Elephant space use in relation to ephemeral surface water availability in the eastern Okavango Panhandle, Botswana

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Declaration

'I know the meaning of plagiarism and declare that all of the work in the thesis, save for that which is properly acknowledged, is my own'.

Anastacia Makati, October 2022

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Thesis outline

Chapter One provides a general background about My study and study area, the eastern Okavango Panhandle. The chapter discusses what elephants are, the impacts of elephant distribution across landscapes, seasonal resource use by elephants, overall drivers of Human elephant conflict (HEC) and drivers of elephant distribution, and introduces the climate, groundwater, and hydrology and vegetation of the study area. The chapter also provides the problem statement and objectives of My study. Chapter two explores ephemeral surface water in the study area and explains the use of spectral indices such as Automated Water Extraction Index (AWEI) to delineate surface water taken from satellite images, specifically Landsat 8. Chapter three discusses movement data, particularly elephant distribution, and basic movement patterns (i.e., daily distance), and describes seasonal variations in seasonal elephant home range size based on collar data from 15 elephants. Chapter four investigates elephant resource use by linking ephemeral surface water and elephant movement data resource selection function and logistic regression to incorporate remotely sensed data and ecological parameters to analyse the effects of environmental variables i.e., NDVI. Chapter five is the synthesis and conclusion that integrates information, findings and recommendations from the data chapters.

Abstract

The movement and distribution of elephants can be influenced by environmental factors over time (Foley, 2002). Examining how features in the landscape such as vegetation productivity, water sources and anthropogenic activities drive the movement of elephants can help in understanding patterns of movement. It can also help to inform the establishment and alignment of protected areas, wildlife corridors and identification of tourism hotspots as well as policy interventions to manage Human-Elephant Conflict (HEC). The Okavango Panhandle in Botswana is a HEC hotspot and the focus of My study. A number of strategies to address HEC are underway in the area, however one longer term strategy that has been proposed in this area involves provision of artificial water sources to influence elephant movements and keep animals away from fields during the cropping season. However, an improved understanding of how elephants utilize their habitats in relation to natural ephemeral surface water and other factors that influence their movements from dryland habitats to the Okavango Delta resources is needed to inform such management decisions.

My study seeks to establish the role of ephemeral surface water on elephant distribution in the eastern Okavango Panhandle, Botswana as well as assess the movement distribution of elephants in relation to the seasonality, proximity and spatial extent of water presence represented by ephemeral surface water. Time series analysis of water extent on ephemeral surface water of the eastern Okavango panhandle will be developed and overlaid with elephant movement datasets. Elephant collar data from 15 elephants (5 males and 10 females) in the eastern Okavango Panhandle, Botswana have been analysed and Home Range (HR) sizes estimated using Kernel Density Estimation (KDE). The relative importance/probability of environmental variables in determining elephants' movement based on the Utilization Distribution (UD) were computed using Generalized Linear Mixed Models (GLMMs). I utilized a remote sensing spectral index, namely the Automated Water Extraction Index (AWEI) to delineate ephemeral surface water in dryland (excluding permanent waters) of the study area.

The results reveal that during the wet season, elephants were evenly spread out all over the study area until the early dry season (April-June) when the ephemeral waterholes dried up. Elephants moved southwards towards the permanent waters of the Okavango River, where there are many human settlements and farms. Male HR sizes were found to be bigger than those of female elephants. Wet season (early and late) home range sizes were also bigger when compared to dry season (early and late) HR size. Mean daily distances were computed to investigate the effect of season on elephant daily distances and the distances ranged between 5km and 6.8km in the late wet and in the early wet and late dry season respectively. The Resource Selection Function (RSF) analysis shows that water adjacent sites are preferred over distant ones and both sexes prefer areas with high NDVI, with this preference being more pronounced in males. The seasonal variation of water use is notable in that it affirms the importance of proximity to water for elephants and has implications for their management and HEC. For example, I found that ephemeral surface water has a significant role in influencing elephant spatial use in the area, particularly during the early and late wet season. As ephemeral pans dried and NDVI (vegetation greenness) decreased, elephants started to move closer to the Okavango Delta and consequently human settlements and fields. However, further investigations into the timing of movements away from ephemeral waterholes and the influence of other environmental factors on elephant movements in the area would be needed before any recommendations can be made regarding artificial water provision in this area.

KEYWORDS

Elephant space use; ephemeral surface water; Home range size; resource use

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NDWI	$$\boldsymbol{NDWI = \frac{NIR - SWIR\,1}{NIR + SWIR\,1}}$$	**(1)**
MNDWI	$$\boldsymbol{MNDWI = \frac{Green - SWIR}{Green + SWIR}}$$	**(2)**
$AWEI_{nsh}$	$\boldsymbol{AWEInsh = 4\,x\,(Green - SWIR1) - (0.25 \times NIR + 2.75 \times SWIR2)}$	**(3)**
$AWEI_{sh}$	$\boldsymbol{AWEIsh =}$ **(green + blue) X 0.25 - (1.5 x NIR) + (SWIR1 – 0.25 X SWIR2)**	**(4)**
Atmospheric correction formular	$\boldsymbol{L = A\ \rho/(1 - S\rho e) + B\ \rho e/(1 - Spe) + Le}$	**(5)**
	$\boldsymbol{L = MQcal + A}$	**(6)**
NDVI	$$\boldsymbol{NDVI = \frac{NIR - Red}{NIR + Red}}$$	**(7)**

Abbreviations

AENP	Addo Elephant National Park
AfESG	African Elephant Specialist Group:
AIC	Akaike Information Criterion
AVHRR	Advanced Very High-Resolution Radiometer
AWP	Artificial Water Provision
$AWEI_{sh}$	Automated Water Extraction Index (with shadaw)
$AWEI_{nsh}$	Automated Water Extraction Index (no shadow)
CKGR	Central Kalahari Game Reserve
CHA	Controlled Hunting Areas
CBOs	Community Based Organisation
CSO	Central Statistics Office
CBNRM	Community Based Natural Resources Management
CITES	Convention on International Trade of Endangered Species of fauna and flora
DEM	Digital Elevation Model
DN	Digital Numbers
DWNP	Department of Wildlife and National Parks
EOS	Earth Observing System
EOSDIS	Earth Observing System Data and Information
EROS	Earth Resources Observation and Science
ESA	European Space Agency
EVI	Enhanced Vegetation Index
ENVI	Environment for Visualizing Images
ETM+	Enhanced Thematic Mapper Plus
ESRI	Environmental Systems Research Institute
FIRMS	Fire Information for Resource Management
FLAASH	Fast Line-of-Sight Atmospheric Analysis of Spectral Hypercube
GDP	Gross Domestic Product
GeoTIFF	Geographic Tagged Image File Format
GLMM	Generalised Linear Mixed Model
GIS	Geographic Information System
GPS	Global Positioning System

HEC	Human Elephant Conflict
HR	Home ranges
HWC	Human Wildlife Conflict
IUCN	International Union for Conservation of Nature
KAZA TFCA	The Kavango–Zambezi Transfrontier Conservation Area
L1TP	Level 1 Precision and Terrain corrected Products
LLM	Linear Mixed Models
LoCoH	Local Convex Hull
LUCIS	Land Use Conflict Information System
MCP	Minimum Convex Polygon
MODIS	Moderate Resolution Imaging Spectrometer
MNDWI	Modified Normalised Difference Water Index
NASA	National Aeronautics and Space Administration
NDVI	Normalised Difference Water Index
NDWI	Normalised Difference Water Index
NDSI	Normalized Difference Snow Index
NIR	Near Infrared
NP	National Park
NGO	Non-Government Organisation
OLI	Operational Land Imager
RS	Remote Sensing
RSF	Resource Selection Function
SPEI	Standardized Precipitation Evapotranspiration Index
SWIR	Short-wave infrared
TAW	Tasselled Cap Wetness
UD	Utilisation distribution
UTM	Universal transverse Mercator
USGS	United States Geological Survey
WMA	Wildlife Management Areas
WDA	Wildlife Dispersal Area

1 GENERAL INTRODUCTION

SUMMARY

Chapter one provides a general background about the study area in the eastern Okavango Panhandle. The chapter discusses elephant biology and ecology, including distribution; population size; feeding behaviour and resource use. It delves into aspects of elephant conservation, including drivers of elephant distribution and resource use and Human Elephant Conflict (HEC). Moreover, the chapter gives perceptions about the socio-economic importance of elephants. The chapter also introduces the climate, groundwater, and hydrology and vegetation of the study area. It concludes with the problem statement and objectives of my study.

1.1 Elephants

The elephant is the largest living terrestrial mammal (Wittemyer et al., 2007b), characterized by a long trunk, columnar legs and large head with temporal glands and broad, flat ears (Caro et al., 2013). Elephants are classified into three species: the African savanna elephant (*Loxodonta africana*), the African forest elephant (*Loxodonta cyclotis*; Fig. 1), and the Asian elephant *(Elephas maximus*). The International Union for Conservation of Nature (IUCN) Red List has declared all elephants to be endangered, as a result of their populations declining due to poaching for ivory, loss of habitat and human-elephant conflict (Gobush et al., 2021). Elephants are intelligent creatures with complicated social lives (Thompson, 2002, Bekoff and Pierce, 2009). They are typically found in three herd types: matriarchal female herds with young (McComb et al., 2001); bachelor herds of males; or lone males (Schulte, 2000). Elephants reach puberty between the ages of 10 and 14 and females can reproduce until they reach the age of 50, (Bates et al., 2008). An elephant's average lifespan is 65-70 years (Firyal and Naureen, 2007). Several authors have estimated African elephant gestation period to be 22 months (Wittemyer et al., 2007a: 44, Smit et al., 2020).

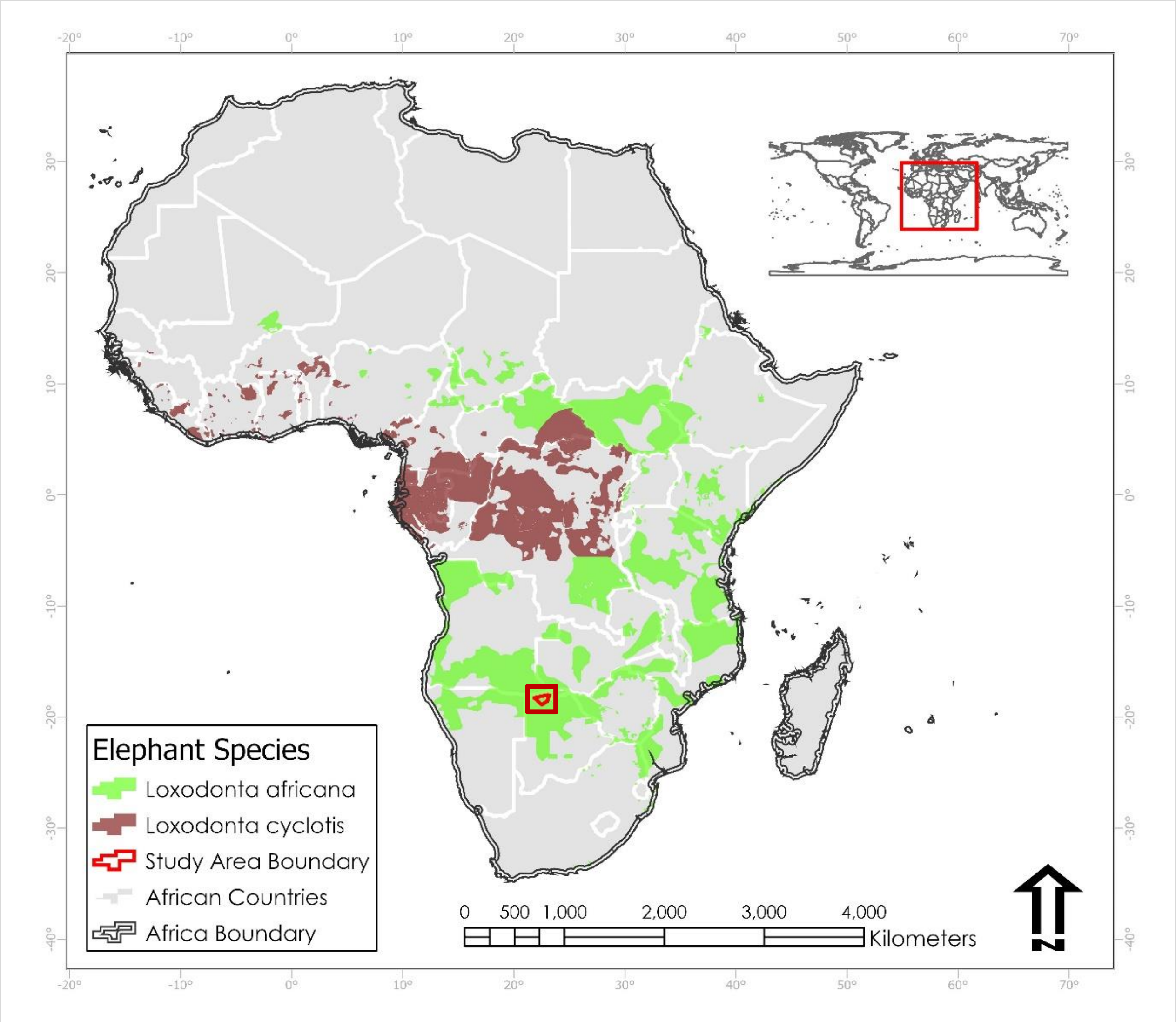


Figure 1. Map of Africa showing the distribution of the elephant classified into species type. Elephant species type are coloured according to location in Africa. Green boundary showing the eastern Okavango Panhandle study boundary. The data were sourced from IUCN Red List of Endangered Species; https://www.iucnredlist.org/search?query=Elephants&searchType=species, Africa boundary was sourced from; (Africa Shapefiles - Datasets - openAFRICA). This map was generated with the software ArcGIS Pro ver. 2.8.0; (Esri Support ArcGIS Pro 2.8); (Environmental Systems Research Institute, 2021) .

1.2 Distribution and Population size

Elephants are most often found in savannas, grasslands and woodlands, but they also inhabit deserts, marshes, and hills in Africa and Asia's tropical and subtropical landscapes (Sukumar, 2003). There are fewer than 50,000 Asian elephants remaining in the wild (Sukumar, 2003) and the current estimated number of African elephants is 415,428 ±20,111 (Thouless et al., 2016). Southern Africa is home to the largest population of the African savanna elephants, supporting over 70%, or 293,000, of the total Africa's elephant population (IUCN, 2016).

