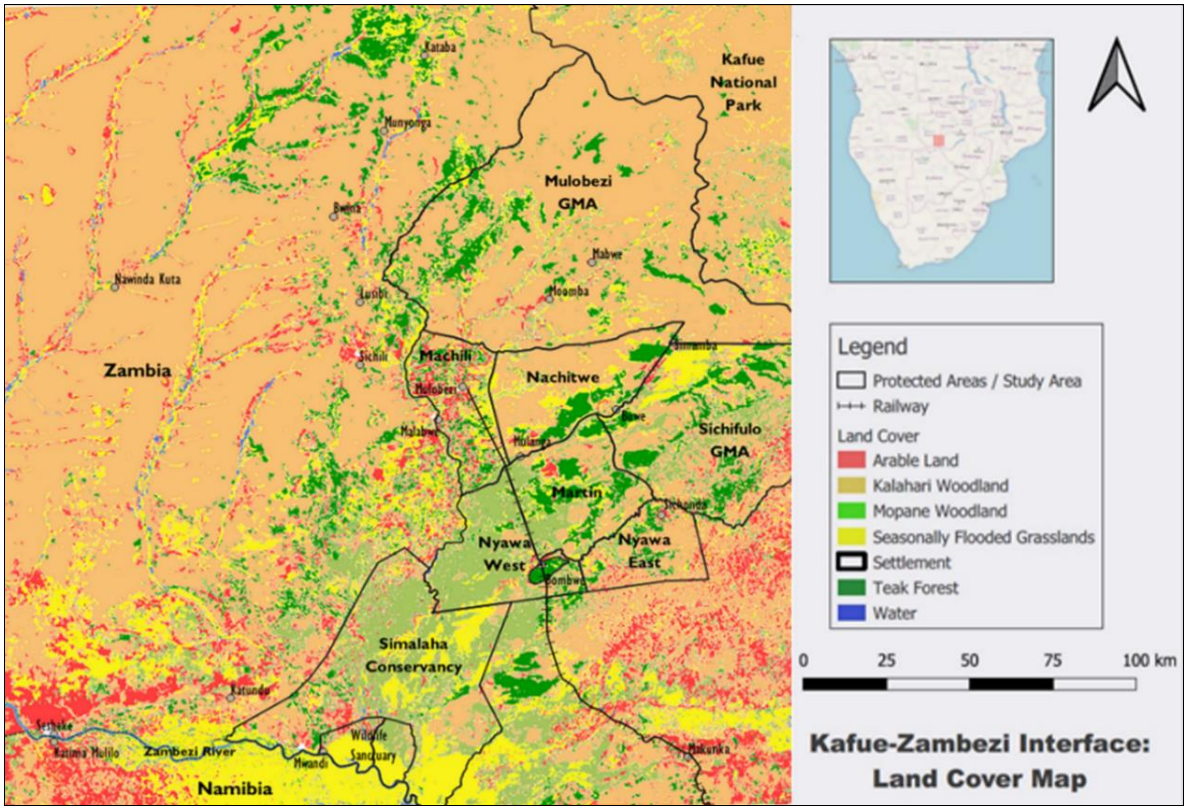

Figure 3.3. Landcover map of the wider study area, indicating wildlife managed areas and larger settlements.

3.3.2 *MaxEnt Habitat Suitability Models*

Three habitat suitability models were built, one for each species (Fig. 3.4). The models for lion had the best AUC (0.81), followed by leopards (0.80) and spotted hyenas (0.79). All models identified Kafue National Park as core habitat with extensive areas of Mulobezi and Sichifulo Game Management Areas, and to decreasing extent the Forest reserves of Nachitwe and Martin. Machili Forest Reserve has been identified as largely unsuitable for all three species. Further south increased variability was exhibited between wildlife managed areas and species, though western areas of Simalaha present poor suitability. Interestingly east of Simalaha was identified as common suitable habitat.

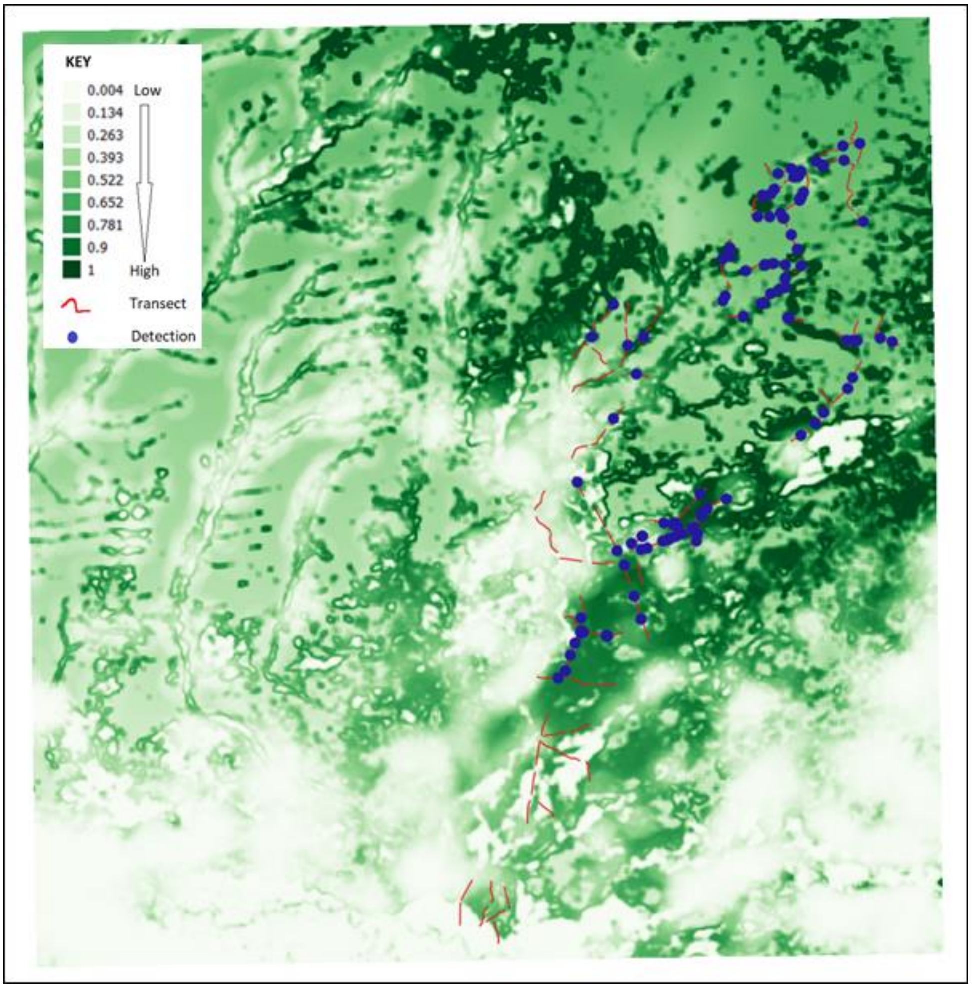

Figure 3.4: Habitat Suitability Map for Spotted Hyena

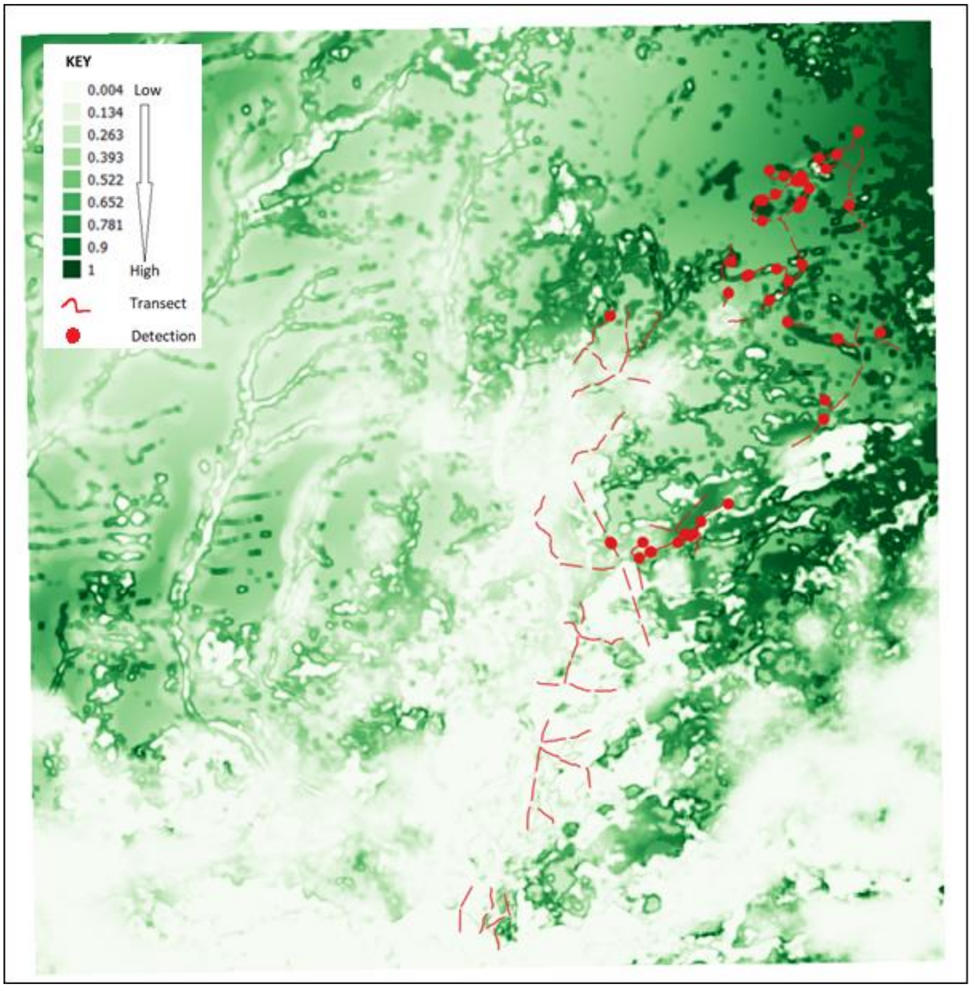

Figure 3.5: Habitat Suitability Map for Lion

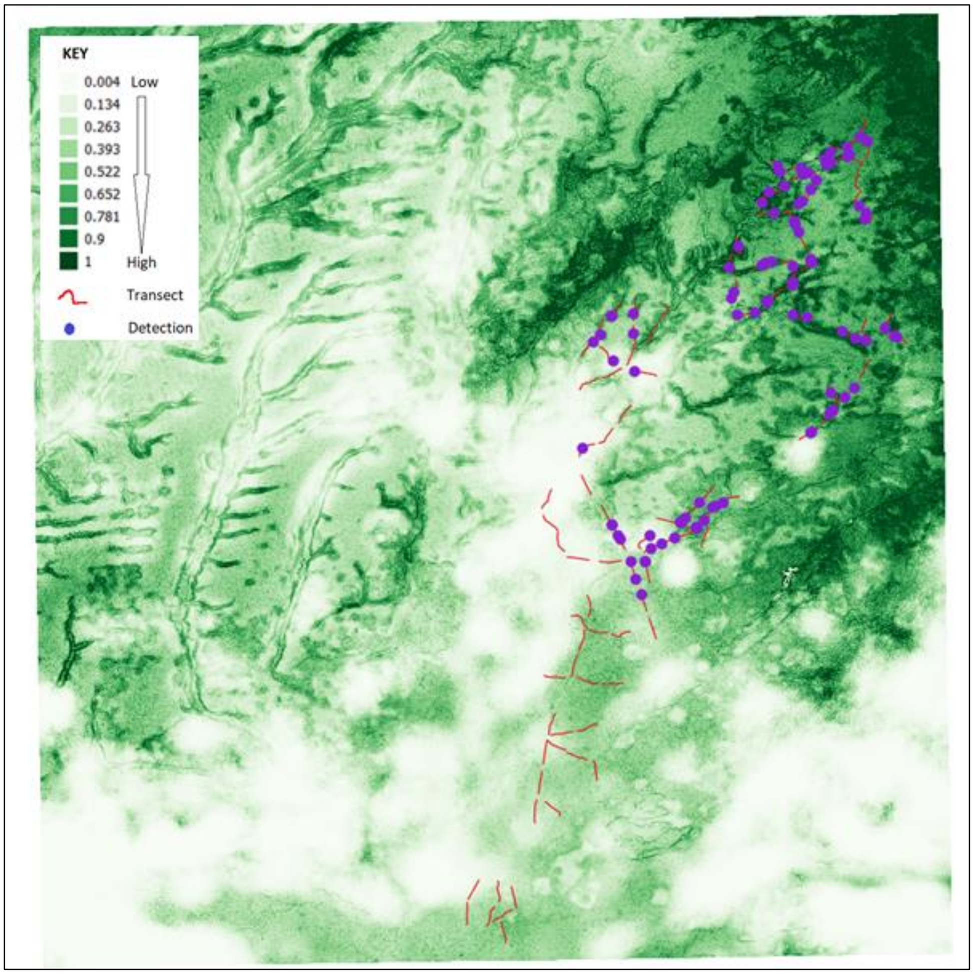

Figure 3.6: Habitat Suitability Map for Leopard

According to model output, the three species distributions are affected by different variables (see Table 3.2). Notably the proportion of settlement, a proxy of human population density, had a negative effect on all species. Proportion of arable land had strong negative effects on leopard and hyena. All three species exhibited strong relationships to road and/or rail infrastructure indicating increased probability of finding all three species the further from roads and/or rail. Proportion of Kalahari woodland cover was positively associated with all species, with Lion positively associated with proportion of all woodland landcover classifications. Proportion of grasslands (lion and hyena) and distance to water (leopard and hyena) were also notable predictor variables.