Botswana has the largest population of savanna elephants in Africa, with approximately 130,000 elephants, mostly occurring in the Okavango and Chobe-Zambezi region (DWNP, 1996, Blanc and Barnes, 2007, Chase et al., 2016, Chase, 2017, Chase et al., 2018). East Africa as well supports a significant population of the African savanna elephants in Africa, with Tanzania having over 60,000 (Idd, 2020) and Kenya 36,000 elephants (Kenya Wildlife Service, 2020). The least elephant populations are found in West and Central African countries. Central Africa is home to 24,000 elephants, accounting for 6% of the total elephant population, whilst West Africa is home to 11,000 or 3% of the total elephant population. A majority of the African forest elephants occur in West Africa. African forest elephants used to occur in North-Africa but they extinct since the European Middle Ages (Thouless et al., 2016).

Most (95%) elephants in Botswana occur in the north of the country (DWNP, 2012). The eastern Okavango Panhandle is an important area for elephants and a central part of the Kavango–Zambezi Transfrontier Conservation Area (KAZA TFCA) (Songhurst et al., 2015). In 1996, the Department of Wildlife and National Parks estimated the elephant population in the eastern Okavango Panhandle at 3782 in a dry season period (DWNP, 1996). In 2010 elephant population had reached 15,429 elephants, indicating a 5-fold increase in a space of 14 years (Songhurst et al., 2015). The current elephant population is estimated to be over 18,000 elephants (Pozo et al., 2018).

1.3 Elephant feeding and resource use

Elephants are mixed feeders, consuming a variety of vegetation such as grasses, fruits, and roots (Landman et al., 2008a). Elephants are bulk feeders and processors of plant material. They preferentially graze when grass forage is green and abundant, especially in wet seasons, and mostly browse during the dry seasons (Owen-Smith, 1989, Thornley et al., 2020). Elephants select greener plant resources wherever they may be found in a larger landscape, which they attain through utilizing vegetation of varied phenologies (Loarie et al., 2009). Forage and surface water availability are important factors in the lives of elephants and are key determinants of elephant seasonal distribution and resource use (Loarie et al., 2009). It has been found, that elephants select seasonal ranges with adequate surface water in Asia (Dzinotizei, 2019), Ghana (Ashiagbor and Danquah, 2017), Tanzania; (Kioko et al., 2015) Mozambique (De Boer and Baquete, 1998), Zimbabwe (Chamaille-Jammes et al., 2007), South Africa (Smit et al., 2007a) and Namibia (Tsalyuk et al., 2019). Elephants can drink up to 100 litres of water in 1 day (Landman et al., 2008b) and need to visit water regularly for mud bathing, drinking and for thermoregulation, to maintain homeostasis and body reserves, especially in semi-arid climates such as in Botswana, Namibia and South Africa (Dunkin et al., 2013, Purdon and Van Aarde, 2017). Elephants are active both during the day and night, with feeding accounting for the majority of their activity (Galanti et al., 2006). African savanna elephants exhibit range-residency, migratory, semi-migratory, and near nomadic movement patterns in various parts of the continent (Rispel and Lendelvo, 2016, Wato et al., 2018). They can travel longer distances in semi-arid environments in search for forage, water and in response to climate conditions for example droughts, (Rispel and Lendelvo, 2016, Wato et al., 2018). Elephant home range sizes vary depending on habitat availability, vegetation productivity and human activities (Owen - Smith, 1989, Loarie et al., 2009, Wall et al., 2013, Thornley et al., 2020, Rispel and Lendelvo, 2016, Wato et al., 2018). see table 1 for sizes of home range in other ecosystems.

Table 1. Size of elephant home range in different ecosystems.

Location	Home range size (km^2)	Country	Reference
Pongola Game reserve	10.5 – 71.5	South Africa	(Shannon et al., 2006)
Shimba Hills	10-80	Kenya	(Douglas-Hamilton et al., 2005)
Lake Manyara NP	10-57	Tanzania	(Douglas-Hamilton, 1972)
Amboseli NP	100-200	Kenya	(Douglas-Hamilton et al., 2005)
Kruger NP	129-1255	South Africa	(Whyte, 1993)
North-western Kunene region	251 to 625	Namibia	(Leggett, 2006)
Queen Elizabeth NP	363-500	Uganda	(Abe et al., 1994)
Hwange NP	1038-2981	Zimbabwe	(Conybeare, 1991)
Tsavo East NP	mean 1580	Kenya	(Leuthold and Sale, 1973)
Waza NP	2484-3066	Cameroon	(Tchamba et al., 1995)
Amboseli NP	3,070 -3,170	Kenya	(Ngene et al., 2017)
Etosha NP and Kaokoveld	5800-8700	Namibia	(Lindeque and Lindeque, 1991)
Home range size listed in ascending order, adapted from (Thouless, 1996, Shadrack et al., 2017)			

NP: National Park

1.4 Drivers of elephant distribution and resource use

African elephants are found in a broad range of environments, from tropical swamp forests to deserts (Blanc and Barnes, 2007, Wall et al., 2021). There are many factors that determine elephant distribution, including deforestation; fire; poaching; minerals; topography; and climate. The key drivers of their distribution are availability of food, surface water, minerals, climate, forest cover and lack of human disturbance in the form of poaching and erection of impenetrable boundaries (Owen-Smith, 1988b, King et al., 2007). Other factors such as range expansion (Thouless et al., 2016) and seasonal dispersals also exert a significant influence in the distribution of elephants within their ranges (Wittemyer et al., 2007b). These driving factors are described in detail below:

1.4.1 Food

Elephants require a large amount of food to maintain their physiological and energy requirements (Münster, 2016). They can travel long distances per day (Owen, 2011: 28), sometimes moving 15-30 kilometres (Ullrey et al., 1997). Elephants consume a diverse range of vegetation in order to sustain their large bodies (Best, 1981). Asian and African elephants differ significantly in the diets they consume as dictated by the food available within their ranges (Romain et al., 2014, Sach et al., 2019). Asian elephants largely consume monocotyledonous plants, such as palms, bamboo, and grasses (Koirala et al., 2016), whereas African savanna elephants are mixed feeders, grazing when grass is abundant and browsing when grass abundance declines (Skarpe et al., 2004). As habitat sizes become smaller, elephant feeding choices decrease (Roux, 2006) and inter-specific competition can intensify (Bodasing, 2011). Elephants feed on all parts of the plant from root to fruit. If the food they seek is too high, they will wrap the trunk around it and shake it quickly. This procedure generally results in a lot of food falling to the ground for them and their offspring to eat. If that fails, the elephant may just pull out or push down the entire tree or plant out of the ground and consume it (Haynes, 2012).

1.4.2 Surface water

Elephants are water dependent species (Smit et al., 2007a) and surface water availability has been found to be a determinant of elephant distribution in South Africa (Landman et al., 2012a), Zimbabwe (Chamaille-Jammes et al., 2007), and Kenya (Bohrer et al., 2014). The influence of artificial water provision (AWP) and fence construction on elephant movement were investigated in seven southern African countries by (Loarie et al., 2009). My study found that AWP diminishes seasonal variations in elephant movement patterns while increasing elephants' local impacts on vegetation. AWP allowed elephants to range more extensively during the dry season, allowing them to utilise and possibly overexploiting vegetation in areas that would normally be inaccessible to them except during the rainy season.(Bohrer et al., 2014).

Other factors that determine elephant distribution include the following;

1.4.3 Minerals

There are 28 minerals known to be important for elephant health, including phosphorous, calcium, and magnesium (Rode et al., 2006). An imbalance in mineral consumption may result in clinical deficiency, reproductive difficulties, and a reduction in life expectancy (Hatt and Clauss, 2006). African savanna elephants have the ability to significantly modify woodlands through debarking trees when seeking their mineral requirements. Vogel et al. (2020) found that nutrient deficiencies in phosphorus and potentially sodium could play an important role in elephant dietary choices and could lead to crop consuming behaviour in some areas.

1.4.4 Climate

Under a reduced precipitation scenario of climate change elephants are likely to aggregate in areas of higher surface water retention, possibly increasing the rate of human-elephant encounters (Kupika et al., 2017). Other drivers emanate from increases in temperature. Elephants are water dependent species, therefore climate change causes water deficiency in semi-arid environments and the simultaneous preference of water adjacent areas by both elephant and humans consequently worsen especially only under climate change. Rainfall is another major underlying factor of elephant distribution as found in studies in Kruger National Park in South Africa (MacFadyen et al., 2019), West Africa, East Africa and Southern Africa (Dejene et al., 2021).Climate change worsens other impacts described above. The Standardized Precipitation Evapotranspiration Index (SPEI) is a new drought index that helps in detecting, monitoring, and analyzing droughts. This can be used to assess trends in precipitation and temperature. Drought events can be characterised by the SPEI over various temporal scales (Ye et al., 2019).

1.4.5 Land use change/ Forest cover / Deforestation

Forest cover and the effects of fire on forest cover is another important driver of elephant distribution in Asia (Songer et al., 2016) and Africa (MacFadyen et al., 2019). Land conversion is a result of ever-increasing human population, as well as simultaneous agricultural and infrastructure growth, all of which are powered by economic and technological developments. Land use change can affect elephant distribution and also exacerbate human-elephant conflict (Pozo et al., 2018). Land use change can also cause direct habitat loss and fragmentation, which can affect distribution and population decline (Mpakairi et al., 2019).

1.4.6 Poaching

Dramatic declines in elephant populations across African countries have been associated with indiscriminate killing and poaching of elephants for the ivory trade (Douglas-Hamilton, 1987, Skarpe et al., 2004, Schlossberg et al., 2018). Between 1979 and 1987 the elephant population was severely decimated, with numbers sharply dropping from 1.3 million to 600,000 elephants (Douglas-Hamilton, 1987). In Kenya alone, the elephant population plummeted from about 130 000 in 1973 to 16000 in 1989 (Cohn, 1990). The reduction led to the ban on ivory trade by the Convention on International Trade of Endangered Species of fauna and flora (CITES) (Burton, 1999). Poaching can also influence elephant distribution, for example in

Samburu and Laikipia in Northern Kenya elephants dispersed to other neighbouring countries due to an upsurge in poaching 1970 (Thouless, 1995). Poaching levels in Botswana are lower than other countries (Schlossberg et al., 2019, CITES, 2021), although Chase et al. (2018) observed that levels have started to increase. Poaching incidents have been found to be episodic (Wittemyer et al., 2014, Robson et al., 2017, van Aarde et al., 2021) and remain a significant cause of Africa elephant mortality and population loss(Thouless et al., 2016). .

1.4.7 Fire

In savanna ecosystems where trees and grasses are dominant and are competitors, the interactive effect of elephants and fires is likely to exert an additive effect on tree density, community structure and composition by reducing the woodland density and tree diameter (Morrison et al., 2016). As the tree density and woodlands become thinner in diameter at breast height, grass production will increase leading to a high accumulation of biomass which subsequently will provide sufficient fuel load for fires (Saito et al., 2014). Elephants on the other hand will bring down mature trees, create open areas as well and promote grass growth that make the area prone to fires because of increased fuel load (Scholes and Archer, 1997, Holdo et al., 2009). Therefore, a combined and interactive effect of fires and elephant herbivory can increase fire frequency in an area and make it a fire hotspot (Cassidy et al., 2022). The combined occurrence of fires and elephant herbivory can reduce diversity in vegetation and homogenises the landscape (Masunga et al., 2013). Fires can also affect the distribution of elephants (Cassidy et al., 2022).

1.5 Ecological significance of elephants

1.5.1 Ecological facilitation

Ecological facilitation occurs “when one species positively impacts the fitness of another” (Zélé et al., 2018). Habitats that have been previously inaccessible to some animal species may become newly available as a result of ecological facilitation (Arsenault and Owen-Smith, 2002, Rees, 2004, Wegge et al., 2006, Makhabu et al., 2006, Ferguson, 2017). For example, Rutina et al. (2005) reported an increase in impala numbers which arose as a result of ecological facilitation in the form of habitat modification by elephants. The impalas were able to benefit from the transformation of woodlands into shrublands which were within the browsing height of the impala (Rutina et al., 2005). The conversion of woodlands into shrublands and grasslands also benefitted grazers such as buffalos *(Syncerus caffer)* which often prefer to graze in open-tree savannas with abundant and good quality grass (Prins, 1996b, Skarpe et al., 2004). Open areas also facilitate predator-avoidance by buffalo (Melletti et al., 2007) although moving from open areas to dense woodlands can be another predator evasion mechanism for buffalo (Bennitt et al., 2015). However, the reduction in tree cover as elephant herbivory increases can have devastating effects on wildlife species, such as sable and bushbuck, that prefer dense woodland habitats, leading to their vulnerability to predators and population declines (Feleha, 2018, Stalmans et al., 2019). When elephant numbers decreased in Tsavo National Park in Kenya, the woodland density recovered, however grazers such as Oryx *(Oryx beisa)* and Zebra (*Equus quagga*) were then affected by the increased woody cover and consequently declined in numbers (Inamdar, 1997). Elephants are ecological engineers and the impacts that elephant can have on ecosystem structure and functioning have been studied extensively across Africa (Chamaillé-Jammes et al., 2007, Landman et al., 2012b).

1.5.2 Human elephant Conflict

Across elephant range in Africa and Asia, human elephant conflict (HEC) is a key conservation issue (Shaffer et al., 2019). Where humans and elephants share the same space and natural resources, human-elephant conflict can occur "when the needs and behaviour of wildlife impact negatively on humans or when humans negatively affect the needs of wildlife" (Mekonen, 2020). Elephants require a large amount of space (Owen-Smith, 1988b, Chase and Griffin, 2009a) and due to their physiology and energy requirements, also need to consume large quantities of food and water each day (Laws and Johnstone, 1970, Sukumar, 1990, Ruggiero, 1992b, Choudhury et al., 2008, Owen-Smith, 1988a). Humans also require large quantities of these limited resources which leads to competition between the two species when they utilise the same habitats (Hoare, 2000).

There are four main categories of HEC which have been identified in the literature (Songhurst, 2012b), including those which have:

a) A direct impact on humans such as crop raiding (destruction and damage to crops), property damage (water installations, fencing etc), injury and death of livestock, injury to humans and loss of human life.
b) Indirect impacts on humans such as restriction on people's movement (especially at night), loss of sleep or reduced school attendance while guarding crops or stores, and early crop harvesting (African Elephant Specialist Group, 1999, Naughton et al., 1999, Di Minin et al., 2021); Indirect impacts on humans such as restriction on people's movement (especially at night), loss of sleep or reduced school attendance while guarding crops or stores, and early crop harvesting (African Elephant Specialist Group, 1999, Naughton et al., 1999).

c) A direct impact on elephants such as loss of habitat as a result of human encroachment, injury to elephants and elephant death through hunting, poaching or problem animal control.
d) Indirect impacts on elephants such as restriction on elephant movement to certain resources.

1.5.3 Human Elephant Conflict in Botswana

The northern Botswana holds majority of elephants in Botswana. The government of Botswana lifted the country's hunting ban in 2019 (Velempini, 2021). This was controversial to many on the hunting moratorium. People in the rural communities live in the frontier of HEC, interactions between people and elephants cause conflicts as they share the same resources like food, water and space. In many situations, rural people are victims of human-elephant conflict, in which elephants' requirements encroach on local people's livelihoods or local people's needs encroach on elephants' (Yurco et al., 2017). The survival of elephants in Botswana is dependent on achieving a healthy balance between elephant and human demands. The eastern Okavango is HEC hotspots as studies indicate (Jackson et al., 2008, Songhurst, 2012a). The most common form of HEC is crop raiding by elephants (Linkie et al., 2007, Rood et al., 2008, Pittiglio et al., 2014, Graham et al., 2010, Von Gerhardt et al., 2014, Gontse et al., 2018). Another form of HEC is displacement of farmers from their crop-fields and barring local communities from harvesting natural resources from the wild (Warner, 2008, Buchholtz et al., 2019, Buchholtz et al., 2020).

1.5.4 Socio economic importance of elephants

Elephants are a keystone species in ecosystems and they also play a significant role economically, as drivers of tourism (Brown, 1993, Bond, 1994). People travel to see elephants for photographic non-consumptive tourism and also for hunting or consumptive tourism. In Botswana, tourism are the second contributor of forex for Botswana's Gross Domestic Product (GDP), after minerals (Mbaiwa, 2009: 90). Most tourists are attracted by elephants as compared to other wildlife species (Mbaiwa, 2009: 198).

1.6 Problem statement

The movement and distribution of elephants can be influenced by environmental factors over time (Foley, 2002). Examining how features in the landscape such as vegetation productivity, water sources and anthropogenic activities drive the movement of elephants can help in understanding patterns of movement. Such understanding is important for informing elephant conservation and Human Elephant Conflict (HEC) management strategies. The eastern

Okavango Panhandle region of the Okavango Delta in northern Botswana is a hotspot for HEC, particularly in the crop production sector where elephants are responsible for both damage and losses to farmers' crops (Songhurst, 2012b, Pozo et al., 2017). The Government of Botswana has been working with people in local communities, Non-Government Organisations (NGOs) and wildlife research organizations to develop strategies for managing HEC. Strategies include short term interventions, such as the use of chili pepper deterrents and scaring with noise deterrents, as well as longer term strategies such as improved land use planning, electric fencing at landscape levels and minimizing human development on known wildlife routes. One longer term strategy that has been proposed in this area involves provision of artificial water sources to influence elephant movements and keep animals away from fields during the cropping season. However, an improved understanding of how elephants utilize their habitats in relation to natural ephemeral surface water and other factors that influence their movements from dryland habitats to the Delta resources is needed to inform such management decisions. Animal movement studies have been done in the eastern panhandle (Ben-Shahar, 1993, Songhurst et al., 2015, Naidoo et al., 2018, Buchholtz et al., 2019, Vogel et al., 2020), but little is known about the relationship between elephant movement and water availability. My study seeks to establish the role of ephemeral surface water on elephant distribution in the eastern Okavango Panhandle, Botswana as well as assess the movement distribution of elephants in relation to the seasonality, proximity and spatial extent of water presence represented by ephemeral surface water. Time series analysis of water extent on ephemeral surface water of the eastern Okavango panhandle was developed and overlaid with elephant movement datasets. The results of My study will inform national and regional elephant management policies and guide the development of HEC strategies. It will also provide a baseline for other habitat use studies in the region.

1.7 Research questions

The general objective of My study was to understand the availability of ephemeral surface water and how this influences elephant space use in the Okavango Panhandle, Botswana. This was guided by the following objectives:

- To explore ephemeral surface water availability
- To determine how elephant space use varies seasonally.
- To illustrate the influence of ephemeral surface water on elephant space use
- To examine the relationship between vegetation greenness and elephant space use

1.8 Study area

My study was conducted between 2014 and 2017 in the eastern Okavango Panhandle (Fig. 2). The study area covers an area of 8,732 km^2 and includes three Wildlife Management Areas (WMAs) called NG11, NG12 and NG13. Rainfall is seasonal and occurs between December and March (Songhurst et al., 2015, Ramberg et al., 2006). The soils in the eastern Okavango Panhandle are predominantly sandy (arenosols) and support deciduous dry woodland, upland grasslands, savannas and wetlands, floodplain grasslands, riparian forest, and shrublands (Thomas, 1991, Ringrose et al., 2003). The topography of the eastern Okavango Panhandle is flat ranging from 937-1068m (Gumbricht et al., 2001), (see Fig. 2).

The eastern Okavango panhandle includes 13 main villages (Mohembo East, Kauxwi, Tobera, Xakao, Sekondomboro, Ngarange, Mogotho, Mokgacha, Seronga, Gunotsoga, Eretsha, Beetsha and Gudigwa) that collectively are home to approximately 16,000 people (CSO, 2011). The population is comprised of three major ethnic groups: Bayei, Bambukushu, and Basarwa (Gceriku/River Bushmen) (CSO, 2011). Human livelihoods are dependent on tourism and agriculture (Songhurst, 2012), mostly taking place on the periphery of the Okavango Delta in NG11, NG12 and NG13. NG12 and NG13 are Wildlife Management Areas (WMAs) and NG11 is a multi-use area with a focus on pastoralism, arable agriculture, and tourism (Songhurst et al., 2015). Crop cultivation takes place mostly in November and January, with harvesting occurring in April (Mosojane, 2004). Throughout much of the study area, seasonal pans hold water during the rainy season. Typically, water persists in these pans into August and the larger pans can retain water until mid-October when the next rainy season begins (Chase et al., 2018). Still, little water is available over large portions of the elephant range in NG11 and NG13 during the latter part of the dry season and elephants need to move to the main Okavango River and Delta for water (Songhurst et al., 2016, Pozo et al., 2018, Chase et al., 2018, Buchholtz et al., 2019).

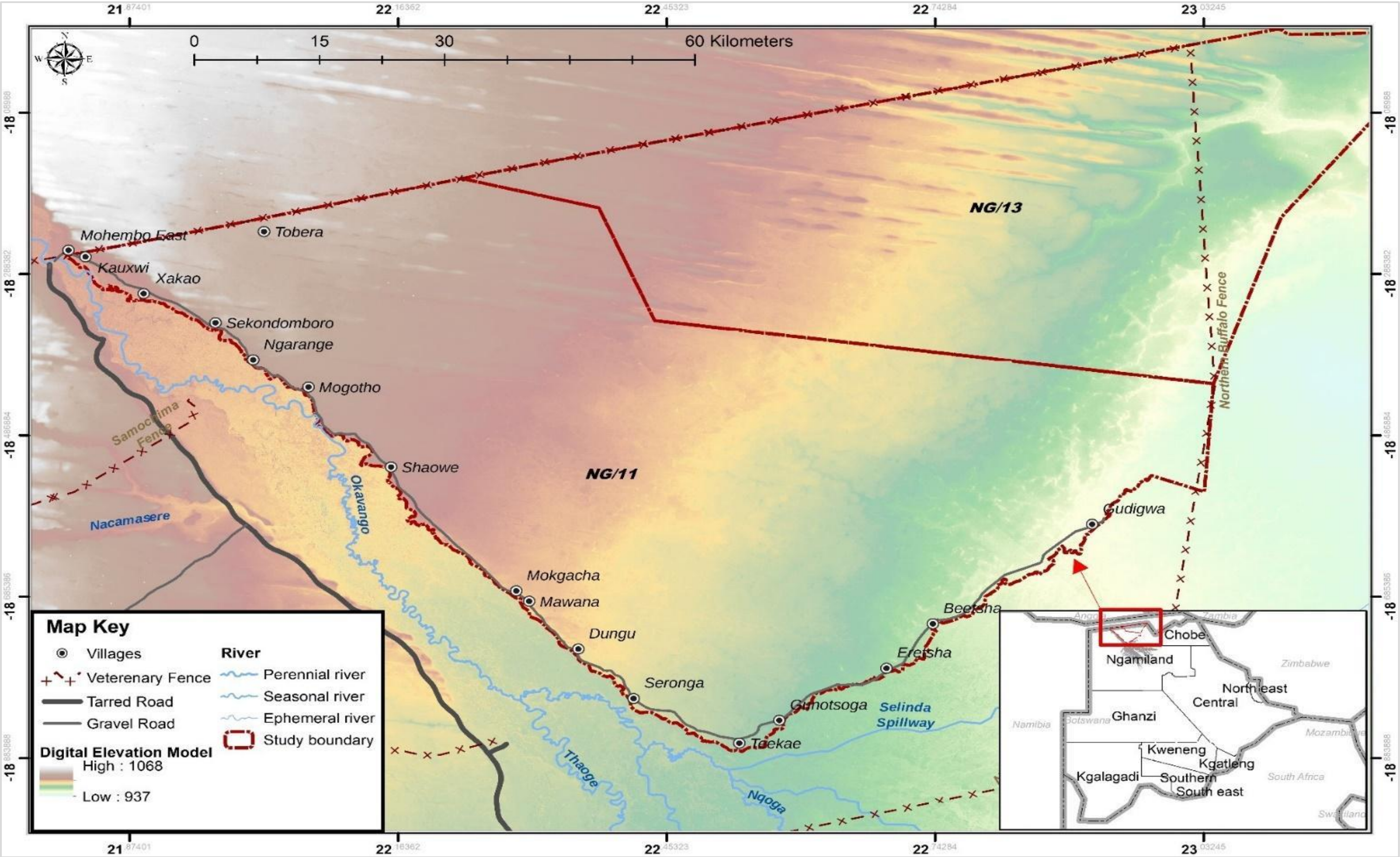


Figure 2. Location of villages in the eastern Okavango Delta Panhandle (Botswana). Whitish-black circles represent the thirteen villages (i.e., Mohembo East, Kauxwi, Tobera, Xakao, Sekondomboro, Ngarange, Mogotho, Mokgacha, Seronga, Gunotsoga, Eretsha, Beetsha and Gudigwa) along the Okavango River. The small southern Africa inset map shows the location of the study area in northern Botswana in white, and the red box showing the eastern Okavango, in Ngamiland. The digital elevation light brownish to light greens shows topography of the area which ranges from 937-1068.

1.8.1 Climate

Ramberg et al. (2006) describe the Delta as a normal continental climate, with annual rainfall ranging from 360 to 500 mm, most of it falling during the rainy season (November to April). Temperatures range from 25–35 degrees Celsius during the day to an average of 8 degrees Celsius at night. The warmest month of the year, near the end of the dry season, is October (May to October). The eastern Okavango has experienced droughts in the past and during the study period 2014-2017 it is evident that there were droughts and fires (Fig. 3 from A-E and Figs. 3,4).

A. Rainfall patterns shown on figure 3 during those times (2001-2018), shows that the rainfall was very low. Precipitation results for the eastern Panhandle indicate high peaks in 2001, 2006, and 2008. A moving average indicates a general upward trend in precipitation in 2002 to 2006 with a climax in 2008 and then a downward trend with mild troughs in 2005 and 2010, the lowest trough was around 2015. This means that high precipitation amounts were in 2001, 2006 and 2008 total rainfall varying annually. In 2006 and 2008 there were 2 high peaks far above normal rainfall.
B. Temperatures are very high starting August – October and low November – April
C. Drought episodes were studied in series using SPEI drought indices at time scales from 1, 3 12 and 48 months from 2001-2018 at the Eastern Okavango Panhandle (Fig. 5). Based on results drought appears in the first 5 years of the study period. April and July 2004 were wetter; however, the following year was drier with SPEI 48 reaching almost -8. The entire study period from 2006-2012 was moderately wet and the dry period persisted from July 2014-October 2017.
D. On a 1-month time scale (meteorological drought), indices demonstrated the following six major drought periods: from 2014-2017, with a little bit of moisture in April and July 2018; and the meteorological droughts were just mild in the preceding years
E. On a 3-month time scale (hydrological drought), both indices demonstrated the following six major drought periods: from 1943 to 1949, 1952 to 1959, 1975 to 1976, in the first half of the 1980s, most of the 1990s, and from 2000 until the end of the analysis period.
F. On a 12-month and 48-month time scale (hydrological drought), both indices demonstrated the following six major drought periods: from 2013, 2015, 2016 and 2017.