Table 3.1. Variable importance for the Maxent models, based on AUC using a single variable. Light grey are the variables with a negative contribution to relative habitat suitability.

Predictor variable	Lion	Leopard	Spotted hyena
Proportion of arable land	-	0.67	0.64
Proportion of settlements	0.57	0.53	0.52
Distance to settlements	-	-	-
Distance to major roads (paved)	-	-	0.65
Distance to minor roads (unpaved)	-	-	-
Distance to major and minor roads (combined)	0.72	-	-
Distance to major and minor roads and rail (combined)		0.70	-
Distance to train tracks	-	-	-
Proportion of Kalahari woodland	-0.64	-0.56	-0.52
Proportion of Mopane woodland	-0.64	-	-
Proportion of Teak woodland	-0.55	-	-
Proportion of grassland	-0.58	-	-0.60
Distance to water	-	-0.60	-0.59
Topographic Position Index	-0.64	-	-
Slope	-	-0.65	-

3.3.3 Connectivity Modelling using Linkage Mapper

Pathways analyses indicates broadly similar spatial routing for all three species, with least-cost corridors consistently following the Kafue National Park border, indicating optimal (core) habitat within Kafue National Park (Fig. 3.5). Irrespective of source nodes, all models produced a least-cost corridor exiting Kafue National Park at the southern border, at the closest spatial point to the southern node. This followed the route through eastern Mulobezi Game Management Area, Sichifulo Game Management Area, the border areas of Martin Forest Reserve and Nyawa Communal Areas, then through the eastern section of Simalaha Communal Conservancy, extending notably east of Simalaha in the case of lion into Open Communal Areas. The Spotted hyena model provided the largest spatial extent of moderate to highly suitable corridor area (depicted as yellow/green/blue shading), followed by leopard then lion.

Minimum corridor width, identified as moderately to highly suitable areas, was 5.1km for lion, 4.3km for leopard and 3.2km Spotted hyena. All three species' paths narrowed noticeably in southern areas, and all reached the Simalaha Wildlife Recovery Sanctuary at the northeast corner.

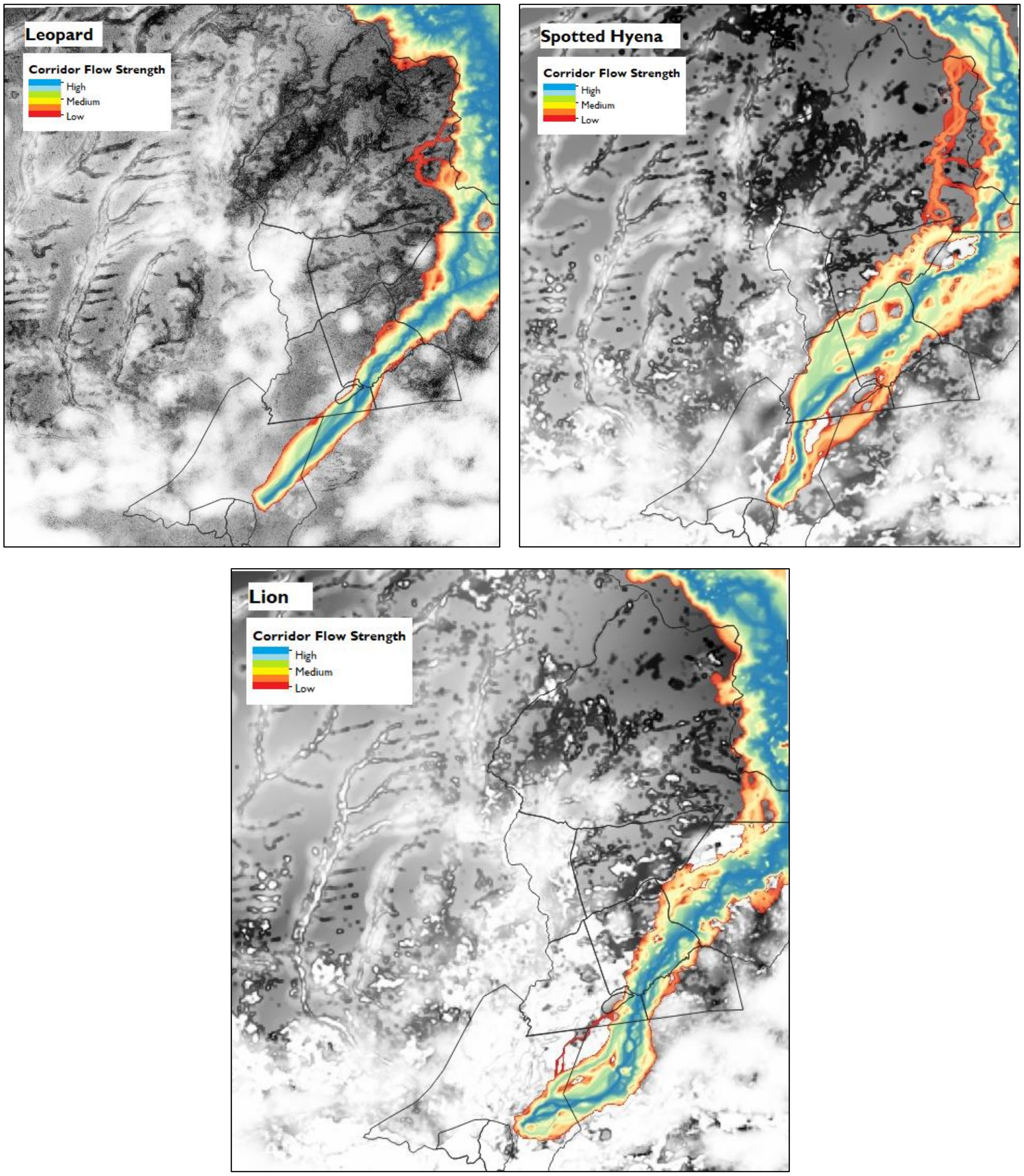

Figure 3.7. Connectivity modelling outputs by species. Habitat suitability following Fig 3.4-3.6. Darker monochrome areas indicate increased habitat suitability.

The derived multi-species model (Fig. 3.8) exhibits broadly similar corridor routing and spatial extent through Kafue National Park and eastern Mulobezi Game Management Area into Sichifulo Game Management Area, before displaying greater variability and a reduction in common corridor routing and current flow strength in central southern areas. A ~25 km long stretch of low current flow, starting at the interface of the Nyawa West Communal Area and the adjacent Open Communal Area, indicate potential constraints to species movement. Moderate-highly suitable current flow, though narrow (<2 km width), converges again within ~10 km from the northeast corner of the Simalaha Wildlife Recovery Sanctuary.

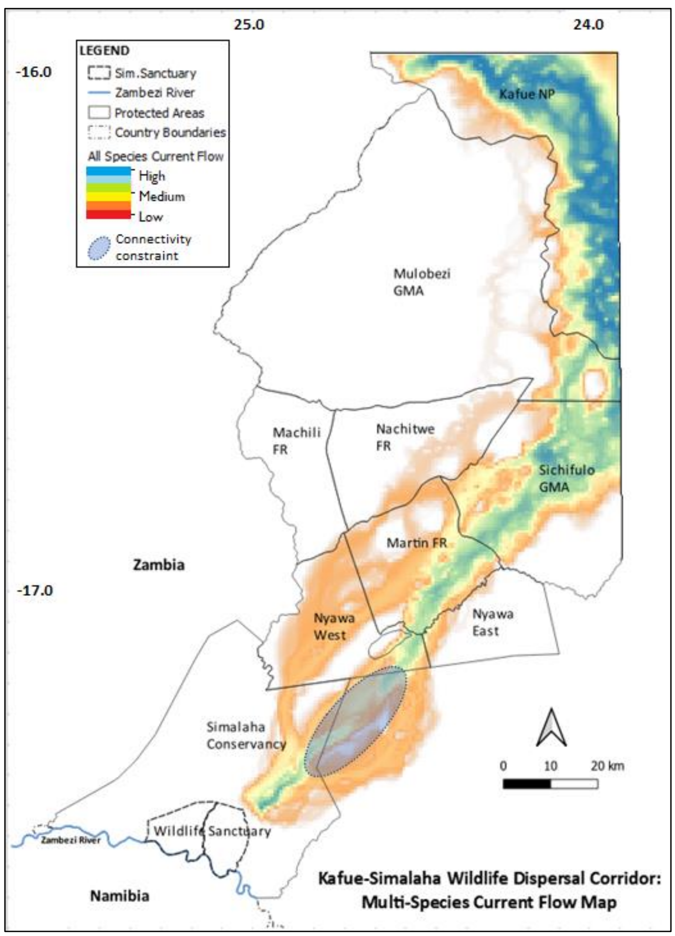

Figure 3.8. Composite connectivity model for 3 species, indicating area with potential connectivity constraint.

3.4 Discussion

Connectivity is an increasingly threatened ecological process and predicted to deteriorate due primarily to issues surrounding human population growth and encroachment around core wildlife areas (Wittemyer *et al.*, 2008), with severe implications for many wide-ranging, low-density species (Ripple *et al.*, 2014; Watson *et al.*, 2015). Maintaining and promoting connectivity in wildlife managed area networks is thus considered an important intervention for the conservation of free-ranging large carnivore populations, elevating the value of the proposed Kafue-Simalaha Wildlife Dispersal Corridor, and providing a test case for explicit goals and outcomes within the KAZA-TFCA Programme.

Developing linkages in heterogenous landscapes presents practical and theoretical challenges surrounding the identification of land that will best meet the requirements for focal species to move between core wildlife managed areas, and how to translate resource selection measurements into resistance (Beier *et al.*, 2008). By choosing a multi-species approach that focuses on wildlife with high susceptibility to human disturbance and resource competition, and those driving broader ecological processes, our approach serves as a model for a collective umbrella under which a wider range of species and processes are factored in, creating a broadly applicable approach pertinent to the wider KAZA-TFCA landscape and beyond. Considering that our approach is based on often available species occurrence data and free to use Sentinel images, it could serve as a general approach in other data-poor regions in Central Southern Africa and beyond.

Our findings indicate that in the area of the proposed Kafue-Simalaha Wildlife Dispersal Corridor, anthropogenic pressures are affecting the distribution of large carnivore fauna, with important implications for landscape and wildlife management in the area. Our results indicate that settlements, arable land and road and rail infrastructure have clear negative effects on all species, albeit to different extents across the species (see Table 2 for response curves). While well documented case studies highlight the occurrence of resident Spotted hyena and leopard populations in and around human settlements, in our case the area under study is not heavily urbanized nor populated as in other cases in the literature (e.g. Yirga *et al.*, 2013; Athreya *et al.*, 2013). Our findings indicate that the effects of settlements are context dependent, demonstrating the importance of understanding broader area and management characteristics (Woodroffe, 2000; Linnell *et al.*, 2001). Road and rail infrastructure in various combinations impacts all species. While literature indicates wide-ranging impacts of transport infrastructure on vertebrate populations (e.g. Trombulak & Frissell, 2002; Coffin, 2007), there are significant limits to our understanding of how transport links affect carnivore populations, though by providing people access to remote areas there are likely broader issues surrounding negative synergistic effects of access at larger scales (Forman *et al.*, 2003).

All species in the study area were habitat generalists, and we therefore predicted strong relationship to a cross-section of habitat types. Lion exhibit a strong preference for woodland cover, a localised characteristic found by Elliot *et al.* (2014), and likely a response partly driven by spatial avoidance of humans (Oriol *et al.*, 2015; Loveridge *et al.*, 2017) and preferred prey availability (Schaller, 1976). The more catholic diet of leopard and hyena allows both species to exploit a wider range of habitats and food sources (Hayward & Kerley, 2008). The relationship of leopard and hyena to dry season surface water poses questions surrounding disturbance competition by seasonal shifting pastoralist activities at water points, including elevated poaching pressure (Lindsay *et al.*, 2013), charcoal production (Munthali *et al.*, 2018) and impacts of fire (Musgrave, 2016).

Our modelled corridor routing for single and multi-species models broadly compliments existing outputs (Cushman *et al.*, 2018 & 2016), indicating limited habitat suitability in southern and central areas, increasing habitat suitability towards Kafue National Park, and also preferential corridor routing along eastern areas of the proposed Kafue-Simalaha Wildlife Dispersal Corridor. At the wildlife managed area scale our output indicated elevated habitat suitability within Kafue National Park which is intuitively encouraging given Kafue National Park is a significant core wildlife area, and specifically for the region's large carnivores (IUCN, 2006b; Jacobson et al., 2016; RWCP & IUCN/SSC, 2015). Given extensive areas of northern and eastern Mulobezi GMA are ostensibly free of direct and much indirect human pressure (Lines, *expert opinion*) there was an expectation for elevated current flow in these areas, though evidently least-cost path models prioritised Kafue National Park and proximity to the destination node, though this does not preclude availability of suitable habitat and prey in remote areas of Mulobezi GMA (Lines *et al.*, 2018). Further south, beyond the Forest Reserves and into the Communal Areas, current flow closely matched expectations, with constrained current flow for all species, and the possibility of a connectivity bottleneck south of Bombwe, representing an area where movement is funneled, curtailed or severed, and connectivity diminished or lost (Berger *et al.*, 2006), in support of the hypothesis offered by Lines *et al* (2018).

Notwithstanding expectations, and given likely compounded error through occurrence, land cover and habitat suitability analyses, the corridor modelling, both at species and multi-species level, clearly reflects reduced connectivity moving south from Kafue National Park into more human disturbed areas. From a connectivity management perspective this is a particularly important area to keep intact, as loss of this area might disproportionally compromise connectivity (Castilho *et al.*, 2015). A greater understanding of implications concerning species-level demography on movement would be a valuable addition to these outputs.

Our integrated approach has extended the analytical framework to provide higher resolution understanding of localized corridor characteristics – notably overlap in multi-species corridor routing and spatial constraints in habitat suitability for central-southern extents of the proposed Kafue-Simalaha Wildlife Dispersal Corridor. This has important implications for practical corridor planning and interventions to counter effects limiting movement. While landscape dynamics will affect individual vs population level movements (Muller *et al.*, 2011), and species-scale demographics will likely influence dispersal mechanisms (Elliot *et al.*, 2014), our approach has clearly provided valuable supplemental detail and understanding to existing broader-scale, species-specific models.

What is clear from the land cover map is the extensive settlement and agricultural development along the majority of watercourses, even deep into Game Management Areas where settlement and agriculture should be precluded from core wildlife zones. The eastern areas of Sichifulo Game Management Area, almost all of Machili Forest Reserve and eastern Nyawa areas have been heavily affected by slash and burn agricultural development as with the central and western sections of Simalaha. Intensive settlement and agricultural development are occurring in all periphery areas bordering the proposed Kafue-Simalaha Wildlife Dispersal Corridor with the exception of the western extents of the Open Communal area bordering Nyawa East and Simalaha. We urge additional research and support in this area as a priority addition to wildlife-based land use planning for the Kafue-Simalaha Wildlife Dispersal Corridor.

3.5 Conclusion

Integration of land cover, habitat suitability and corridor modelling at the landscape level produced an output broadly in line with existing literature and implying constriction of connectivity for all three species approaching the southern areas of the Kafue-Simalaha Wildlife Dispersal Corridor, but identified a potentially important new area in which to focus conservation efforts. Additionally, at the KAZA TFCA scale, the fencing of the Simalaha Wildlife Recovery Sanctuary and effects of the Zambezi River on wildlife movement south to the central cluster of wildlife managed areas centered on Zambezi Region in Namibia and Chobe National Park in Botswana have not been modelled.

With the human population increasing, and expanding conversion of wildlife habitat for agriculture, any existing bottlenecks hindering wildlife movement, both for large carnivores and their prey, will likely increase in the absence of effective land use planning and implementation, including control of poaching and human-wildlife conflict. Nonetheless, our analyses have produced the first empirical data for evidence-based corridor planning for Zambia’s key linkage in the KAZA-TFCA programme.

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Chapter 4: Utility of Human footprint pressure mapping for large carnivore conservation: The Kafue-Zambezi Interface

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Abstract

Increasing human pressures are driving large carnivore declines within and beyond wildlife managed areas. Edge effects, attractive sinks and bottlenecks constrain connectivity, isolating populations, and hindering development of wildlife-based land uses at local to Transboundary scales.

The development of proxies for monitoring changes to human disturbance against which species responses can be quantified provides a novel conservation tool to model and map species distribution and likelihood of distribution change. This can improve our understanding of threshold pressures at which species can persist, are extirpated or might recolonize human-dominated landscapes.

We integrated high resolution remote sensing data and *in situ* mapping of human pressure variables with an existing landcover map to generate a site-specific, fine scale human footprint pressure map for 3.9 m ha of rangelands at the Kafue-Zambezi interface - a key linkage in the Kavango-Zambezi Transfrontier Conservation Area programme. We then modelled human footprint pressure against empirically derived occurrence data for Lion (*Panthera leo*), Leopard (*Panthera pardus*) and Spotted Hyena (*Crocuta crocuta*). Using these data, we then generated human footprint pressure threshold ranges at which each species were persisting or extirpated within ten wildlife managed areas linking Kafue National Park to the Zambezi River.

Fine scale model results overcame many limitations inherent in existing large-scale human footprint pressure models, providing encouraging direction for this approach. Human footprint pressure thresholds at which species persisted or were extirpated from wildlife managed areas were broadly in line with expectations, indicating this approach is valid for site- and species-specific modelling.

Model performance will improve as additional datasets come available and with improved understanding of how asymmetrical and nonlinear threshold responses to footprint pressure changes across spatial-temporal scales. This approach has broader utility for local and regionwide conservation planning where mapping and managing the ubiquitous impact of humanity will determine species persistence throughout protected area networks.

Key words: Human footprint pressure, Thresholds, Large Carnivores, Kafue, Kavango-Zambezi Transfrontier Conservation Area, Connectivity

Word count: 6110

4.1 Introduction

The ubiquitous impact of humanity on the planet stretches from the deep ocean to mountaintops, manifesting through our direct demands on natural resources and indirect effects of these demands on wider global systems (Vitousek *et al.*,1997; Wackernagel *et al.*, 2002). The wide-ranging implications of increasing spatial-temporal resource demands include loss and fragmentation of key wildlife habitats (Riitters *et al.*,2000; Foley *et al.*, 2005), constraining species movement (Tucker *et al.*, 2018) and the reduction and extinction of wildlife populations at multiple scales (Maxwell *et al.*, 2016; Ceballos & Ehrlich, 2002; Ceballos *et al.*, 2015).

While the decline in human pressures on natural systems is presenting new opportunities for rewilding and carnivore conservation throughout much of continental Europe (Navarro & Pereira, 2015), many of the world's developing regions supporting large tracts of existing wildlife habitat and high levels of biodiversity (Brooks *et al.*, 2006) are experiencing intensifying spatio-temporal human pressures in and around protected areas (Newmark, 2008; Geldmann *et al*., 2014). Increased human resource demands in these areas are also impacting conservation efforts and political support for the maintenance and expansion of wildlife-based land uses and wildlife economies at regional, national and transboundary scales (Duffy, 2006; Gren *et al.*, 2018).

These anthropogenic pressures have been characterized as the human footprint and manifest through *inter alia* population growth, the expansion of built areas and settlement, transport infrastructure and linkages, agropastoralism and extractive industries (Sanderson *et al.*, 2002).

Significant human footprint pressure habitually results in profound and complex effects impacting the structure and function of ecosystems, including changes to key resources driving socioecological system productivity and resilience (Walker & Salt, 2012) and livelihood opportunities for communities residing within them (Venter *et al.,* 2016). Elevated human footprint pressure decrease structural and functional connectivity between wildlife managed areas for many species of conservation concern (Ayram *et al.,*2017).

Existing human footprint pressure analyses have traditionally been generated at relatively low resolution to provide overviews and indicators of human footprint pressure impacts on states of interest, such as habitat change and protected area integrity at global scales (Venter *et al.,* 2016; Jones *et al.,* 2018; Watson *et al.,* 2016).

Increasingly the focus of human footprint pressure is shifting to consider its utility as a proxy or predictive indicator for measuring and understanding finer scale impacts on species and processes, including studies on species movement (Tucker *et al.,*2018), behaviour (Gaynor *et al.,*2018), extinction risk (Di Marco *et al.,*2018), range use (Di Marco & Santini, 2015) and more broadly as a conservation planning tool (Tombulak *et al.,* 2010). These approaches seek to overcome many of the questions and limitations surrounding data availability, accuracy and resolution posed by conventional larger scale multivariate models.

Generating site- and species-specific human footprint pressure models that can be used as a proxy or indicator of species-level habitat suitability and sensitivity to human pressure can aid our understanding of thresholds at which species persist, are extirpated or are likely to recolonize both protected and non-protected areas, leading to improved application of conservation science in management (Sutherland *et al.,* 2004). But beyond large scale assessments (Di Marco *et al.,* 2018), these tools are poorly understood and developed owing chiefly to an absence of integrated fine-scale remote sensing and *in situ* data, precluding appropriate accuracy and resolution (Woolmer *et al.,* 2008).

The Kavango-Zambezi Transfrontier Conservation Area (KAZA TFCA) in central southern Africa seeks to promote connectivity between clusters of wildlife managed areas at the interface of five neighboring countries (KAZA, 2011a). Connectivity at the species and scale of interest are poorly studied within and between many of the proposed landscape-scale linkages (Cumming, 2011), but with ubiquitous human pressure increasing throughout the region (Newmark, 2008; Wittemyer *et al*., 2008), there is a need to understand how human footprint pressure are impacting connectivity for key species of interest throughout core linkages.

Large carnivore guilds exert significant top-down influence on ecosystems, imparting strong regulatory pressures driving ecosystem structure and function (Ripple *et al.,* 2014, Estes *et al.,* 2011). They are highly susceptible to direct and indirect human activities including (legal and illegal) hunting, reduction of wild prey and habitat fragmentation and loss (Maxwell *et al*., 2016; Riggio *et al.,* 2018). Large carnivores are also a key asset for the development of wildlife-based land uses and wildlife economies (Funston *et al.,* 2013), and have been identified by the KAZA TFCA Programme as target species for conservation action, including the stabilization and growth of populations in key habitats, and maintenance of secure and active connectivity pathways between core wildlife managed areas (KAZA, 2018). In concert these factors indicate large carnivores as appropriate target species against which to model human footprint pressure.