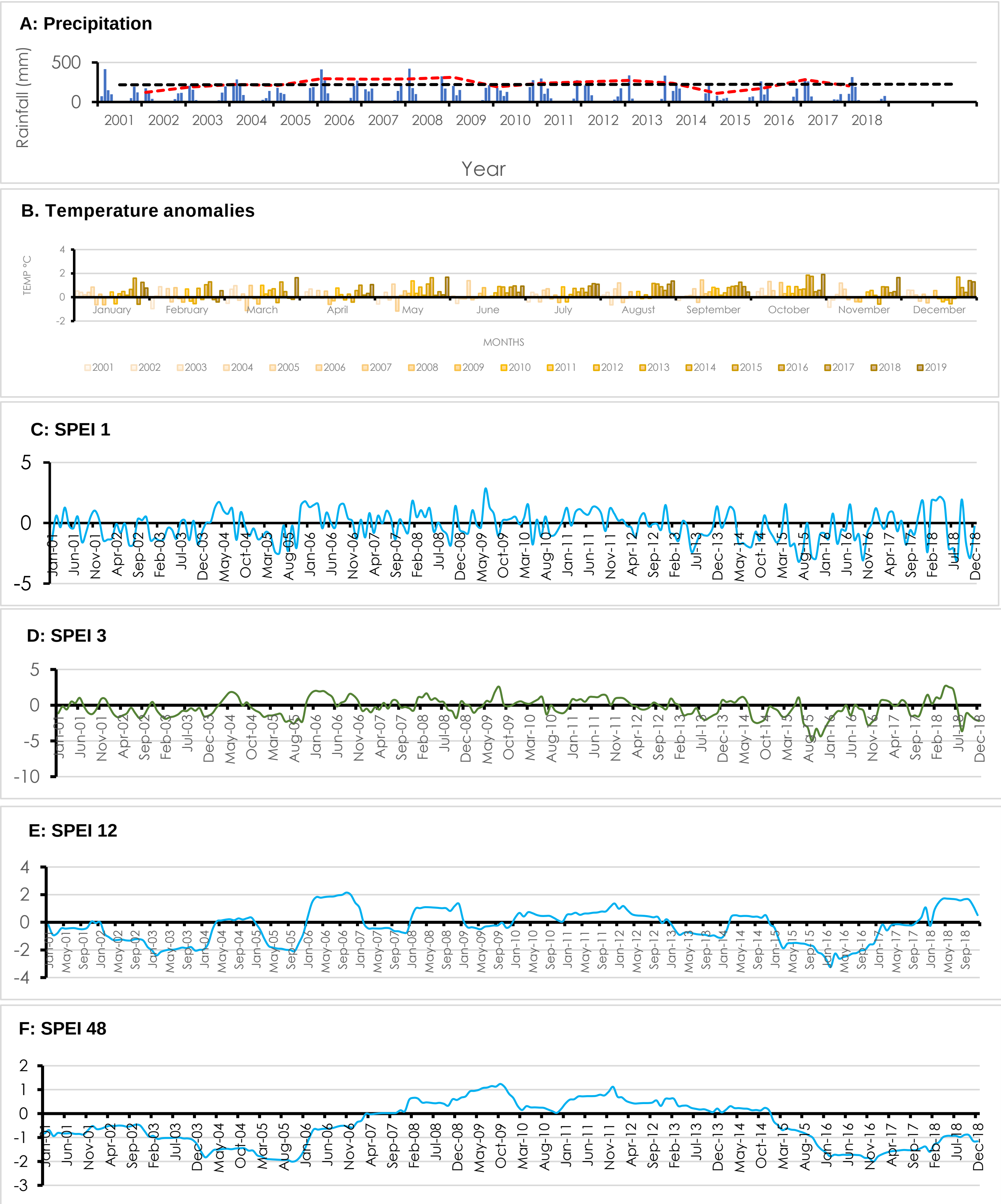


Figure 3. Climate trends showing A: Precipitation and red line indicates moving averages – the line helps to show overlaps from 1 year to the other. Black line shows mean over the entire study period, Precipitation data downloaded from http://chrsdata.eng.uci.edu/. B: temperatures in the eastern Okavango, data downloaded from C-F: droughts shown using Standardized Precipitation Evapotranspiration Index (SPEI). SPEI 1 – representing meteorological droughts, SPEI 3 – agricultural droughts, SPEI 12 - and 48 – hydrological droughts. SPEI data were downloaded from SPEI Global Drought Monitor online portal; https://spei.csic.es/map/maps.html and is available at a one-degree spatial resolution

Data source; (Center for Hydrometereolohy and Remote Sensing, 2020)

1.8.1.1 Climate of the eastern Okavango Panhandle

Climate diagrams show that between 2014-2017 during the study period, rainfall patterns were very low especially between 2014-2016, they were better in 2017. Temperatures were very high when there were no rains (see fig. 4A-E). Drought index showing metrological drought shows very dry conditions, whilst Agricultural droughts also show similar trends. These were worse in 2015. The hydrological droughts which represent rivers shows water scarcity as demonstrated in SPEI 12 and 48. The year that was worse is 2015-2016 for SPEI 12. SPEI 48 shows that almost the whole study period was extremely dry (See fig. 4A-E). The highest rainfall was recorded in January and February while the lowest amounts are recorded in May-October. The biggest trough signifying droughts occurred in 2015. Based on moving average lines, there was another dry spell after 2017 into 2018. Rainfall amounts increased from below average (> 200) to 420mm in 2001, 2006, and 2008.

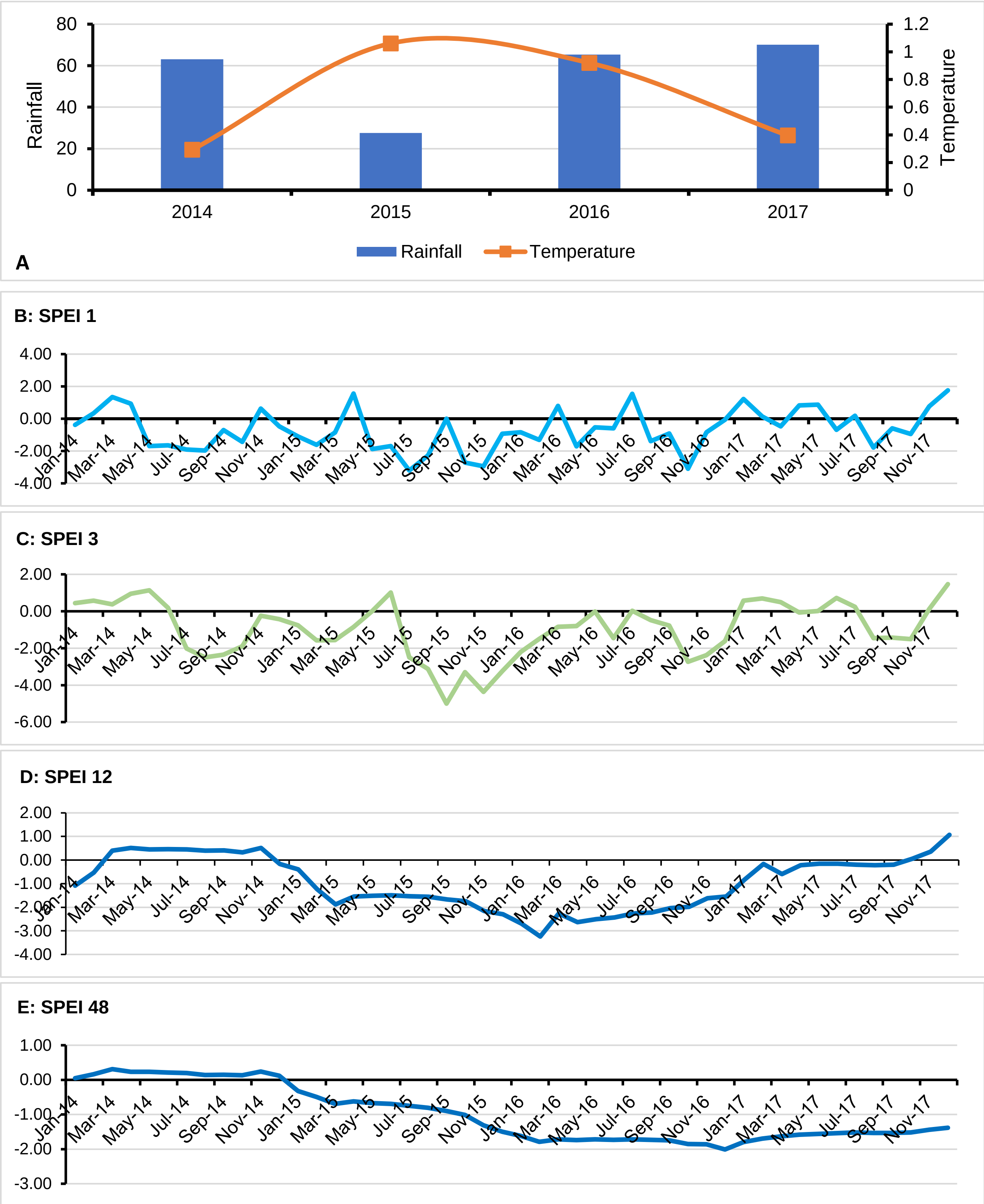


Figure 4. Climate trends showing A: rainfall, rainfall data downloaded from http://chrsdata.eng.uci.edu/. and temperatures in the eastern Okavango, data downloaded from C-F: droughts shown using Standardized Precipitation Evapotranspiration Index (SPEI). SPEI 1 – representing meteorological droughts, SPEI 3 – agricultural droughts, SPEI 12 - and 48 – hydrological droughts. SPEI data were downloaded from SPEI Global Drought Monitor online portal; https://spei.csic.es/map/maps.html and is available at a one-degree spatial resolution for the period 2014-2017

1.8.2 Vegetation

Vegetation communities and species vary throughout the study area depending on soil type (see Fig. 5), wetness, topography, and precipitation (Sianga and Fynn, 2017). The eastern Panhandle is semi-arid; deep Kalahari sands prevail in NG11, NG12 and NG13, with the primary vegetation types being shrubland at dune crests with (*Burkea africana*) and shrubbed forest with mixed mopane (*Colophospermum mopane*) (Mosojane, 2004, Pröpper et al., 2010) see figure (Fig. 5). *Terminalia sericea* sandveld, mixed marginal floodplain woodland (*Acacia nigrescens* and *Hyphaene petersiana*), acacia woodland (*Acacia erioloba*, *Acacia tortillis*), and perennial swamp woody communities dominate the vegetation cover (Roodt, 1998). NG12 is mostly made up of seasonal floodplains and the state of vegetation is dynamic and determines movement of elephants (Buchholtz et al., 2019).

1.8.2.1 NDVI

An indicator that can be used to look at the environmental conditions of an area is the Normalized Difference Vegetation Index (NDVI) which is an index that is used to estimate the amount and vigour (photosynthetic activity) of vegetation in the landscape and is used as a proxy for vegetation productivity. NDVI measures the quality of vegetation available in an ecological landscape (Pettorelli et al., 2011). While a healthy, green vegetation has an NDVI value that ranges between 0.5 - 1, a variegated/motley/flush or 'not-too-good' vegetation structure has a value that ranges between 0.2 – 0.49. A very poor and parched vegetation environment has an NDVI value that ranges from -0.00 to -0.9. This spectral index has been employed in many studies to test how plants reflect certain ranges of the electromagnetic spectrum (Bhandari et al., 2012, Pettorelli, 2013). The NDVI in remote sensing measures the state of the vegetation within an area. Several multispectral and hyperspectral sensors can used to compute NDVI. NIR and RED are the amounts of near-infrared and red light reflected and recorded by a satellite's sensor. NDVI is calculated using the red/near-infrared reflectance ratio (Duffy et al., 2011). By using this reflected light in the visible and near-infrared wavelengths, the NDVI index identifies and measures the presence of living, green vegetation (Guerschman et al., 2009). Elephants feed on grasses including roots (Ruggiero, 1992a) and forbs (Forbes, 2008) in the wet season but when these type of foods dry out in the winter elephants consume an increasing amount of leaves and twigs from woody vegetation (Owen-Smith and Chafota, 2012, Clegg and O'Connor, 2017), including bark and roots as leaves are shed (Owen-Smith and Chafota, 2012). Because of varying food availability throughout the seasons diets are adjusted by elephants (Owen-Smith, 1988a).

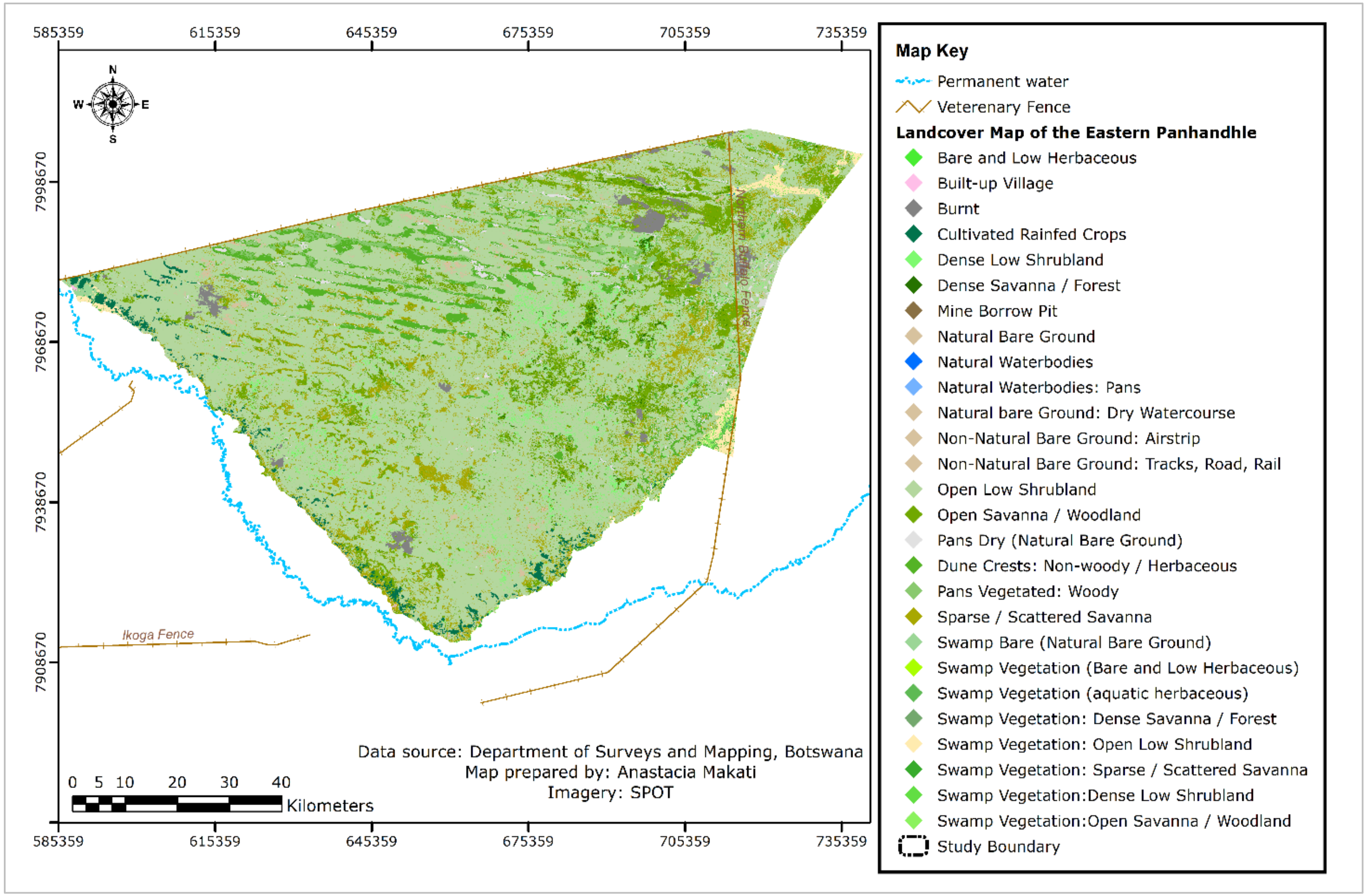


Figure 5. eastern Okavango Panhandle of Botswana Land Cover map derived from SPOT. Data sourced from Department of Surveys and Mapping, 2020.