This study aims to generate a site-specific, fine scale map of human footprint pressure to test 1) the validity of this appropriate for predicting species occurrence and 2) explore if this approach can determine discernible human footprint pressure thresholds at which target species persist or are extirpated at the wildlife managed area scale.

4.2 Methods

4.2.1 Study Area

The KAZA TFCA covers c.520,000 km^2 of central Southern Africa, spanning the borders of Angola, Botswana, Namibia, Zambia and Zimbabwe, and centered around the Kavango and Zambezi River basins (KAZA, 2014). The KAZA TFCA landscape incorporates a network of ~70 protected areas in IUCN I-VI and *Not Reported* categories (UNEP-WCMC, 2015). These protected areas are characterized by a wide spectrum of investment and management effectiveness (Lindsey *et al.*, 2014).

Spatially, these protected areas fall broadly into three major and five periphery clusters, with connectivity between protected area clusters identified as one of KAZA TFCA Programme’s central objectives (KAZA, 2014).

Kafue National Park and surrounding protected areas, collectively known as the Greater Kafue System, represents the KAZA TFCA’s major northern cluster (Fig. 4.1) and Zambia’s majority contribution to the KAZA TFCA Programme (KAZA, 2014). Connectivity between Kafue National Park and adjacent protected areas, centered on Chobe National Park and East Zambezi Region in Namibia, is contingent on movement across eight partially and nominally protected areas plus an adjacent open Communal Areas identified by Lines *et al.* (2020 *in review*) as potentially important for corridor planning. In concert these areas span ~13,000 km^2, extending140-170 km from the Kafue National Park border south-southwest towards the Zambezi River at the confluence of Zambia, Namibia and Botswana (Lines *et al.*, 2018).

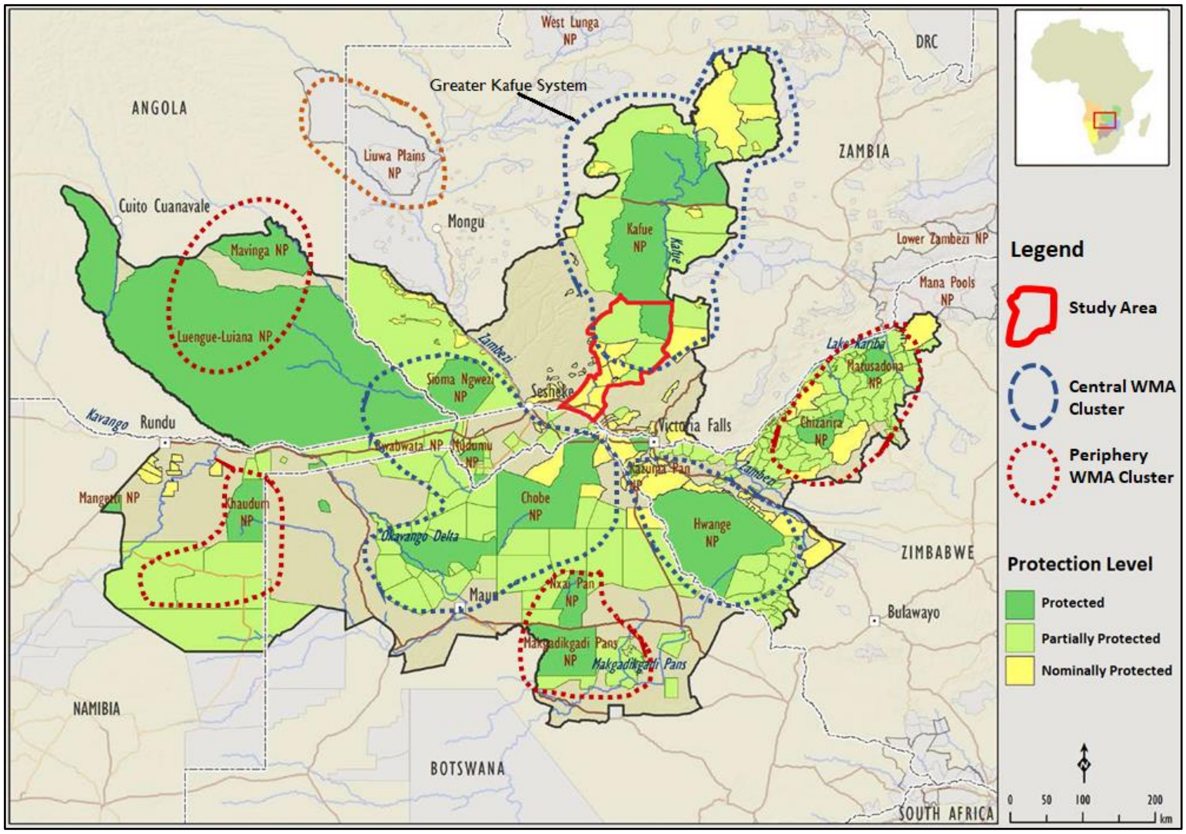


Figure 4.1. The Kavango-Zambezi Transfrontier Conservation Area landscape, indicating study area, clusters of wildlife managed areas (WMAs) and their degrees of protection. Protected = National Parks; IUCN II; Partially Protected = IUCN III-VI; Nominally Protected = IUCN *Not Reported* (*adapted* from KAZA, 2011a).

The landscape is historically, and remains, characterized by dynamic spatiotemporal human pressures, though few data on the areas' wildlife and human population are available prior to the 1960's (Lines *et al.,* 2018; CSO, 2019). Much of the study area was sparsely settled until the development of a railway from Livingstone to Mulobezi from 1923-4 to exploit the region extensive tracts of Zambezi Teak forest (*Baikiaea plurijuga*). Access to formerly remote areas had profound impacts on its people and wildlife (Calvert, 2005). Southern areas around Simalaha, bordering the Zambezi River, were heavily depopulated during the 1966-1990 Angolan Bush War, and thereafter increasing numbers of agro-pastoralists have settled this landscape (Yeta, *pers comms*), with significant increases in human disturbance (Lines *et al.,* 2018). Systematic census from 2000 onward indicate Districts with boundaries intersecting the study area have experienced annualized population growth of ~2.8%, with an average population density of ~4.5/km^2 (CSO, 2019). But these larger scale surveys hide significant finer scale variation.

4.2.2 Generating human footprint pressure maps

Early Geographical Information System-based versions of the human footprint pressure sought to build on the concept of Ecological Footprint mapping (Rees *et al.,*1996), utilizing availability of new Earth observational data sets and advances in satellite imagery capabilities covering human activities and the physical world, including land use and cover, transport linkages and human population density. This increase in resolution and grain has facilitated the development of geographical proxies for inferring variation in global human influences believed to have the most important direct pressure on wildlife and wildlands (Sanderson *et al.,* 2002). With this baseline multivariate model Venter *et al.* (2016) duplicated the methodology of aggregating pressure scores at a global 1 km^2 resolution, based on long-term datasets, to generate updated human footprint pressure and trends over time.

While the Kafue-Zambezi landscape lacks long term datasets from which to derive trend data, our reworking of the Sanderson *et al.* (2002) and Venter *et al.* (2016) methodology sought to integrate the highest resolution data sets currently available for the landscape to generate comparable outputs at two orders of magnitude fine scale. There is no current available data on pastureland, which we omitted from our fine scale reworking, leaving 7 pressure scores (Table 4.1).

Individual variable pressure scores weights are estimates of relative human pressures following Sanderson *et al.* (2002), with many co-occurring at the same spatial scale. Using our calculation the maximum human footprint pressure score is 43.8

1. *Settlement* data was derived from Bonafilia *et al.* (2019) at 30m resolution. All pixels overlapping settlement areas were given a pressure score of 10 representing the highest level of direct pressure (implying settled area were unsuitable for wildlife), with all other pixels given a score of 0. The raster layer was then rescaled to 10 m resolution and written to file.

   While recognizing the complexity and limitations surrounding downscaling, we argue here that scaling from 30 m to 10 m represents a small downscaling in context of settlement characteristics, insofar as the area immediately outside buildings might reasonably be considered part of the building/living area in local rural contexts, and thus downscaling should not pose real or theoretical problem to broader analyses.

2. *Human Population Density* data was unavailable at sufficiently fine scale for the landscape to include as a stand-alone data layer. Given the largely homogenous nature of settlement throughout the area – an absence of large multi-story buildings and dense conurbations versus ubiquitous single-story concrete block and tin buildings with scattered clay (adobe) and grass huts throughout rural area (Lines, *pers obs*), we generated average population density for the study area at the District scale using 2019 population census projected data (CSO, 2019). We then overlaid this on the rescaled settlement layer and applied Venter *el al's*. (2016) methodology to provide an addictive pressure score of 7.363 for every pixel overlaying settlements. This layer was written to file at 10 m resolution.
3. *Roads*: The roads layer pressure scoring followed Venter *el al.* (2016) providing a pressure score of 8 for 0.5 km either side of roads, indicating high direct human pressures on and close to roads with immediate access, and a pressure score of 4 decaying out to 15 km from 0.5 km either side of the roads, indicating lower indirect pressures moving away from the roads, considered the approximate distance a person might reasonably access on foot within a day.

   Firstly, we manually modified a vector roads layers supplied by Peace Parks Foundation (*unpublished data*) to define major tar and secondary dirt roads linking settlement nodes in QGIS (QGIS, 2018), omitting tertiary dirt tracks from analyses due to their dynamic nature and inconsistent mapping. We then created a base raster layer using R (R core team, 2018) with 10 m pixels to cover the study area for both road types giving a value of 1 for each pixel that intersects a road and 0 for all other pixels, then generated a distance raster showing the distance of each '0' pixel to each '1' pixel (the roads) using the GRASS add-on in QGIS with the command r.grow.distance and the ‘Euclidian’ parameter. This created two rasters with continuous values of distance in meters for each road pixel. We assigned all pixels 0m to 500 m from the road with a pressure score of 8, and all pixels more than 15 km from the road to N/A so they are ignored when the exponential decay model was applied to calculate human pressure score within 15 km of roads Starting with a pressure score of 4 at 500 m from roads we applied the exponential decay function to a pressure score of 0.25 out to 15 km (you cannot decay out to 0 or the calculation never ends). Both rasters were then aggregated and the final layer was written to file at 10 m resolution.

4. *Railways* represent direct drivers of habitat conversion and conduits of access into wildlife areas, and indirect effects in adjacent areas, similar to roads, although as passengers cannot commonly disembark at will, indirect effects away from the railway line are considered minimal. Following Venter *el al.* (2016) we gave railways a direct pressure score of 8 for a distance of 500 m either side of the railway using the same method as for roads at 10 m resolution. The layer was written to file.
5. *Navigable Waterways*, like roads, provide direct access to wildlife habitat along the waterway, and indirect access in periphery areas. The Zambezi River is the only permanent navigable waterway in our study area, and following Venter *el al.* (2016), we gave this waterway a direct pressure score of 4, exponentially decaying out to 15 km as with the roads layer methodology. The layers were written to file at 10 m resolution concurrent with the base landcover map generated from Lines *et al.* (2020, *in review*).
6. *Arable land* throughout the Kafue-Zambezi interface is characterized by majority maize and pulses cultivated using the traditional Chitemene low input, rain fed, slash and burn farming method (Musgrave, 2016). Arable landcover classifications are considered by

Venter *el al.* (2016) to provide intermediate disturbance to wildlife though direct reduction of wildlife habitat.

For Arable land the Arable class was selected from the 10 m resolution landcover map classification generated from Lines *et al.* (2020, *in review*) and rasterized onto the 10m base layer, with a pressure score of 7 for pixels intersecting an area of Arable land, and 0 for all other pixels. This layer was then written to file.

7. *Night-time light infrastructure*, while sparse and low intensity throughout much of our study area, is considered a direct human pressure limiting wildlife through a range of negative impacts (Rich & Longcore, 2013).

   The "vcm-orm-ntl" (VIIRS Cloud Mask - Outlier Removed - Night-time Lights) annual average layer was used (NOAA, 2019) and rescaled to 10 m. Pixels with a value 0 (no light) were excluded from the layer, and following Venter *et al.* (2016) we applied the same log formula used for pop density resulting in pixels with scores ranging from 0 to 8.971. This layer was then written to file.

8. *Aggregating the layers:* The score layers were added together in R, to give the final modified human footprint pressure, which was then saved to file-at 10m resolution.

Table 4.1. Modifications to Human Pressure Variables and Pressure Scoring.

Variable	Pressure Score	Source	Naïve Resolution	Details
Settlement	0,10	Bonafilia *et al.*, 2019	30m	All settled areas mapped given score of 10
Population Density	0–10 Continuous	Bonafilia *et al.*, 2019	30m	Pressure score=3.333×log (population density+1)
Roads	0,8 Direct impacts 0–4 Indirect impacts	PPF, *unpublished data*	10m	Direct pressure score of 8 for 500m either side of road, exponentially decaying out to 4 at 15 km
Railways	0-8	PPF, *unpublished data*	10m	Direct pressure score of 8 for 500m either side
Navigable Water	0–4	PPF, *unpublished data*	10m	Pressure score of 4 exponentially decaying out to 15 km
Arable	0,7	Lines *et al.*, 2019	10m	All areas mapped as crops given score of 7
Night Lights/NTL	0-9	NOAA, 2019	100m	Pressure score=3.333×log (NTL+1)

4.2.3 MaxEnt Habitat Suitability Modelling

Following the methods described in Lines *et al.* (2020, *in review*), habitat suitability maps for lion, leopard and spotted hyaena were generated using MaxEnt (Phillips *et al.*, 2008) which performs well compared to other modelling techniques using presence only data (Elith *et al.*, 2011), and has been repeatedly used to model large carnivores distribution (e.g. Jackson *et al.*, 2016; Di Minin *et al.*, 2013; Angelieri *et al.*, 2016; Ahmadi *et al.*, 2017).

We incorporated empirically generated occurrence data from Lines *et al.* (2018). In total, 102 x 4 km transects, optimized for site conditions, were surveyed on foot three times by the author and two experienced local trackers from the safari hunting industry, amounting to 1,224 km of spoor transects during the dry season of May–October 2015, based on a pilot study to determine optimal sampling effort to detect target species and cover the landscape in a single field season (Lines & MacKenzie, *unpublished data*, see Appendix 1 for more detail and explanations).

To account for sampling bias problems relevant to prediction accuracy and model fitting, we spatially filtered occurrence records for all species by thinning records within 500m of each other (incorporating a 500 x 500 m pixel-size grid of the area) using spThin package in R (Aiello-Lammens *et al.,* 2015). In total, 43 occurrence records were used for lions, 84 for leopards and 78 for spotted hyenas. While we sought to incorporate occurrence data for the entire extant large carnivore guild known from the Greater Kafue System, sample sizes were too small for Cheetah (*Acinonyx jubatus*) and African wild dog (*Lycaon pictus*) to include in final analyses. The predictor variable modelled against single occurrence was the aggregated human footprint.

The relationship of large carnivores to changing human footprint pressure is well established at the global scale (Di Marco *et al.*, 2013, 2015). However, application of this relationship towards an understanding of thresholds at which species occur, are locally extirpated, or might recolonize areas is poorly developed, irrespective of its clear utility as a conservation tool (Tombulak *et al.,* 2014). A supplemental exploratory analysis was undertaken to investigate species sensitivity to human footprint pressure at the wildlife managed area scale.

To undertake this analysis we extracted mean human footprint pressure at the wildlife managed area scale against empirically derived occurrence data for lion, leopard and spotted hyena following Lines *et al.* (2018). Outputs were compared against species-level sensitivities to extinction from Di Marco *et al.* (2018), and the ranking of sensitivities to localized extirpation following Riggio *et al.* (2018).

4.3 Results

4.3.1 Human footprint pressure

The 10 m resolution map (Fig. 4.2) indicates areas of high to low human pressure, with notable areas of highest human footprint pressure around Sesheke/Katima Mulilo in the southwest, along the Zambia/Namibia border following the east-west tar road, along much of the Zambezi River and in the central/eastern areas dominated by access roads, settlement and agricultural development. Broadly, settlement and agricultural development is widespread throughout the landscape, concurrent with the formal and informal road network.

Areas of low apparent human footprint pressure include Kafue National Park (where settlement and agriculture are illegal and non-existent), and adjacent areas of northern Mulobezi, Sichifulo Game Management Areas, Nachitwe and Martin Forests.

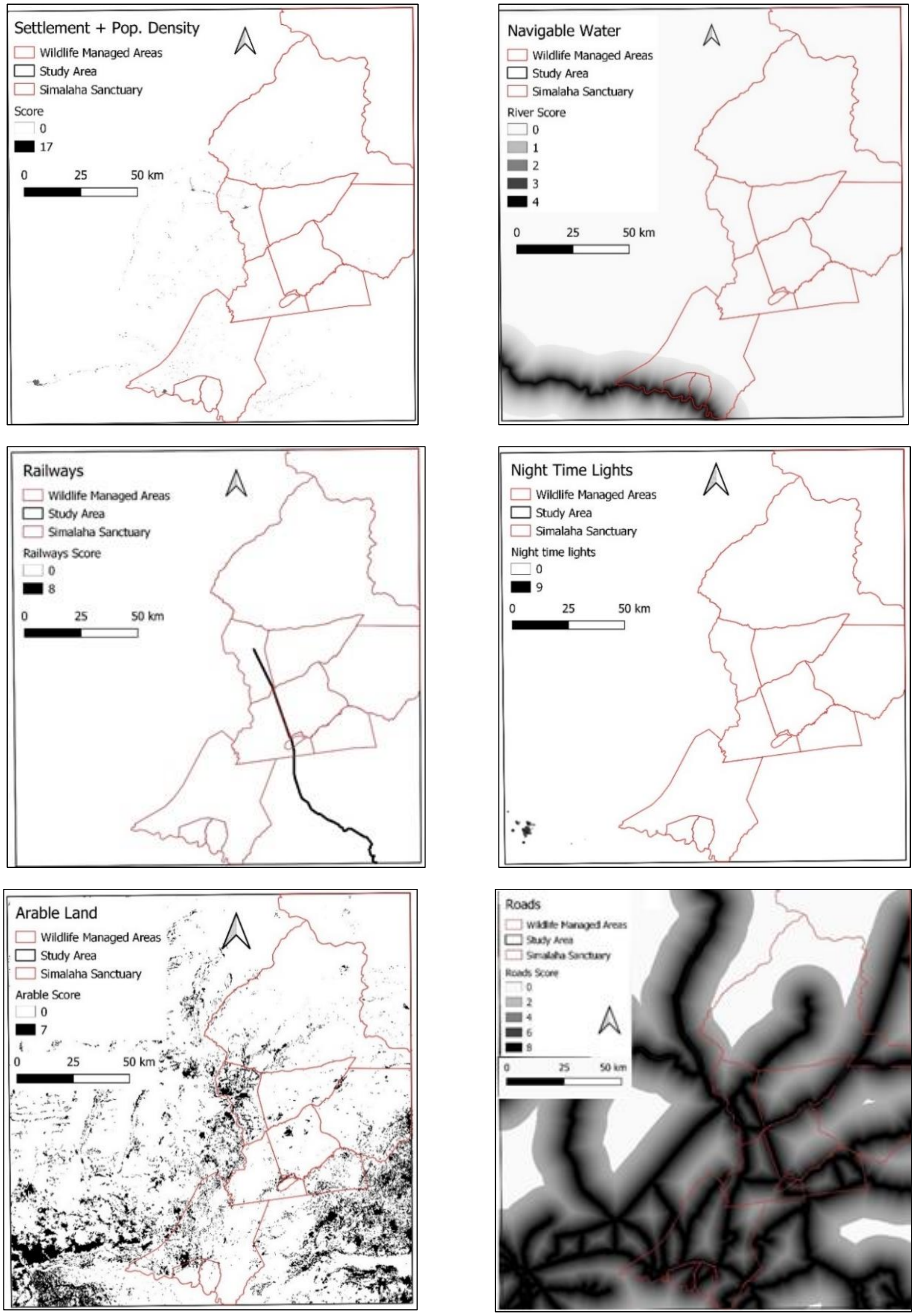


Figure 4.2. Dissagregated Human Footprint layers overlaid on wildlife managed areas. Darker areas represent higher human footprint pressure.

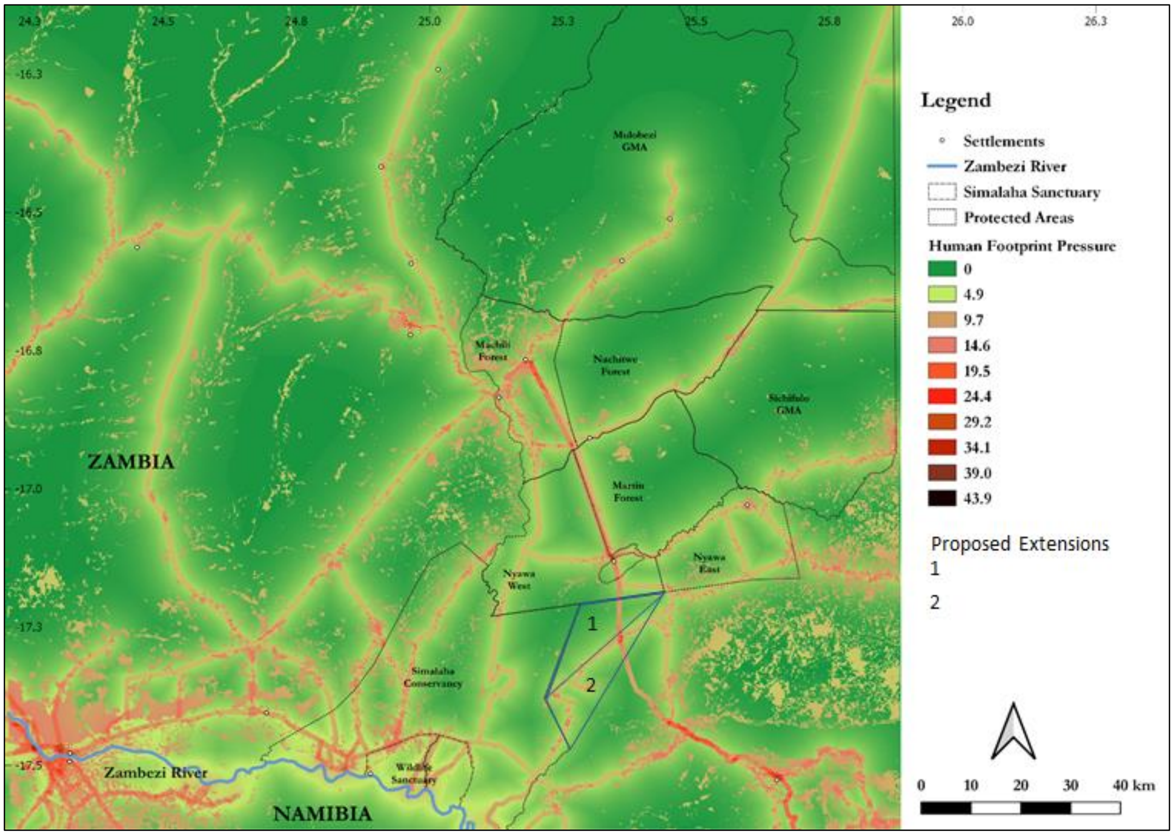


Figure 4.3. Human footprint pressure, Kafue-Zambezi Interface, 10m resolution.