Data source on fig.5: (Department of Surveys and Mapping, 2011: 31)

1.8.2.2 Soils

Soils found in the eastern Okavango include gleyic aerosols and Okavango soils in the Okavango Panhandle. To the southeast of the study area ferralic and Gleyic soils are found whilst Haplic soils predominately cover most of the study area (See figure 6).

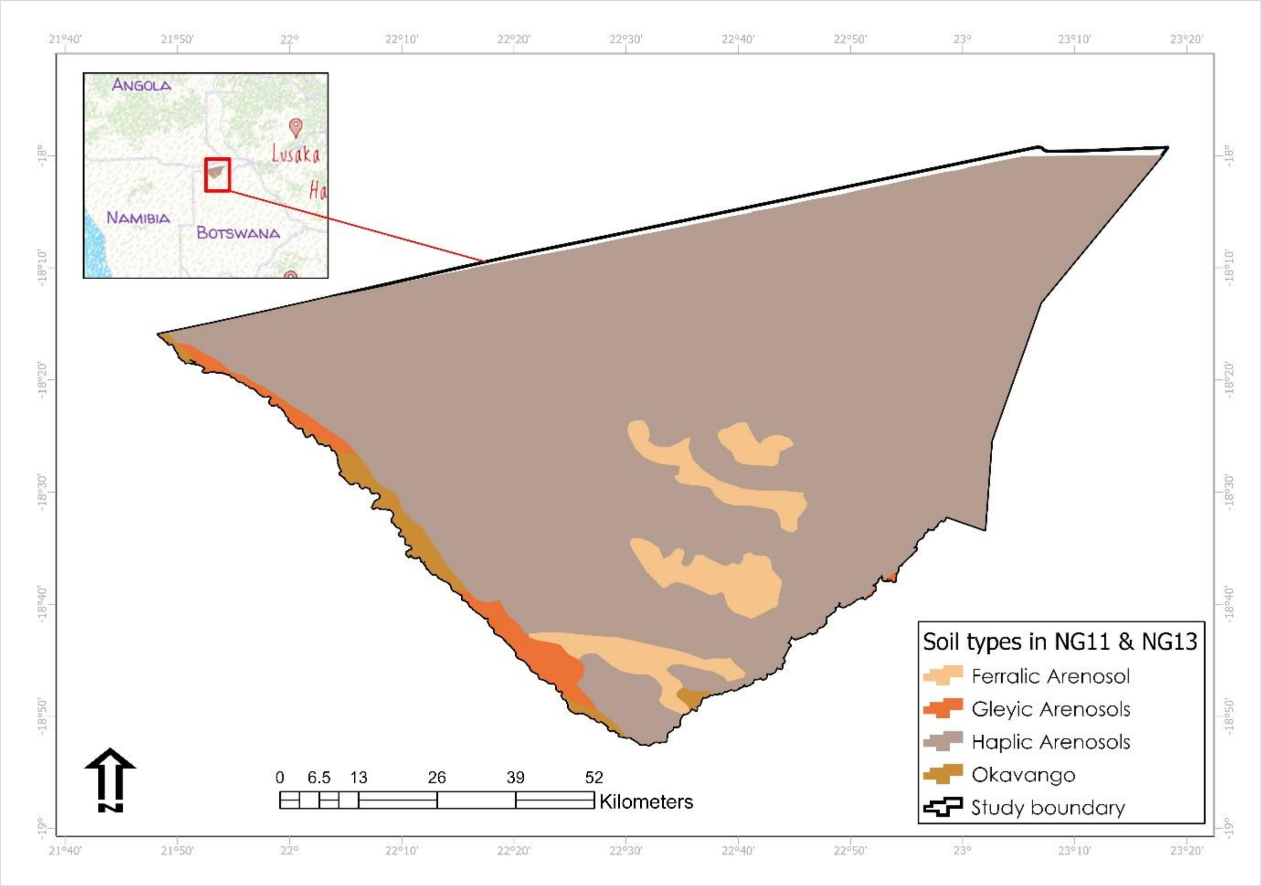


Figure 6. Soils at NG11 and NG13 in the eastern Okavango Panhandle of Botswana

Data source: (Tawana Land Board, 2019)

1.8.3 Hydrology

1.8.3.1 Hydrology of the Okavango Delta

The Okavango Delta is geologically described as a half-graben situated within the south-westerly extension of the East African rift valley (McCarthy and Ellery, 1998, McCarthy, 2013). The eastern Okavango Panhandle is a part of the large Okavango River basin and extensive dry Kalahari sand region. The largest geographical feature in the Okavango River Basin is the Okavango Delta, the largest inland wetland that floods annually, covering over a 12,000 km^2 area in Botswana (Dangerfield et al., 1998). The Delta is primarily maintained by rainfall water originating from the highlands in northern Angola (Ramberg et al., 2006). The water is transported through the Cuito and Cubango rivers in Angola which merge in Namibia and drain into the Okavango River in Botswana. Rainfall in southern Angola and northern Namibia and

Botswana is also an important source of water to the Okavango Delta. It is estimated that water from the rainfall occurring over the Okavango Delta and water from Cubango and Cuito Rivers each contribute a similar amount of water to the seasonal flood of the Okavango Delta (McCarthy and Ellery, 2000).The Okavango Delta is a raised terrain surrounded by floodplains and channels (Ellery and McCarthy, 1998, Bauer-Gottwein et al., 2007). Islands' edges are usually raised and dominated by broadleaf vegetation but are depressed in the middle (Ellery and McCarthy, 1994, McCarthy and Ellery, 1998). The water table below these formations of up to 500km^2 (Wolski et al., 2006) is shallow, leading to high rates of evapotranspiration that could reach 1860mm p.a., exceeding precipitation by a factor of three (Bauer-Gottwein et al., 2007).

The hydrology of the Okavango Delta has been extensively studied and many theories and mathematical models developed (Dincer et al., 1987, Obakeng and Gieske, 1997, McCarthy et al., 2005, Wolski et al., 2006). It has been found that the hydrology is highly variable due to prevailing climatic conditions across the Okavango Basin and the Okavango Delta (Dincer et al., 1987, Ellery and McCarthy, 1994, Milzow et al., 2009a). Dry season inflow is largely affected by rainfall in the upper catchment (Milzow et al., 2009b, Gieske, 1996, Mendelsohn et al., 2010). Inflow in the area is usually preceded by sporadic local rainfall, which is believed to recharge groundwater storage (Bauer et al., 2004, Gumbricht et al., 2004, Milzow et al., 2009b). Hydrological models in the area largely consider the biological, geological as well as meteorological processes in order to strengthen their validity. Despite the work on hydrological models of the Okavango Delta spanning more than 40 years, the models are still under development and driven by critical comments. Milzow et al. (2009b) proposed a simple numerical model based on various cells for each distributary channel and extrapolated for the whole of the Delta. This model showed variations in flow distribution for each of the cells studied (Dincer et al., 1987, McCarthy and Ellery, 1998, Milzow et al., 2009a). It was concluded then that the model was competent for conditions of the whole Delta, as well as to predict human impacts on the flow of the system (Dincer et al., 1987). The model was made robust by incorporating groundwater data into the model (Dincer et al., 1987). Improvements to the modelling of the Delta flow have since been improved to account for surface evaporation occurring in channels, floodplains, and island surfaces (Ramberg et al., 2006). Evapotranspiration and infiltration at the island fringes has also been accounted for in the new models (Obakeng and Gieske, 1997, Ramberg et al., 2006). The Delta is described hydrologically as an endorheic alluvium fan and has a low gradient (1:330017) and restricted local relief (Bauer et al., 2006, Ramberg and Wolski, 2008), with multiple sinuous distributaries. Improvements to the modelling of the Delta flow have since been to account for surface evaporation occurring in channels, floodplains, and island surfaces (Ramberg et al., 2006).. It experiences seasonal hydrological loading of 5-11 million tonnes of water when the

Okavango River floods, and another 5 million tonnes from the summer rainfall. Within this load, other tonnes come in the form of sediment and bedload.

1.8.3.2 Hydrology of pans

Pans are normally found in semi-arid environments and are tiny confined intracontinental sediment sinks (Eckardt et al., 2008, Eckardt et al., 2022). They occur on a worldwide scale (Schüller et al., 2022) and are known by a number of names, including continental sabkha, salina, dry lake, saline lake, ephemeral lake, salar, salt or clay pan, groundwater discharge zone or complex, playa lake and they are usually not deep but are wide (Rosen, 1994). They cover 1% of dryland area (Holmgren and Shaw, 1997, Rosen, 1994, Eckardt et al., 2008)... Studies show that in the Kalahari basin there are more than 4,000 pans in the Kalahari Schwele (Lancaster, 1978). The Okavango Panhandle consists of two contrasting hydrological settings namely the Okavango Delta and Kalahari. This study consists of two types of surface water. The one is largely perennial and the other one is largely ephemeral. The Okavango Delta and the panhandle is fed by water, which travel a large distance, primarily in the form of rainwater into the Okavango catchment from Angola, Namibia and Botswana. There is a distinct seasonality to this process and floodwaters arrive after the rainy season in the panhandle. The surface water in the sandy Kalahari areas, have pans or inter dune areas that flood. So, this water is almost entirely driven by rainfall.

The rainfall is very short lived and highly localized, resulting in a build-up of water in some small water bodies, which dries up quickly through evaporation and recharge (Seely et al., 2003). Recharge means the water goes underground and it adds to the groundwater, which determines the length of time the water is at the surface (Eckardt et al., 2013). In the eastern Okavango Panhandle the presence and occurrence of some of these ephemeral water bodies and pans vary, with some more permanent than others. Shallow groundwater which could sustain the surface water or the shallow groundwater, could also discharge (Eckardt et al., 2022). The water is very much controlled by the surface composition. A clay pan will largely recharge (Yidana et al., 2014), and the saline pan is an indication of some discharge at the water is ephemeral (Li et al., 1996, Seely et al., 2003)(see Fig. 7).

Figure 7. Example of clay pans in the eastern Okavango panhandle

The study area, for example in NG13 is drained by fossil river channels the main one being the ephemeral Kuru, Qonisha, Ngwetsi, Ngwikei, Haichawa, Quaquli and Ngonya river channels that enter Botswana from Namibia to the north of the study area (see fig. 8). Ephemeral pans are found in NG11 and NG13 and vary in size.

Photo credit on fig.7: (McCulloch, 2020)

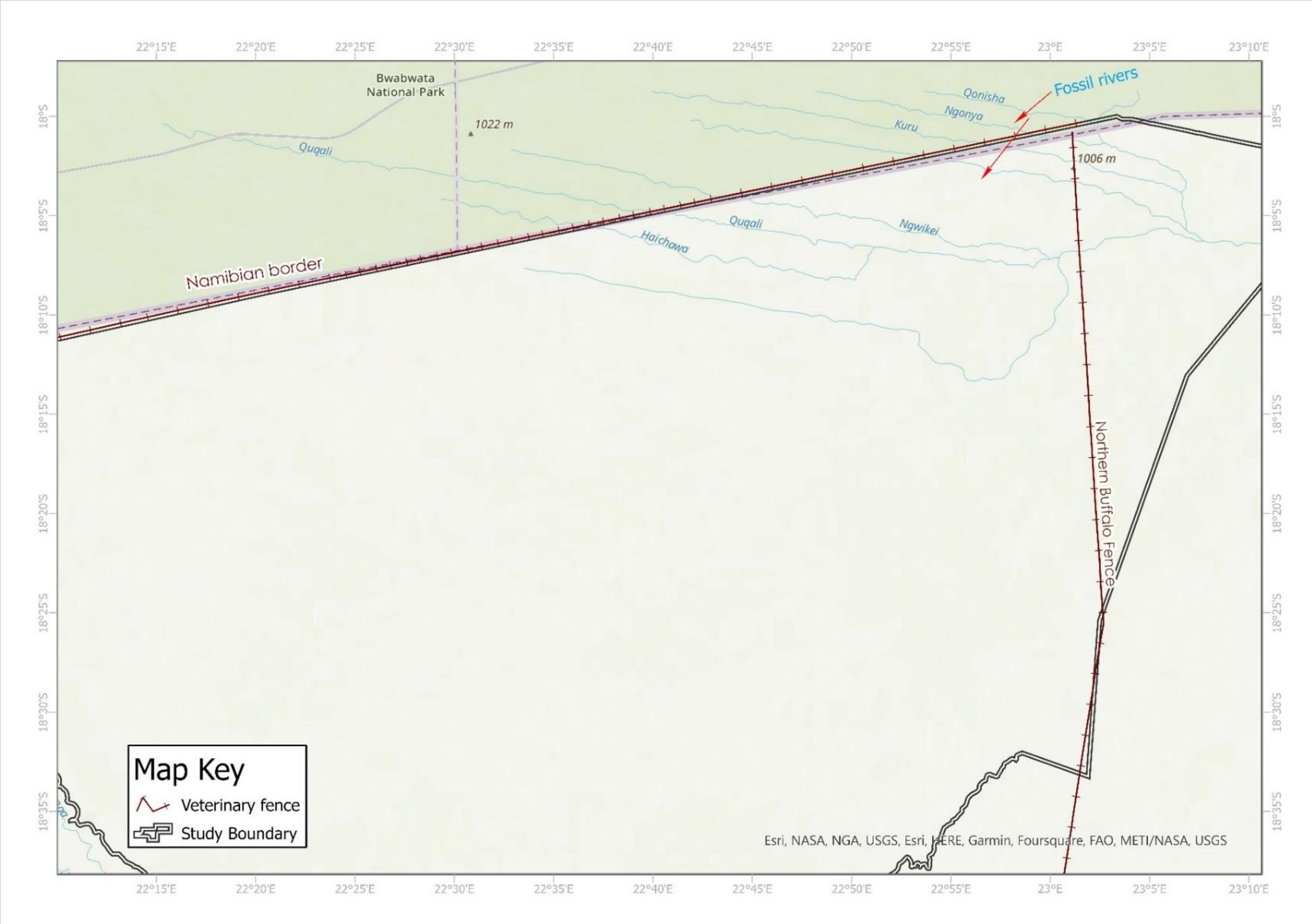


Figure 8. Fossil rivers north of the study area in the eastern Okavango Panhandle, Botswana

Ephemeral pans are used in a number of ways, including as a source of water for livelihood activities, livestock, and wildlife (Chanda et al., 2003). Local communities living in and around NG11 and NG13 use these pans to source water for domestic use and other livelihood activities such as hunting and fetching of veld products (VanderPost, 2003). The pans in the eastern Okavango panhandle have an alluvial basement characterised by a thick underlying layer of vertisols and silt that support tall and abundantly growing water tolerant herbaceous vegetation which includes grasses such *Cymbopogon excavatus, Sorghum versicolor and* sedges such as *Fimbristyis* or *Cyperus* species (McCarthy et al., 2002, Stanistreet and McCarthy, 1993). Grassy pans are found across the large landscape but occur in depressions surrounded by thickets of woodlands as shown on Fig.9a-b. These thickets surrounding the pans arose as a result of the presence of nutrient-rich vertisols that accumulated over a long time and can hold water for some time (Greenway, 1973, Mucina and Rutherford, 2006), Fig. 9a-b. These low-lying areas are fed by rainfall water coming from nearby elevated areas.


A
Photo credit: (Stronza, 2020a)

Figure 9a-b. A: Thickets of woodlands and B: an example of ephemeral surface water after a rainy season in the eastern Okavango Panhandle, Botswana

During the wet season elephants disperse into NG11 and NG13 and around April-May (late wet) they move towards the permanent waters of the delta in larger numbers to access the grasses, fruit and water. This timing coincides with the arable harvesting season, and elephant crop raiding incidents are most prevalent during this time (Ecoexist, 2015b). The Okavango Delta provides permanent water during the dry season for elephants (Buchholtz et al., 2019, Buchholtz et al., 2021).

1.8.4 Groundwater

In the Okavango, information on the groundwater regime is limited, especially for the north-eastern Okavango Delta. The piezometric surface in and around the Okavango Delta was created using data from excavated wells and boreholes (McCarthy and Ellery, 1998).The water table is shallow under the active Delta but deepens further from the marsh. The water table slope is notably steep on the Delta’s western edge, although it flattens to the southwest and south (McCarthy, 2006), see fig. 10. The piezometric surface’s general form implies a huge groundwater recharge mound centered on the Delta. This groundwater recharge is linked to seasonal flooding (McCarthy, 2006). Seasonal floods peak in the Panhandle around April or early May and reaches the Delta in July- August (McCarthy, 2006). Inundated areas increase as the water moves through sheet flooding and through the soils, which are mostly sandy and porous (Obakeng and Gieske, 1997). Dissolved solids are low in concentration (McCarthy and Ellery, 1998, McCarthy, 2006), comprising predominantly silica calcium, and magnesium (see fig. 10).

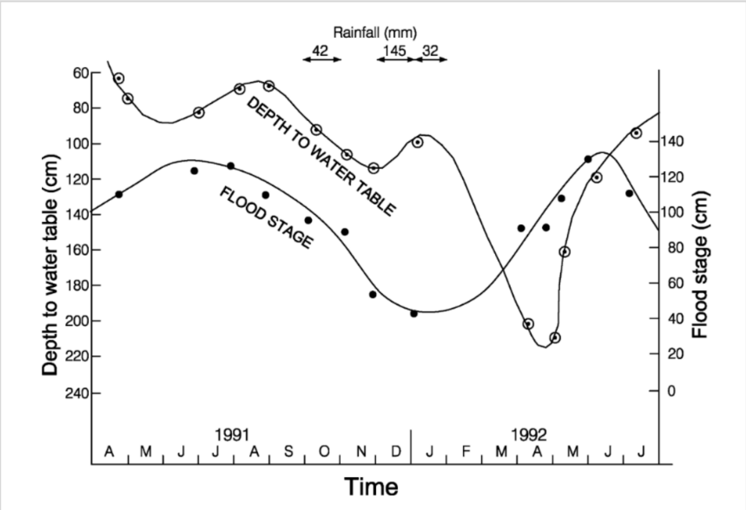


Figure 10. Example of the water table (at island centre) as it differs and the flood stage for the 1991 and 1992 flood cycles at Xaxaba (McCarthy and Ellery, 1994).

Adapted from: (McCarthy, 2006)

1.8.5 Wildfires

Wildfires are a widespread phenomenon both in temperate and tropical climatic regions (Huang and Rein, 2014). In Africa, they are common and frequent in semi-arid savanna ecosystems, and have shaped these ecosystems for over millennia, by transforming woodland savannas into open grasslands (Midgley and Bond, 2015). Although fires can be caused by natural factors such as lightning, anthropogenic causes have become more common as slash and burn agriculture, arson, and wildlife poaching increase. Fires are widespread and a natural occurrence all around the world, especially on the African continent. Fires can be used to clear dormant plants and prepare the area for the green flush that frequently follows (Christensen and Muller, 1975, Trollope, 1984). Grazers, both cattle and animals, are drawn to burnt regions to feed on the nutrient-rich fodder and ash on the ground surface (Putman, 2012: 79). Fires can be used to kill ticks, parasites, and prickly plant species, particularly acacia bushes and spiky herbaceous plants like *Cenchrus biflora* (Laliberté, 2007, Laliberte et al., 2007). At the vegetational landscape level, fires enhance spatial and temporal patterns throughout a region, influencing livestock and animal migration and distribution (Belsky, 1995). Between 2001 – 2018 fire occurrence has been in the north side of the study area in NG13 and south-eastern parts of the study, see figure 11.

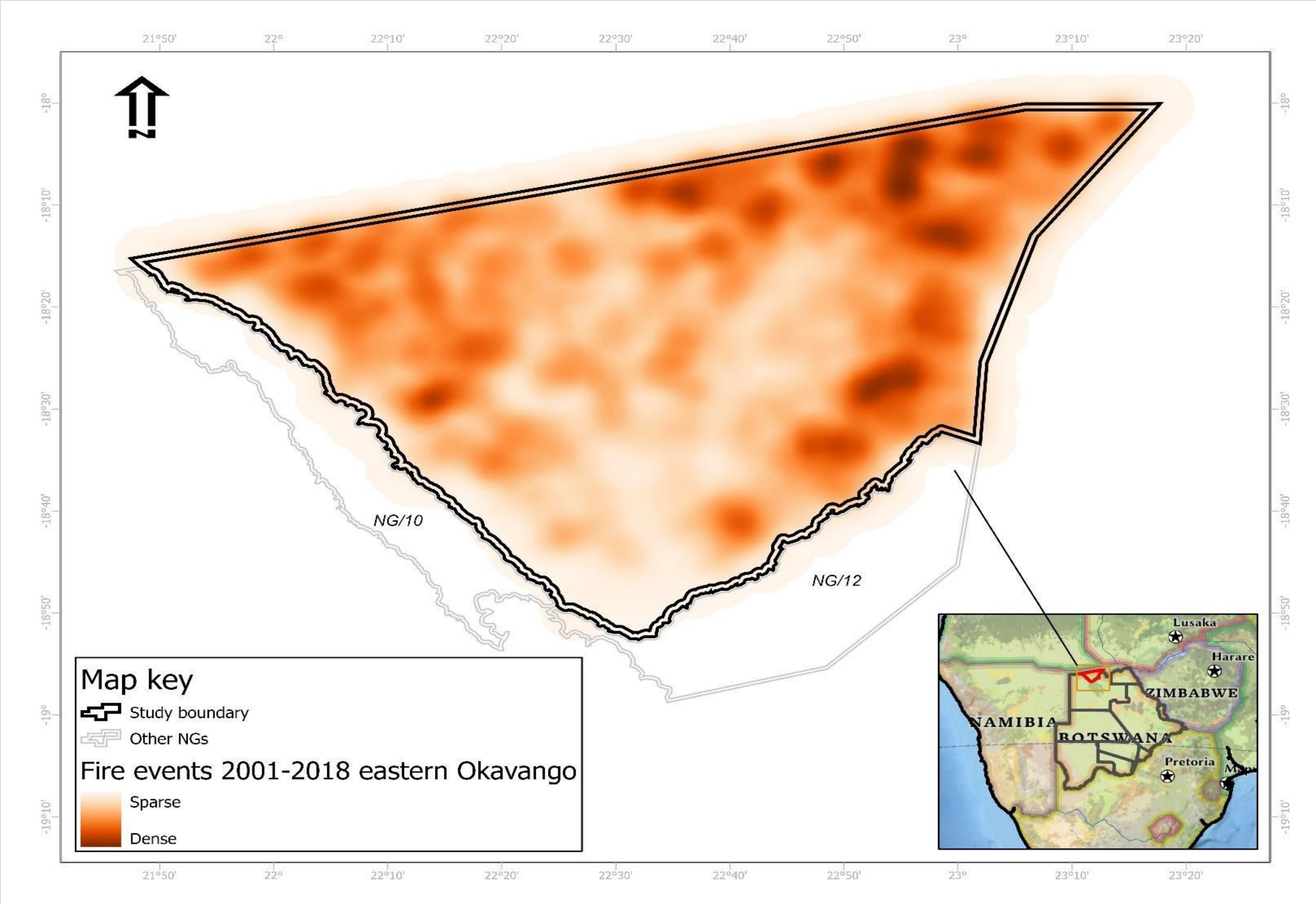


Figure 11. Showing fire incidents at NG11 & 13 in the eastern Okavango Panhandle, Botswana. Fire density map derived from using MODIS active fire data and can be downloaded here; https://firms.modaps.eosdis.nasa.gov/download/create.php. ArcGIS Pro 2.8 was used to create the density map

1.8.5.1 Fires in the eastern Okavango between 2014-2017

In the eastern Okavango Panhandle wildfires in the area mostly occurred in the north of the study area in NG13 and in the southeast (Fig. 11 & 12). Anthropogenic activities poaching and different land use practices (Archibald et al., 2009) are believed to be the main cause of fires in the north (Cassidy et al., 2022). The same can be stated for the fires in the north near the Namibian border, which are clustered near cattle posts. Even though, there aren't many people living in NG13, there are a few cattle posts, and it's possible that fires will be started to burn off old vegetation and increase the short-term grazing options (Cassidy et al., 2022). Some of the burning may be caused by cross-border fires in addition to local ignitions because the area is closer to the Namibian border (Kazapua et al., 2009). Fires are infrequent in the middle of NG11, most likely because of limited human activity in that area. In the eastern Okavango Panhandle, fires occur between July – October of every year as shown on Fig. 12. Although the study period (2014-2017) is short fewer active fires were discovered in 2015 and more in 2017).

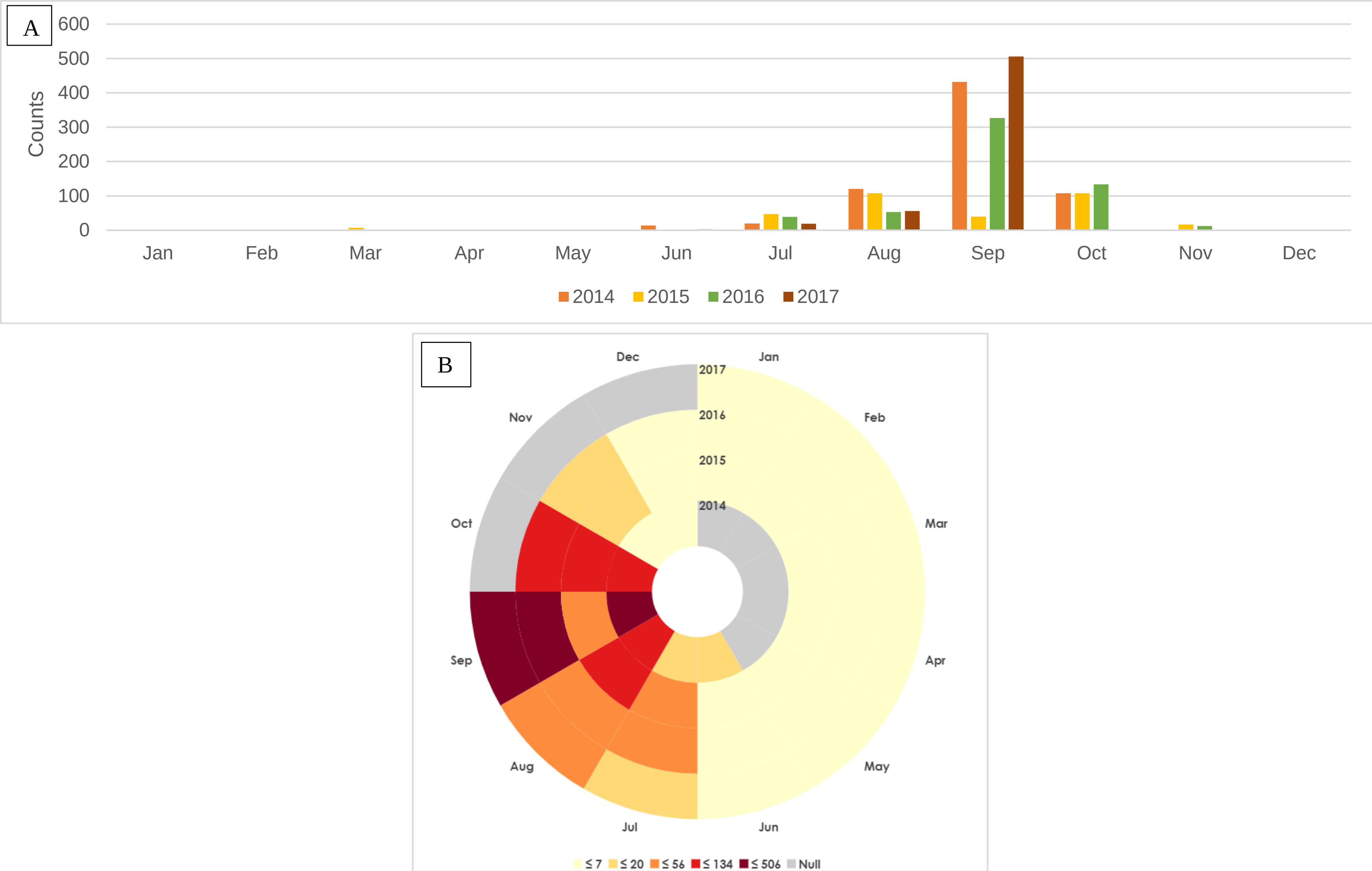


Figure 12. Fire incidents at NG11 & 13 in 2014-2017 in the eastern Okavango Panhandle, Botswana. A: bar graph showing their visual distribution. B: shows a data clock each month and Year. Fire incidents derived from using MODIS active fire data and can be downloaded here; https://firms.modaps.eosdis.nasa.gov/download/create.php. ArcGIS Pro 2.8 was used to create the density map