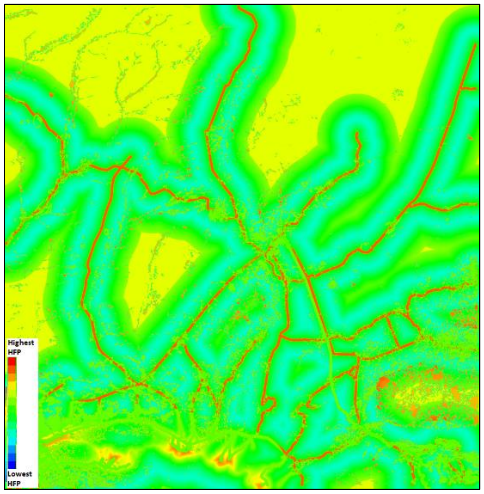
4.3.2 MaxEnt Habitat Suitability Modelling Outputs

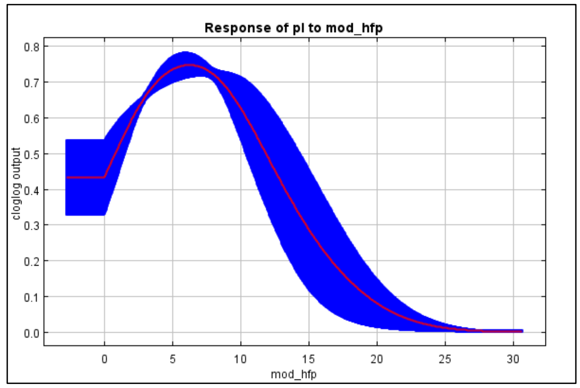
The best performing model was for lion with an AUC of 0.76 followed by leopard (AUC 0.70) and finally Spotted hyena (AUC 0.61), indicating strong to moderate model performance, and a negative correlation between aggregated human pressure and species occurrence (Fig 4.4).

Human footprint pressure had the greatest impact on lion, then leopard and hyena, with extensive unsuitable areas for all species in central-southern areas, and especially along the river parallel to the main tar road where much settlement and agriculture also occurs. Another notable linear feature of human pressure affecting all species followed the railway line and parallel roads, interspersed with settlement and arable lands, where transport infrastructure, settlement and agricultural development are driving the human footprint pressure throughout this landscape.

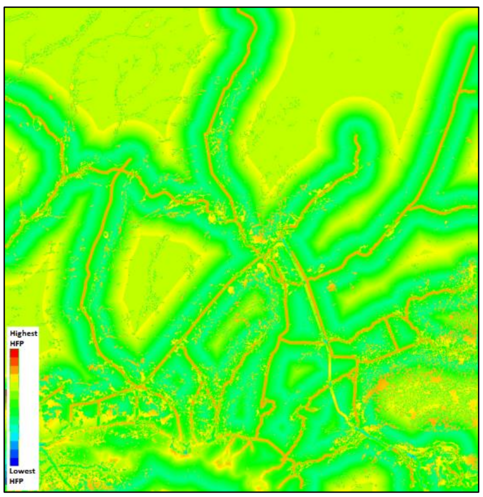
At the wildlife managed area scale human footprint pressure was lowest in Kafue National Park, Mulobezi and western parts of Sichifulo Game Management Areas. Both Nachitwe and Martin Forest Reserves appear relatively intact, though exhibiting elevated pressure towards their western boundaries. Machili Forest Reserve is heavily impacted throughout by human pressure. There are still areas within Nyawa communal lands with relatively low human pressure and again to the northeast and eastern sections of Simalaha, extending into the adjacent Open Area. Extensive pressure exists around the settlement of Bombwe, formerly a registered Forest Reserve, although now degazetted in recognition of unmanaged human pressures degrading the forest and natural resources (Inyambo-Yeta, *pers comms*). Simalaha Wildlife Recovery Sanctuary, sandwiched between the Zambezi River and main Tar road running between the borders of Namibia and Zimbabwe, is subject to elevated human pressure, including settlement and agriculture both within the Sanctuary and on its borders.

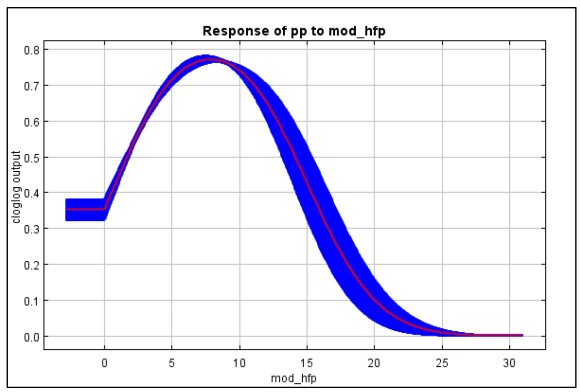
Lion: HFP / Mean AUC: 0.764



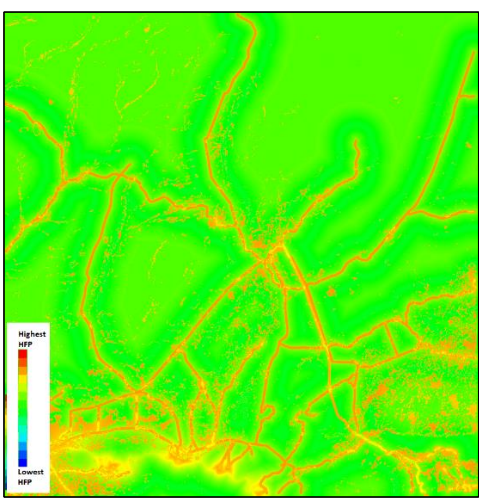


Leopard: HFP / Mean AUC: 0.699





Spotted hyena: HFP / Mean AUC: 0.606



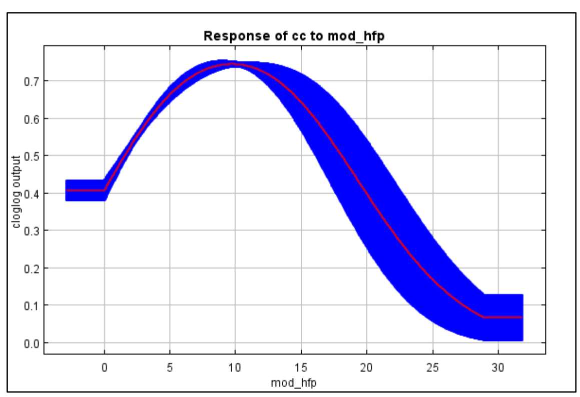


Figure 4.4. Human footprint pressure-based Habitat Suitability Models

Response curves in Fig 4.4 are an indication of species sensitivity to human footprint pressure, showing highest sensitivity for lion followed by leopard then spotted hyena, as expected by availability of suitable habitat.

4.3.3 Human footprint pressure thresholds and Species Persistence

The gradient of mean human footprint pressure at the wildlife managed area scale varied from 1.1 in Kafue National Park to 6.8 in the western section of the Simalaha Sanctuary, with IUCN categorized protected areas experiencing lowest mean Human footprint pressure (Table 4.2). With the exception of Machili Forest (human footprint pressure 5.6) there was a steady increase in human footprint pressure moving south away from Kafue National Park towards the Zambezi River.

The human footprint pressure threshold (Table 2) at which each species occurs in each wildlife managed area revealed broadly similar high sensitivities. Lion exhibited the highest sensitivity to human footprint pressure with an occurrence threshold between 2.4-3.7, followed by hyena and leopard, with threshold values between 3.7-4.6, mirroring species sensitivity presented by Riggio *et al.* (2018).

An apparent anomaly is Machili forest reserve, with extensive settlement, agriculture and transport infrastructure, having a mean human footprint pressure score of 5.6, and with both leopard and spotted hyena occurring.

The proposed supplemental addition to the protected area network identified in Lines *et al* (2020 *in review*), Open Area extension 1 (& 2), has a mean human footprint pressure of 3.9, within threshold limits presented here sufficient to imply likelihood of suitable habitat for leopard and Spotted hyena.

Table 4.2: Mean human footprint pressures by Wildlife Managed Areas against Species Occurrence

Area	IUCN	Area Ha	Mean HFP	Occurrence		
				Leopard	Lion	Hyena
Kafue National Park	II	206,314	1.1	Yes	Yes	Yes
Mulobezi GMA	VI	347,481	1.2	Yes	Yes	Yes
Sichifulo GMA	VI	133,734	2.2	Yes	Yes	Yes
Nachitwe Forest Reserve	*unreported*	71,075	2.3	Yes	Yes	Yes
Martin Forest Reserve	*unreported*	62,948	2.4	Yes	Yes	Yes
Nyawa West	*unreported*	57,439	3.7	Yes	No	Yes
Simalaha Conservancy	*unreported*	181,936	4.6	No	No	No
Open Area extension 1*	*unreported*	32,712	3.9	Yes?	No?	Yes?
Open Area extension 1+2*	*unreported*	73,660	3.9	Yes?	No?	Yes?
Nyawa East	*unreported*	39,565	4.6	No	No	No
Machili Forest Reserve	*unreported*	49,269	5.6	Yes	No	Yes
Simalaha Sanctuary E	*unreported*	11,020	5.8	No	No	No
Simalaha Sanctuary W	*unreported*	11,282	6.8	No	No	No

*proposed extensions to protected area network within HFP thresholds limits for selected species

4.4 Discussion

Human footprint pressure modelling has traditionally been undertaken at global scales, and typically at low spatial resolution, characteristic of available datasets (Sanderson *et al.*, 2002; Leu *et al.*, 2008). Where analyses have sought to overcome resolution constraints through availability of finer scale data, rescaling has facilitated improved accuracy and applications for conservation planning (Woolmer *et al.*, 2008), including deriving impacts of human pressure at more appropriate site-and species-specific scales where proxy utility as a conservation tool is most valuable (Trombulak *et al.*, 2010). Our study takes this approach a step further, successfully overcoming limitations to Venters *et al's*. (2016) existing model by generating and integrating site-specific, multiple high-resolution data sets at two orders of magnitude finer scale, then applying it directly to key questions surrounding the impacts of human footprint pressure on large carnivores throughout a network of wildlife managed areas under varying degrees of human footprint pressure representative of a key proposed corridor in the KAZA TFCA.

Model output performed best for lion with lower predictive power for leopard and hyena - species known for intrinsic ecological traits and behavioural plasticity enabling greater coexistence in human dominated landscapes than lion, which exhibits very high sensitivity to human disturbance (Riggio *et al.*, 2018). Site-and species-specific sensitivity to complex, interrelated human disturbance variables is hypothesised to explain why the best performing model output was for the species most sensitive to human pressure.

While there are limits to the predictive power of single variable models, predictive power of this model would likely benefit from supplemental data layers, when available, notably interference and exploitative pressures of pastoralism and (legal and illegal) wildlife consumption (Everatt *et al.*, 2019), and synergistic effects between human behaviour and climate change (Brodie, 2016). There is also debate over the appropriate scale or extent at which to measure human footprint pressure, whether that be at the population level, proportion of species total range, home range or other scales (Di Marco *et al.,* 2013). Additionally, there is scope for a greater understanding of site-and species-specific pressure score calibrations, including impacts of formal and informal road linkages (Woolmer *et al.*, 2008).

Model response curves and secondary explorative analyses of thresholds at which species are extirpated at the wildlife managed area scale closely match global mammalian human footprint pressure extinction thresholds (Di Marco *et al.*, 2018) along with Riggio *et al's.* (2018) sensitivity analysis of African large mammals with high susceptibility to human disturbance. Collectively these data provide compelling evidence that human footprint pressure scores ranging between 2.4-4.6 represent a threshold limit for these three species of large carnivores beyond which they are unlikely to persist in human-dominated landscapes using Venter *et al's*. (2016) existing pressure score methodology. The persistence of leopard and hyena in Machili Forest, with a mean human footprint pressure score of 5.6, is likely explained by proximity of this area to extensive lower human footprint pressure areas closer to Kafue National Park, considered the landscapes core wildlife managed area. In this regard Machili Forest could be characterised as a threshold area or an attractive sink, limiting range expansion of these species to broader areas with lower human footprint pressure.