2 EXPLORING EPHEMERAL SURFACE WATER AVAILABILITY IN THE DRYLANDS

SUMMARY

The management and conservation of wildlife species is reliant on the availability of reliable data sources on environmental information. This includes landcover, land use information and surface water distribution. Surface water delineation is one technique widely used to distinguish water bodies from dry land surfaces. Landsat imagery is one of the most extensively used data sources in water resource remote sensing, and whilst multiple methods for extracting surface water from Landsat data are detailed in the literature, the AWEI spectral index was identified as the best tool to represent ephemeral surface water in various sized waterholes. In this chapter, the AWEI spectral index was used to explore the availability of ephemeral surface water within the study area, within the dryland areas. Based on results, in NG11 and 13 the concentration of ephemeral surface water is towards the southern ends of the study area. Persistent ephemeral waterholes are found not far from Gudigwa.

2.1 Introduction

Surface water is defined as any body of water that is above ground, such as streams, rivers, lakes, marshes, and reservoirs or any other water found on the Earth's surface and it is a vital part of many ecosystems (Du et al., 2010). Surface water bodies are fed by precipitation and runoff and lose water through evaporation and seepage into the earth (Lee and Swancar, 1997). Many plant and animal species rely on surface water and their related ecosystems for their survival. Surface water is classified into three types: perennial, ephemeral, and human made. Surface water that is perennial, or permanent, lasts all year and is supplemented by groundwater when there is minimal precipitation. Surface water that is ephemeral or semi-permanent occurs only for a portion of the year (UNDP, 2012). Small streams, lagoons, and water holes are examples of ephemeral surface water (see fig. 13). Artificial structures, such as dams, waterholes and built wetlands, are examples of human-made surface water (UNDP, 2012).

In arid and semi-arid environments, surface water is a critical resource for people, wildlife and livestock (Chamaille-Jammes et al., 2007, Smit et al., 2007b). Such water in arid environments is usually found in ephemeral water bodies or water holes (springs, ponds or rivers) that only exist for a short period after heavy rains (Williams, 1996), (see fig. 13). Some models predict increasing variability of rainfall with the effect of long dry seasons and droughts in some areas while others experience extreme precipitation in the future as a result of climate change (Wato et al., 2016, Kanagaraj et al., 2019). Botswana's water supplies are mostly surface water (in rivers, ponds, and dams of varying sizes) and subterranean water in aquifers, some of which are fossil resources and do not replenish. Botswana shares all its perennial rivers with neighbouring nations. The Okavango, Zambezi, Orange-Senqu, and Shashe-Limpopo River basins are shared. Botswana's surface water is constrained by several factors including its low and erratic run-off, lack of available dam sites, and high evaporation rates (Du Plessis and Rowntree, 2003).

Figure 13. An example of ephemeral surface water, elephants mud bathing drinking around a waterhole, and healthy green vegetation for food in the eastern Okavango Panhandle in Botswana

Photo credit for fig.13: (Stronza, 2020b)

With the advent of Geographical Information Systems (GIS) and Remote Sensing (RS) techniques and applications, surface water can be delineated and mapped especially in data-scarce and often inaccessible environments such as the Okavango Delta (Cohen and Goward, 2004, El Nahry et al., 2011, Feyisa et al., 2014, Dauwalter et al., 2017). Remote sensing enables repeated surveillance and monitoring of dynamic themes such as water, land, and agriculture (Guanter et al., 2015). The rationale behind delineating surface water from other landcover types from optical images considers the lower reflectance of water compared to other classes in a landcover map, importantly in the infrared channels (Frazier and Page, 2000). A variety of approaches have been used to calculate the water resources (i.e., aerial extent) using satellite data. For example, Qi et al. (2019) developed a model to discriminate inland water from high-resolution panchromatic images in China. This method was designed on an analysis of the image texture based on textual analysis. The spectral traits of water were not considered in this method, but rather the method is supervised by the analyst in obtaining training samples.

Other studies developed methods that could be used for surface water delineation (McFeeters, 1996, Krause and Bronstert, 2005, Margane et al., 2008, Xie et al., 2016a, Acharya et al., 2016, Acharya et al., 2018, Wang et al., 2019). One example is a simple method using density slicing where a single infrared band is used to derive a water map (Frazier and Page, 2000). Classification methods such as unsupervised (where the computer does the work) and supervised (where an analyst trains the computer to output a landcover) were used. Spectral water indices have also been developed that use two or more bands to categorize water and non-water features (Ma et al., 2019, Ma et al., 2020). In the 1980s Crist and Kauth (1986) proposed the Tasseled Cap Wetness (TCW) index which used 6 bands of surface reflectance and set a threshold of 0 to differentiate water and non-water classes..

Delineating any kind of surface cover type from optical images is based on an object's ability to reflect radiant energy within a certain spectral channel. Additionally, spectral water indices (e.g., Normalised Difference Water Index); Modified Normalised Difference Water Index (MNDWI); and Automated Water Extraction Index (AWEI) vegetation indices (i.e., Normalised Difference Vegetation Index (NDVI); and Enhanced Vegetation Index (EVI) have played a great role in the delineation of water bodies, and showed more success than classification methods. In the 1990s, McFeeters (1996) developed the NDWI, which uses a simple index using the input of two spectral bands, the Near Infrared (NIR) bands and shortwave bands to delineate water bodies on satellite images. The output from the NDWI shows water classes with low reflectance from the visible portion of the electromagnetic spectrum (Ali et al., 2019). Water bodies in their liquid state generally have higher reflectance on the blue (0.4 - 0.5 µm) spectrum than on the green (0.5 -0.6 µm) and red (0.6 – 0.7 µm) spectra. Utmost reflectance in the blue band of the visible spectrum shows clear water, which means that water appears blue. Turbid water has higher reflectance in the visible spectrum. There is no reflection in the NIR and beyond. NDWI can be calculated by the following formula:

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR} \quad \text{(McFeeters, 1996)} \qquad \textbf{(1)}$$

e.g., For Landsat 8 data; $NDWI = \frac{NIR - SWIR\,1}{NIR + SWIR\,1}$

While McFeeters (1996) development of the index added value to the scientific community, the method had shortcomings. Studies that used the method showed that it is sensitive to clouds and built-up areas, and in most cases, it will miscalculate/overestimate water classes (Xu et al., 2006, Singh et al., 2015). Water bodies have stronger absorbability in the shortwave infrared than the NIR and built-up areas have greater radiation in the SWIR band than in the NIR band (Ji et al., 2009, Du et al., 2016). To correct the shortfalls of the NDWI, Xu et al. (2006) developed the MNDWI, which utilizes the green and shortwave infrared bands to segregate water classes, which replaced the middle-infrared band for the near-infrared band. The resulting values representing the water features and non-water features had values equaling to 0. Positive values show the presence of water.
Below is the formula.

$$MNDWI = \frac{Green - SWIR}{Green + SWIR} \quad \text{(Xu et al., 2006)} \qquad \textbf{(2)}$$

For Landsat 8 data, $MNDWI = \frac{Green - SWIR\,1}{Green + SWIR\,1}$

Among these remotely sensed indices, the MNDWI is superior in delineating water (Sunder et al., 2017, Dzinotizei et al., 2018, Huang et al., 2018, Nandi et al., 2018). MNDWI uses the Green and SWIR bands for the enhancement of open water features. It diminishes the built-up areas feature that is often correlated with open water in other indices i.e. NDWI (Xu et al., 2006). MNDWI also eliminates fire scars but fails to avoid clouds. Studies such as (Mohammadi et al., 2017, Chen, 2019) show that between NDWI and MNDWI, the latter is more stable in surface water delineation because of the SWIR bands which are more sensitive to the concentration of sediments than near-infrared bands. However, like other indices the shortfall of MNDWI is that it cannot classify snow, shadows and clouds, which is why studies such as (Choi and Bindschadler, 2004, Salomonson and Appel, 2004), used the Normalized

Difference Snow Index (NDSI), which was developed to classify snow cover. This also meant that cautious consideration in snow/cloudy areas must be applied when using the MNDWI.

Recently, Feyisa et al. (2014) proposed the Automated Water Extraction Index (AWEI), which collectively had more than two spectral bands in the delineation of surface water. AWEI index has two kinds; 1) The type that caters for extraction of water pixels from shadows ($AWEI_{sh}$) areas that are mountainous, have clouds, and other obstructing objects, 2) the kind that caters for images without shadows ($AWEI_{no\ shadow}$) utilizing 5 spectral bands. The method is robust because one could distinguish water bodies from time series Landsat imagery using a single threshold (Feyisa et al., 2014). Although Landsat 5 was used in the initial use of the index, imagery products from other Landsat platforms can also be used, by simply replacing bands as necessary. The AWEI index has been used in previous small waterbody studies (Feyisa et al., 2014, Xie et al., 2016a, Nandi et al., 2018).

My study aimed to map ephemeral waterholes in the eastern Okavango Panhandle using Landsat 8 satellite imagery. The $AWEI_{noshadow}$ spectral index was used to map the waterholes, which represented ephemeral surface water in various sized waterholes.

2.2 Methods

2.2.1 Remote sensing data

Although there are several multispectral images varying in spectral, temporal, spatial (250m – 10m) characteristics available (i.e., MODIS, Sentinel, and SPOT), for My study the recently launched Landsat 8 satellite imagery were used, which is collaboratively run by the National Aeronautics and Space Administration (NASA) and acquired from the United States Geological Survey (USGS EarthExplorer, 2019). Landsat has been in use since the 1970s and has the advantage of short revisit period (16 days) that is useful for long term monitoring of surface water (Ji et al., 2015, Ogilvie et al., 2018, Huang et al., 2018). The spatial resolution of 30m x 30m and allows the detection of typical sized patches of ephemeral surface water (30m and larger) that are found in the study area. Landsat is one of the most significant remote sensing data sources for detecting surface water monitoring (Table 2).

The Landsat 8 scene at path/row 175/073 covered the entire study area extent. Images were downloaded from the (https://landsatlook.usgs.gov/viewer.html), one scene per month for March-October on 2014-2017 (Table 2). As mentioned previously due to extensive cloud cover during the months of November-February which rendered them unusable, these months were excluded from the data analysis. To eliminate discrepancies resulting from seasonal variations in solar elevation and the dynamics of soil, water, and plant, images were downloaded at dates that were as similar as feasible (Joseph, 2005: 299), see table 3. The obtained Landsat 8 data were Level 1 Terrain Corrected (L1T) GeoTIFF products and they were pre-georeferenced to UTM zone 34 South projection using WGS-84 datum. The advantage of using Landsat 8 over previous versions is because of its radiometric, temporal resolution, and spectral heterogeneity (see table 2) which allows surface water mapping (Mueller et al., 2016, Nguyen et al., 2019, Lymburner et al., 2016).

Table 2. Specifications of Landsat 8 OLI data

Satellite/sensor	Band	Wavelength (μm)	Name	Resolution (m)
Landsat 8/OLI	1	0.435–0.451	Coastal Aerosol (CA)	30
	2	0.452–0.512	Blue	30
	3	0.533–0.590	Green	30
	4	0.636–0.673	Red	30
	5	0.851–0.879	Near Infrared (NIR)	30
	6	1.566–1.651	Shortwave NIR 1 (SWIR1)	30
	7	2.107–2.294	Shortwave NIR 2 (SWIR2)	30
	9	1.363–1.384	Panchromatic	15
	10	10.6-11.2	Thermal infrared	100
	11	11.5-12.5	Thermal infrared	100

Table 3. Acquisition days of the month for Landsat 8 images used to derive surface water availability in the Eastern Panhandle, Okavango Delta, Botswana

Year	March	April	May	June	July	August	September	October
2014		25	27	12	14	15	16	02
2015	27	28	14	15	17	18	19	21
2016	29	14	16	17	19	20	21	07
2017	16	17	19	20	22	23	21	10

2.3 Data Analysis

My study used 30m resolution Landsat 8 images to identify small water bodies that were small and hard to spot. I adopted the $AWEI_{no\ shadow\ (nsh)}$ index because the images utilized in my study had 0% cloud cover. $AWEI_{nsh}$ index uses the green (band 3), near-infrared (band 5) and shortwave infrared (band 6) to effectively discriminate surface water.

2.3.1 Ephemeral surface water

Using ENVI 5.5.3 the two types of formula were computed as follows;

$$\mathbf{AWEI_{nsh}} = 4 \times (Green - SWIR1) - (0.25 \times NIR + 2.75 \times SWIR2) \quad \text{(Feyisa et al., 2014)} \qquad \mathbf{(3)}$$

$$\mathbf{AWEI}_{sh = (green + blue) X 0.25 -} (1.5 \times NIR) + (SWIR1 - 0.25 \times SWIR2)$$

With indices, a threshold is chosen whereby pixels are classified as water and non-water. Available global-scale data analysis products produced by Pekel et al. (2016) are also used increasingly to assess the distribution of surface water. Such datasets leverage the wide availability of cloud-based geospatial imagery to analyse large datasets, such as Landsat and MODIS to compute surface water extent over the globe. Whilst such datasets are useful in covering larger water bodies, they are often inefficient in mapping small ephemeral water bodies (surface water). For instance, the Automatic Water Extraction Index method used was able to identify small and turbid ephemeral water bodies that had otherwise been missed by global analysis products.