The identification of potential additions to the protected area network in Open Areas east of the Simalaha, first suggested in Lines *et al.* (2018), and further posited here, serves two-fold purposes: 1. The increase in wildlife habitat for a range of species and 2. The likely increase in scope and scale for connectivity between Kafue National Park and the Zambezi River for both leopard and spotted hyena in areas of low human habitation and agricultural development, limiting scope for negative interactions (human-wildlife conflict) in the otherwise increasingly human dominated landscapes that characterises the central-southern extents of the Kafue-Zambezi interface.

These site-specific, high resolution maps have broad utility as a baseline against which subsequent changes to human footprint pressure can be mapped and modelled over time as more data sets come available to refine this iterative process. Pressure score calibration merits more explicit treatment to improve model response given species and/or process of interest.

The value and applicability of generating standardised approaches to mapping human footprint pressure surrounds their use as a proxy or indicator of broader drivers impacting habitat degradation, ecosystem function, species loss, or potential for species recovery which presents new conservation challenges surrounding e.g. human-wildlife conflict.

Progress with human footprint pressure modelling depends in part on understanding and addressing limitations and assumptions of model development (Halpern & Fujita, 2013), and recognition of the dynamic nature of human pressure in terms of asymmetrical and nonlinear threshold responses to total footprint pressure changes across spatial-temporal scales (Toews, 2016; Venter *et al.*, 2016).

4.5 Conclusion

Our human footprint pressure analyses demonstrate utility for determining habitat suitability for a suite of large carnivores of conservation value, including predicting species persistence, extirpation and potential for recolonization, even at this preliminary, proof-of-concept stage of model development.

Model output broadly follows existing data in support of understanding human pressure impacts on landscape-level connectivity at the Kafue-Zambezi interface, providing a valuable additional tool in conservation planning for this landscape, the broader KAZA region and beyond.

As additional data layers become available and the pressure score calibration process evolves, site-specific human pressure maps can be expanded to the broader Zambian and

KAZA landscape to model how spatiotemporal human pressure impacts species and processes of interest to key Programme objectives.

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Chapter 5: Final Discussion

5.1 Recapitulation of Study Scope & Key Findings

The KAZA TFCA promotes landscape connectivity between core and periphery wildlife managed area clusters, both within and between five bordering countries. The Greater Kafue System represents Zambia's majority component in this TFCA but narratives surrounding connectivity have been promoted largely in the absence of any systematic research or empirical evidence of species-level connectivity prior to this study.

Given the dearth of quantifiable evidence in support of connectivity narratives this study sought to delve into key questions surrounding the status and argument for landscape connectivity at the large carnivore scale between Kafue National Park and the Zambezi River, bordering adjacent wildlife managed areas in Namibia and Botswana.

I approached the study from a holistic perspective, building an argument for connectivity based on accumulating contemporary evidence while considering historical data and information compiled from a range of published and grey sources.

Historical data suggests widespread occurrence of the intact large carnivore guild and majority common prey species throughout the Kafue-Zambezi landscape until emergence of widespread commercial hunting in late Nineteenth century, followed by further wildlife declines caused by Rinderpest epizootic, expansion of commerce, transport infrastructure, human settlement and associated human disturbance. Spillover of impacts from Regional border wars further increased pressure on wildlife following Zambia's Independence in 1964 at a time when wildlife conservation resources declined.

In recent decades wildlife conservation budgets have remained significantly below minimum requirements throughout this landscape, and near zero in many wildlife managed areas. In concert with widespread increases in human settlement, infrastructure and agro-pastoralism activities high quality wildlife habitat has reduced and fragmented.

Wildlife occurrence and distribution has declined further, especially in southern wildlife managed areas. There were no quantifiable data on any large carnivores occurrence within 60km of the Zambezi river, and large scale reductions in common prey assemblages and distribution.

While large carnivore mobility implies scope for movements between Kafue National Park and the Zambezi river, and pockets of suitable habitat exist, we conclude that there are no resident large carnivores throughout large areas of the Kafue-Zambezi interface.

Although somewhat beyond the scope of this study, I was unable to establish quantifiable or anecdotal records for any large carnivore movements across the Zambezi river.

5.2 Contributions to conservation science

5.2.1 Chapter 2: Species Assemblages and Distribution

The absence of accurate baseline data and metrics limits capacity to effectively monitor and evaluate conservation management performance (Sutherland *et al.,* 2004; Hockings *et al.,* 2000). Existing area-specific literature (PPF, 2008) failed to detect or accurately quantify the large mammal assemblage from Kafue National Park through the Zambezi River. Resulting outputs effectively provided presence only data for limited species, from limited areas, and misclassified the extent of the range for many species of conservation concern, including the extant large carnivore guild.

While no systematic research apart from this study has been undertaken on carnivores and their prey throughout this landscape, larger scale research on Cheetah (Durant *et al.,* 2017) and African wild dog (RWCP & IUCN/SSC, 2015) failed to incorporate known range beyond Kafue National Park. Findings from Stein *et al* (2016) and ZAWA (2009) approximates findings from this study for Leopard and Lion distribution. Current reassessment of Spotted Hyena status (Weise *et al., in prep*) utilises data from this study.

Our published research compiled the most comprehensive data available on five large carnivores and 26 principle prey species against which performance of existing and subsequent conservation interventions throughout ten wildlife managed areas can be monitored and evaluated over time to ascertain changes to species assemblage and distribution by wildlife managed area. Management implications concern species-level connectivity throughout the Kafue-Simalaha Wildlife Dispersal Area and longer-term persistence of large carnivores throughout the Greater Kafue System as a driver of balanced and resilience food webs and wildlife-based land uses.

5.2.2 Chapter 3: Landcover Mapping, Habitat Suitability and Connectivity Modelling

The life history traits of large carnivores make them highly susceptible to human disturbance (Crooks, 2002). Increasing human disturbance within and surrounding wildlife habitat is having devastating effects on these species (Maxwell *et al.,* 2016; Venter *et al.,* 2016), with significant secondary effects throughout food webs (Ripple *et al.,* 2014; Estes *et al.*, 2011) hindering the development of wildlife-based land uses (Funston *et al.*, 2013).

With the advent and availability of high-resolution satellite imagery and associated analytical software there has been a revolution in the practical value and application of remote sensing for conservation science and planning (de Klerk & Buchanan, 2017). These developments are expanding our knowledge and understanding of drivers impacting species distribution and persistence throughout increasingly human-impacted environments (Kerr & Ostrovsky, 2003; Pettorelli *et al.*, 2005; Watson *et al.,* 2015).

By incorporating extensive ground-truthing and the latest Sentinel imagery we were able to develop high resolution landcover maps for 32,000km^2, covering the majority of the Kafue-Zambezi interface and all ten wildlife managed areas within the proposed Kafue-Simalaha Wildlife Dispersal Corridor at over 91% accuracy. This output clearly shows the extent and spatial characteristics of human activities on the landscape, both within formal wildlife managed areas and peripheral Open Communal Areas. Agriculture, settlement, transport links and associated human disturbance pressures are pervasive wherever permanent and seasonal water access permits settlement and grazing camps in all but the most remote Game Management Areas and Kafue National Park.

This landcover map represents the highest current resolution against which all subsequent landcover analyses will be measured and provides a valuable tool for land use planning across for a range of stakeholder activities including zoning areas for wildlife and tourism development, agricultural expansion, forestry and species-level conservation planning.

Subsequent habitat suitability and current flow models indicate priority areas required to maintain species persistence and connectivity throughout this landscape and highlights the value of unprotected (Open) areas for large carnivore conservation (RWCP & IUCN/SSC, 2015). Linkage Mapper corridor routing performed largely to expectations, and broadly complimented existing analyses (Cushman *et al*., 2018 & 2016), indicating narrowing and sub-optimal current flow in southern areas of the proposed Kafue-Zambezi Wildlife Dispersal Corridor, both at single and multi-species scales. These findings provide management with targeted areas for conservation intervention to increase species-level persistence and movement throughout the landscape.

5.2.3 Chapter 4: Human footprint pressure

Acknowledging the near-ubiquitous human impacts on natural resources within and bordering protected areas, the development and refinement of functional proxies predicting species response to human disturbance represents a valuable development in conservation biology (Zipkin *et al.,* 2010; Di Marco *et al.,* 2014). Importantly, novel methods to monitor and evaluate human impacts on habitats and species of interest over time provide planners and managers with valuable tools to assess and the effectiveness of conservation interventions and direct resources

I tested the utility of this approach through analysis of large carnivore occurrence to a composite measure of human footprint pressure based on existing methodologies (Sanderson *et al.,* 2002; Venter *et al.,* 2016). My site-calibrated datasets utilised the highest available data resolution, overcoming much limitation in existing analyses.

Outputs provided a striking visual representation of human pressure throughout 33,000km^2 of wildlife managed areas and rangelands comprising the majority Zambian component of the KAZA TFCA, highlighting both the extent and intensity of pressures, and facilitating finer scale analyses against which to model species response.

Response of species to human footprint pressure at the wildlife managed area scale expands our understanding of thresholds at which species can exist in increasingly human-dominated landscapes at scales more appropriate to understanding species persistence.

Encouragingly my human footprint pressure mapping analyses produced outputs broadly similar to my landcover, habitat suitability and current flow analyses. Notably I identified important areas for addition to the protected area network in the Kafue-Zambezi Wildlife Dispersal Corridor that incorporated human footprint pressure thresholds below which large carnivores might reasonably occur, and concurrently are not utilized extensively by local communities.

Our proof-of-concept analysis is pertinent in context of trends in human pressure and resource demands within and surrounding wildlife managed areas (Wittemyer *et al.,* 2008), and given challenges surrounding the maintenance, integrity and connectedness of African protected areas (Newmark, 2008).

5.3 Methodological Insights / Limitations

Integration of qualitative and quantitative data sources provides a robust approach to generating species-level occurrence data given sufficient understanding of *in situ* field conditions and survey approaches required to cover a diverse mosaic of land uses and species at a large scale in a single sampling season.

Initial attempts to operationalise the multi-species, multi-scale, Bayesian Hierarchical models of Whittington *et al.* (2015) were frustrated by imprecise parameter estimates from the model, likely derived from coding problems associated with modifying the existing framework from a single species to multi-species approach. Recent statistical developments (Petracca *et al.,* 2019) appear to have extended the framework to account for multiple species, and, in doing so, mitigate estimation imprecision through shrinkage (the borrowing of statistical strength from a community level distribution).

Notwithstanding initial modelling challenges, data was sufficiently robust to facilitate application of the alternative MaxEnt and Linkage Mapper approaches which produced results largely in line with expectations and related studies (Cushman *et al.,* 2016 & 2018).

Human footprint pressure mapping will benefit from supplemental layers as they become available, and more in-depth treatment of site-specific pressure variable calibrations and the appropriate scale at which to model species occurrence. There is also scope for approaching subsequent model analyses from an occupancy perspective (e.g. Petracca *et al.,* 2019), incorporating detect/non-detection data sets versus simple occurrence.

Additionally, pressures for which we have no local data, but are known to exert significant negative effects on habitat suitability (e.g. poaching and direct/indirect impacts of pastoralism and its spatial characteristics) will likely generate addictive pressures limiting habitat suitability. This implies model outputs are conservative and habitat suitability is over-estimated.

Notwithstanding model performance, the responses of large carnivores to individual and cumulative human pressures is likely dynamic and non-linear, so we can expect a continuum of species-level responses to modelled pressures across the landscape over time as interacting human pressures change.

5.4 Broader Contribution of the Study to Literature

5.4.1 Transboundary conservation

While generalities surrounding the impacts of dynamic human pressures on wildlife are increasingly understood, the identification and calibration of human pressures at site-and species specific scales is a novel direction in applied research. My approach reflects real-world challenges in natural resource management throughout protected areas mosaics under varying degrees of conservation effectiveness. In the case of the KAZA-TFCA existing narratives surrounding landscape connectivity have failed to identify site-and species specific challenges within proposed landscape-level corridors and wildlife dispersal areas. These constraints limit practical application of conservation science to promote biodiversity conservation and the development of wildlife-based land uses. The strategic approach offered in this thesis and accompanying publications provides a repeatable and robust technique for understanding localised questions surrounding species persistence, extirpation and potential recolonization in key linkages throughout transboundary networks.

5.4.2 Protected areas

Mosaics of protected areas under varying conservation management intensity and effectiveness present a range of challenges for species persistence and movement, with few existing areas in Southern Africa designated with these specific considerations in mind. Given our approach and findings, clear utility exists for expanding protected areas to incorporate contemporary concerns, and scalable to other protected areas mosaics in the KAZA-TFCA and beyond where varying human pressures present site-specific challenges to wider conservation objectives.

5.4.3 Understudied landscapes

The value of many understudied landscapes lies in their potential roles for supporting key aspects of biodiversity conservation and natural economies, including the persistence, recolonization and movement of key wildlife species between and within protected areas mosaics. The conclusions presented in this work capitalises on my novel integration of multi-methods throughout formerly unstudied landscapes, raising issues related to existing connectivity narratives whilst presenting new options to fulfil said objectives.

5.4.4 Local issues

Complexities surrounding *inter alia* land use ownership, livelihood practices and sensitivities of the local communities and their leaders to biodiversity conservation cannot be addressed by board brush approaches that fail to understand and integrate multi-faceted local issues into conservation and development planning. Typically, the cumulative pressures exerted by human populations at local scales vary over space and time, and this research has emphasised the value of understanding and capturing these nuances at a scale appropriate to planning for large carnivore conservation.

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Appendix: Methodological Explanations / Exploratory analysis / Data manipulation

1: Spoor Tracking Surveys

A number of key constraints were identified in developing an appropriate survey method:

- Cryptic nature of target species;
- Unknown status and ranging behaviour of target species throughout study area;
- Large spatial scale of the survey area;
- Requisite requirement to sample the entire area in a single season;
- Limited and inconsistent network of access roads and tracks;
- Variable substrate conditions;
- Security and other logistics issues.

To overcome constraints a planning/pilot study was developed to map all navigable tracks and assess substrate condition, to determine if vehicle or foot based surveys would be appropriate, and also sampling intensity required to detect target species and cover the entire study area in a single season. Necessary trade-offs were acknowledged.

With the assistance of State wildlife officers and hunting safari operators we mapped the available road and track network by 4x4 vehicle and on foot and entered into a GIS. The network was then categorized as roads or tracks and further sub-categorized as graded (ideal substrate for spoor tracking), ungraded (functional with/without additional preparation) or overgrown (unusable for tracking). Using expert opinion it was clear insufficient graded roads precluded vehicle-based surveys.

Taking 400 km^2 as the approximate survey block area considered sufficient to cover home range of target species from IUCN Redlist data, I overlaid a 20x20 km grid on our road/track map, providing 31 blocks overlapping the study area. I then selected 2 sample blocks with >25 km of existing graded roads to determine survey effort required to detect target species – the minimum distance we could reasonably cover on foot during 3-4 hours of spoor tracking after dawn and again before dusk – optimum times for detecting tracks when the sun was not overhead and shadows highlighted fresh tracks.

In each sample block 8 x 4 km tracks were spread throughout the road/track network on optimal substrate and walked by two experienced trackers and the project manager at 4 km/hr, noting every large carnivore and common prey track within each 0.5 km sub-section. Tracks were marked so as not to be recounted on subsequent counts.

While cheetah were known from the landscape from other sources they were not detected in the pilot study and omitted from formal analyses.

Detection probability was then calculated for the remaining 4 large carnivore species at 0.5 km sub-sections to determine optimal survey length and no of transect repeats required to optimize detection of target species. Data indicated 4 km transects surveyed three times would be sufficient to reach a P(det) of >0.61 for lion, leopard and spotted hyena. African wild dog were infrequently detected and omitted from further spoor tracking analyses.

At this survey effort ten sample blocks could be surveyed in a single season, equating to 102x4 km transects sampled three times.

With these data we randomly selected 10 sample blocks from 22 that contained >25 km of useable roads/tracks, and overlaid transects over optimal substrate within these sample blocks (mean 40.8 km/sample block, range 28-64 kms, 7-16 transects).

I optimized transect substrate with controlled burns and grading, dragging a heavy log over the track with a 4x4 until a consistent surface was achieved. Transects were then left a week before any surveys commenced. In that way I overcame limits to inconsistent surface tracking conditions and limited bias in transect selection and detection probability.

Surveys commenced in the northern-most block adjacent to Kafue National Park and I worked south to the Zambezi River. 1-2 teams covered between 6-16 transects a day in each block, repeating the transects three times in each survey area over a period of 7-10 days, with 2-3 days between repeat surveys.

Table 5: Summary of exploratory analyses to determine sampling strategy

Hyena
Naive occupancy estimate = 0.6471

Individual Site estimates of <psi>

	Site		estimate	Std.err	95% conf. interval
psi	**1 site1**	**:**	**0.7129**	**0.0560**	**0.5922 - 0.8094**

Wild dog
Naive occupancy estimate = 0.1961

Individual Site estimates of <psi>

	Site		estimate	Std.err	95% conf. interval
psi	**1 site1**	**:**	**0.4452**	**0.1789**	**0.1625 - 0.7684**

Lion
Naive occupancy estimate = 0.3529

Individual Site estimates of <psi>

	Site		estimate	Std.err	95% conf. interval
psi	**1 site1**	**:**	**0.5252**	**0.0988**	**0.3372 - 0.7062**

Leopard
Naive occupancy estimate = 0.5980

Individual Site estimates of <psi>

	Site		estimate	Std.err	95% conf. interval
psi	**1 site1**	**:**	**0.6053**	**0.0492**	**0.5059 - 0.6967**

	Estimated coefficients				
		hyaena	**leopard**	**lion**	**wild dog**
	psi_int	26.72	2.97	0.54	1.30
	p_int	-0.35	-0.58	-2.66	-1.71
	p_dist	0.29	0.42	0.78	0.31

	Parameter estimates				
parameter	transect (km)	hyaena	leopard	lion	wild dog
psi		1.00	0.95	0.63	0.79
p	0.5	0.45	0.41	0.09	0.17
	1	0.49	0.46	0.13	0.20
	1.5	0.52	0.51	0.18	0.22
	2	0.56	0.57	0.25	0.25
	2.5	0.59	0.62	0.33	0.28
	3	0.63	0.67	0.42	0.31
	3.5	0.66	0.71	0.52	0.35
P (det)	4	0.69	0.75	0.61	0.38

	transect (km)	Number of surveys			
p	0.5	7	7	20	15
	1	6	6	15	13
	1.5	6	5	12	13
	2	5	5	8	10
	2.5	5	4	6	8
	3	5	4	5	8
	3.5	4	4	3	7
	4	3	3	3	6

Appendix 2: Landcover Mapping

Mapping dynamic and diverse landscapes, such as this study area, where a high degree of heterogeneity and variation is exhibited between dry and wet seasons, is challenging and the use of time series satellite data is indispensable (Lucas *et al.*, 2007). The images were processed at Level 1C which includes a geometric correction and acquisition of Top of Atmosphere (ToA) Reflectance values. For the analysis only the 10 bands provided at spatial resolutions of 10 m (Bands 2,3,4 and 8) and 20 m (Bands 5,6,7,8a,11 and 12) were employed with the later resampled at 10 m. Prior to analysis an absolute atmospheric correction was applied using the Dark Object Subtraction algorithm (DOS). During the classification process various spectral ratios were calculated including Normalized Difference Vegetation Index (NDVI; equation 1), Normalized Difference Wetness Index (NDWI; Equation 2), Normalized Difference Moisture Index (NDMI; Equation 3), Near InfraRed/Red (NIR/Red; Equation 4).

$$\textit{Equation 1}: NDVI = \frac{(\mathrm{Band8} - \mathrm{Band4})}{(\mathrm{Band8} + \mathrm{Band4})}$$

$$\textit{Equation 2}: NDWI = \frac{(\mathrm{Band3} - \mathrm{Band8})}{(\mathrm{Band3} + \mathrm{Band8})}$$

$$\textit{Equation 3}: NDMI = \frac{(\mathrm{Band8} - \mathrm{Band12})}{(\mathrm{Band8} + \mathrm{Band12})}$$

$$\textit{Equation 4}:\ NIR/RED = \frac{\mathrm{Band8}}{\mathrm{Band4}}$$

Table 6: Sentinel 2 Spectral Bands and central wavelengths

Band Number	Central Wavelength (nm)	Spatial Resolution (m)
Band 1	443	60
Band 2	490	10
Band 3	560	10
Band 4	665	10
Band 5	705	20
Band 6	740	20
Band 7	783	20
Band 8	842	10
Band 8a	865	20
Band 9	940	60
Band 10	1375	60
Band 11	1610	20
Band 12	2190	20

Various post-classification refinements were employed in order to avoid a noise in the final product. Isolated objects surrounded by one particular class and with a size smaller than the minimum mapping unit were reclassified at the enclosing class. Furthermore, isolated objects with a size smaller than the minimum mapping unit neighboring more than one class were classified to the one where it had the longest common border.

Table 7: Accuracy assessments by landcover classification

		Observed							
Predicted		**Arable Land**	**Kalahari Woodland**	**Mopane Woodland**	**S/F Grasslands**	**Teak Forest**	**Water**	**Total**	**Accuracy**
	Arable Land	2114420	522	125	95899	22	12	2211000	**0.956**
	Kalahari Woodland	158	8923489	152422	489	4522	52	9081132	**0.983**
	Mopane Woodland	15	898522	1452600	106	1256	589	2353088	**0.617**
	S/F Grasslands	990	1230	458	2525589	58	15369	2543694	**0.993**
	Teak Forest	12	11256	1235	58	1332689	0	1345250	**0.991**
	Water	0	0	0	185699	146389	217325	549413	**0.396**
	Column Total	2115595	9835019	1606840	2807840	1484936	233347	18083577	
	Producers accuracy	**0.999**	**0.907**	**0.904**	**0.899**	**0.897**	**0.931**	**Overall**	**0.916**
		Arable Land	**Kalahari Woodland**	**Mopane Woodland**	**S/F Grasslands**	**Teak Forest**	**Water**		
	Arable Land	0.117	0.000	0.000	0.005	0.000	0.000	0.122	
	Kalahari Woodland	0.000	0.493	0.008	0.000	0.000	0.000	0.502	
	Mopane Woodland	0.000	0.050	0.080	0.000	0.000	0.000	0.130	
	S/F Grasslands	0.000	0.000	0.000	0.140	0.000	0.001	0.141	
	Teak Forest	0.000	0.001	0.000	0.000	0.074	0.000	0.074	
	Water	0.000	0.000	0.000	0.010	0.008	0.012	0.030	
	Column Total	0.117	0.544	0.089	0.155	0.082	0.013	1.000	
		Θ1	0.916						
		Θ2	0.327						
		K	**0.875**						

Appendix 3. Key Interventions and Outcomes in Promotion of Landscape Connectivity.

3.1 Diagnosing challenges to maintaining biodiversity at the landscape scale.

Majority challenges to the long-term maintenance of large carnivores and biodiversity throughout this landscape differ little in essence from other increasingly human-dominated wildlife areas throughout southern Africa and beyond. Encouraging our understanding of the science underpinning endangered species and biodiversity management has never been clearer, and with political support for the KAZA TFCA programme from a wide range of stakeholders, appropriate interventions to halt and reverse effects of deleterious human pressures are realistic and feasible.

Human populations are increasing, education and poverty levels, especially surrounding protected areas and concerning youth, require financial and technical support. The current cost-benefit ratio to rural communities of co-existing with wildlife versus conversion of wildlife habitat into agro-pastoralism land uses disincentives development of green economies and capitalising from more sustainable wildlife-based land uses. Existing agro-pastoralist approaches are inefficient and typically degrade natural resources, jeopardise livelihood security and threaten wildlife populations. Political and financial support for law enforcement, combatting corruption and illegal wildlife trade remain key challenges.

While site-specific variation in these broad challenges, including social, economic, and political factors, determines the tailored interventions required to improve biodiversity conservation and livelihoods, a number of broad approaches are applicable in the Kafue-Zambezi landscape.