Several studies have successfully mapped Surface water using AWEI index (Feyisa et al., 2014, Zhai et al., 2015, Zhou et al., 2017, Sarp and Ozcelik, 2017, Nandi et al., 2018, Khalid et al., 2021, Tang et al., 2022), however limitations with spectral indices is failure to cater for environmental conditions like clouds and fire scares. The AWEI has demonstrated good results in the case of the above. The AWEI performs well in delineating water pixels from shadow at high albedo features due to the broader range of wavelengths in the band rationing (Feyisa et al., 2014). Other limitations is when the water bodies are very small and difficult to spot.

Ephemeral surface water was delineated using ENVI 5.4.1 (L3HARRIS Geospatial, 2020) to calculate surface water using Landsat 8. Below are the pre- processing steps which were followed (Figure 14):

1. Radiometric calibration - digital numbers (DN) were converted into surface reflectance. This is important because reflectance is better than comparing DN values, since the first is a fixed characteristic of a target, while the last is a function of radiometric resolution.
2. The atmospheric correction was performed to obtain reflectance at the surface through the removal of atmospheric effects that may cause absorption and scattering of electromagnetic radiation (Wang et al., 2018). The Fast Line-of-Sight Atmospheric Analysis of Spectral Hypercube (FLAASH) module was used in ENVI to convert the raw quantized calibrated pixels values to surface reflectance(Schroeder et al., 2006, Malahlela, 2016, Yan and Roy, 2020). ENVI computes atmospheric correction using the following formula;

$$L = A \frac{\rho}{1-S\rho e} + B \frac{\rho e}{1-S\rho e} + Le$$ (Du et al., 2016, Hayatbini et al., 2019) *(5)*

Where ***L*** is the pixel spectral radiance, ***ρ*** is the pixel surface reflectance, ***ρe*** is the averaged surface reflectance, ***S*** is the atmosphere spherical albedo, *Le* is the radiance backscattered by the atmosphere whereas parameters A, B, S, and *Le* are calculated by the ENVI processing software (Feyisa et al., 2014). Moreover, ***L*** can be obtained from raw ***q***uantized calibrated pixel values (Q_{cal}) which can be computed in ENVI 5.5.3 as;

$$\mathbf{L = MQ_{\mathit{cal}} + A}$$ (Du et al., 2016) *(6)*

Where **M** is the band-specific multiplicative rescaling factor and **A** is the band-specific addictive factor. The parameters **M** and **A** are included in the OLI metadata file –.MTL file (Nguyen et al., 2019).

3. Images were geometrically corrected to the WGS 1984 Universal Transverse Mercator (UTM) 34S coordinate system to avoid spatial distortion (Esposito et al., 2019), as well as to allow the integration of other spatial layers and then resampled to 30m with the nearest neighbor option. Images were geometrically corrected for pixel-by-pixel comparison.
4. Images were clipped to the study area extent using the “subset to the region of interest plugin” in ENVI 5.5.3. Permanent water sources were excluded from this analysis (i.e., the Okavango River)

Landsat 8 images were displayed with a 7:5:3 band combination to see water features better and the delineation of surface water was performed in ENVI 5.4. In ArcGIS 10.8.1, using the Spatial Analyst extension, the resulting output raster was converted into a binary image of water and non-water classes using the ‘classify tool’. The ‘raster to polygon tool’ was used to convert the water classes into vector polygon features to overlay with existing spatial datasets.

The $AWEI_{nsh}$ index has been used widely by research scholars in small waterbody studies (Feyisa et al., 2014, Xie et al., 2016b). Out of the 2 types of My study has adopted the $AWEI_{nsh}$ index because the images utilized in My study had 0% cloud cover, see fig. 14 for the methodology workflow.

Anomaly graphs were done to demonstrate long term conditions even though the assessment was for a shorter period (2014-2017).

2.3.2 Persistence maps

Surface water maps were derived by using a spectral indices $AWEI_{nsh,}$ the resultant image was then converted, from raster file to shapefile so that it is easy to work with other spatial layers. Monthly surface water maps were made by showing how ephemeral surface water was distributed in the area. Yearly maps were also developed by adding all months mapped in a particular year (e.g., 2014, 2015, 2016 and 2017), in total 2014 had about 7 surface water maps stacked, whilst 2015, 2016 and 2017 had about 8 each. Another stack of all surface maps included a stack of all 4 years of ephemeral surface water altogether. Finally, four classes of ephemeral waterhole which had water ≤ 19 were extracted to see waterholes which were highly persistent (see Fig18a-d and Fig. 19a-b). Raster calculator in ArcGIS Pro 3.0 were used to derive the persistent maps.

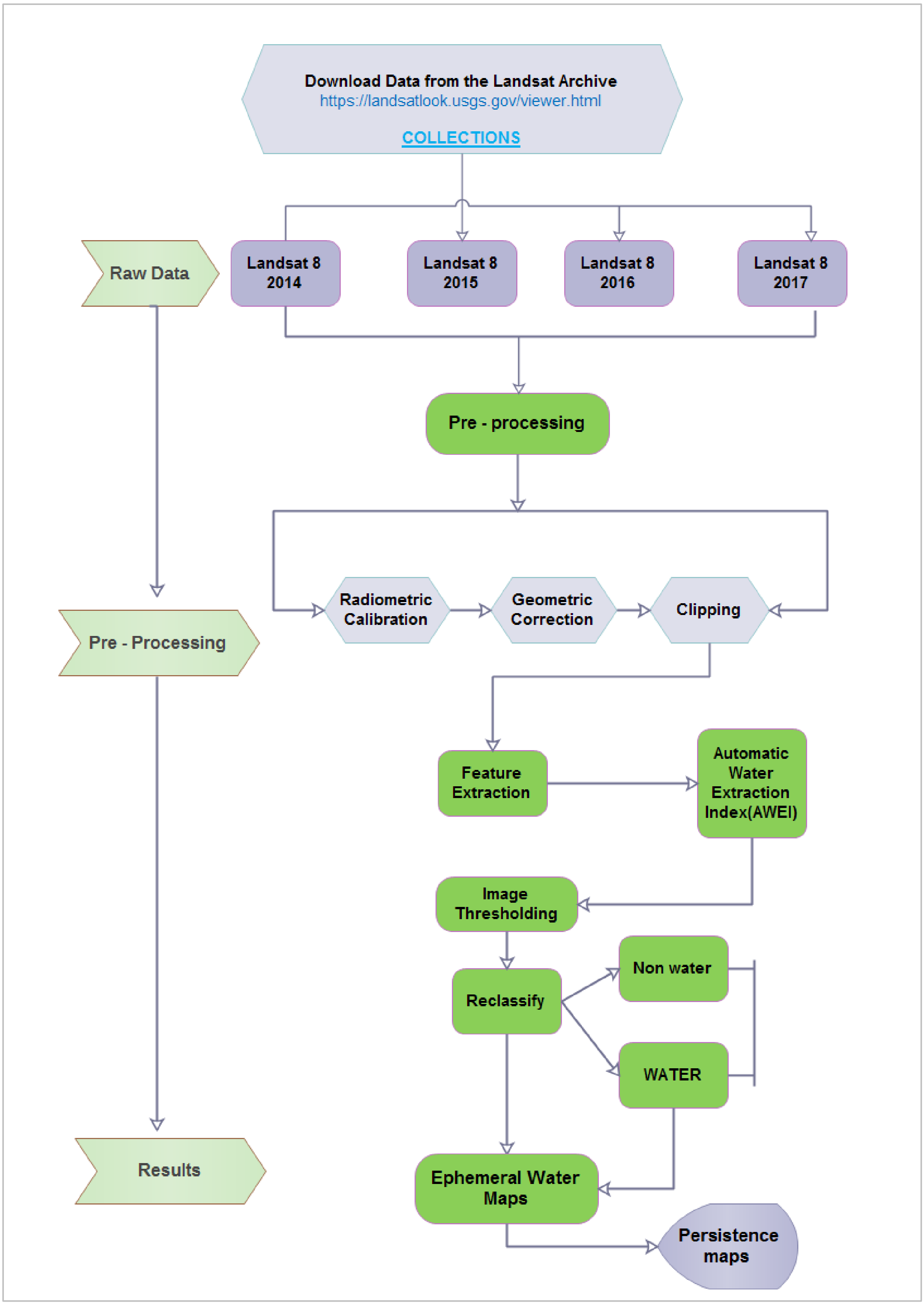


Figure 14. Ephemeral surface water methodology flow diagram from starting to downloading raw Landsat images, to pre-processing and delineating ephemeral surface water. Pre-processing was done using ENVI and conversion of raster to shapefile was derived using ArcGIS 10.8.1., (Environmental Systems Research Institute, 2021)

2.4 Results

A Landsat imagery dataset covering 4 years (2014-2017) was used for ephemeral surface water mapping in the drylands of the study area (NG11 and NG13). However, due to cloud cover obscuring the imagery in the first 2 months (January -February) and the last 2 months (November – December) of the year, only the months of March - October each year could be used in the analysis, except for 2014 whereby only April - October were included because deployment of elephant movement data started on that month. Monthly surface water inundation anomaly in the study area is the difference between the average inundation for a particular month of a given year (2014-2017) and the average inundation for the same month over 4 years of the study period. The positive monthly inundation anomaly tells that there was above average rainfall and therefore availability of surface water for elephants in a particular month and year relative to what is considered the normal (mean) for that month. Negative inundation anomalies would represent reduced or lower rainfall during those months than the mean (see figure 15).

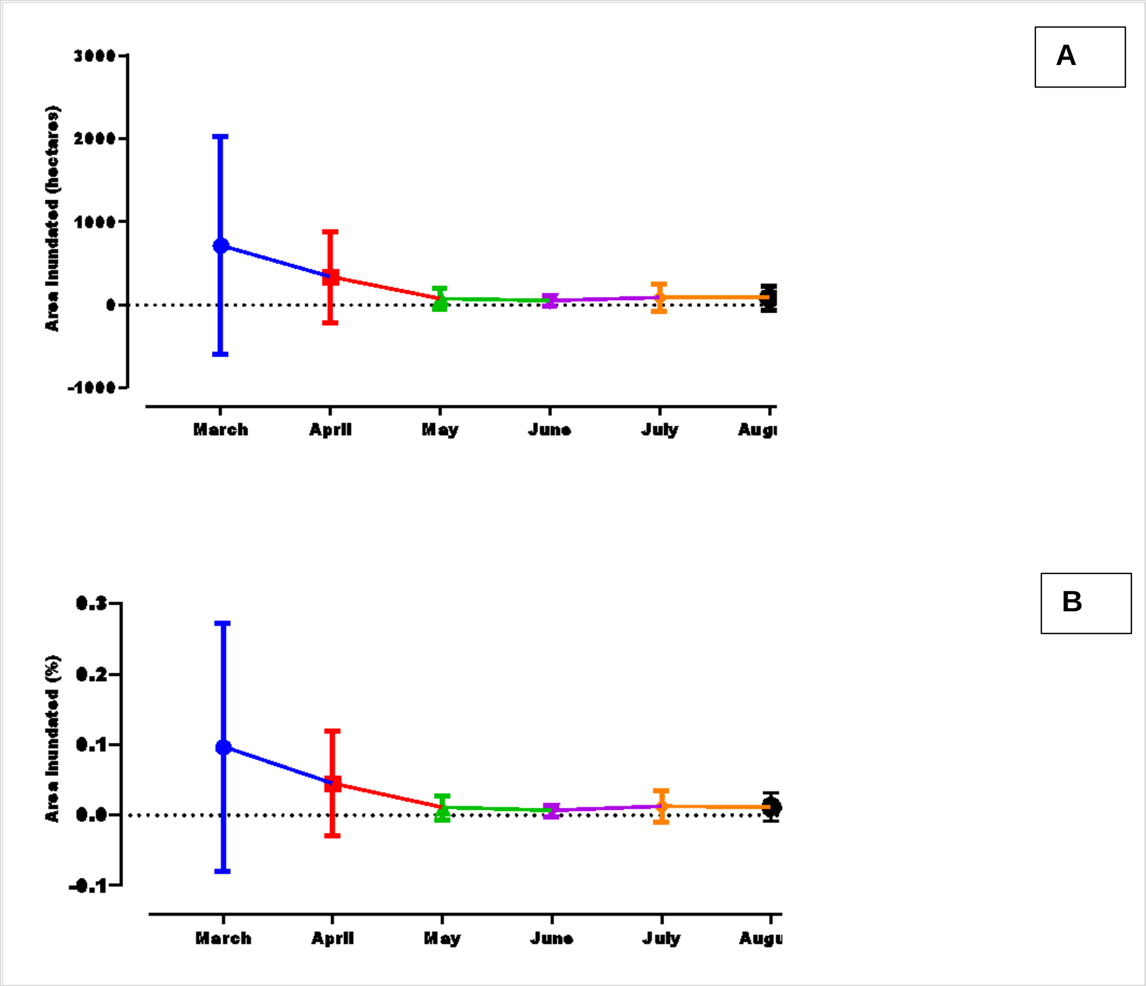


Figure 15. Positive area inundated anomalies in March and April, representing greater surface water availability during those months' 4-years mean than during the rest of the other months when normal rainfall was experienced over the study area in the eastern Okavango Panhandle

Time series of the area inundated from 2014-2017 (A & B) in the eastern Okavango Panhandle, Botswana. Surface area was calculated using Landsat imagery of 30m resolution. Error bars represent S.E. The above suggest a normal dry season or little rainfall at the start of the wet season when compared to the 4 years mean (Fig. 15)

2.4.1 Ephemeral surface waterholes

Using the Automated Water Extraction Index technique, all waterholes were successfully delineated (see figure 16 and for monthly product output, (see fig. 17-19A-D) as well as persistent maps on figure 18A-D and figure 19A-B). The mapped surface water products were used with other environmental variables in a resource selection function to link to the elephant data.

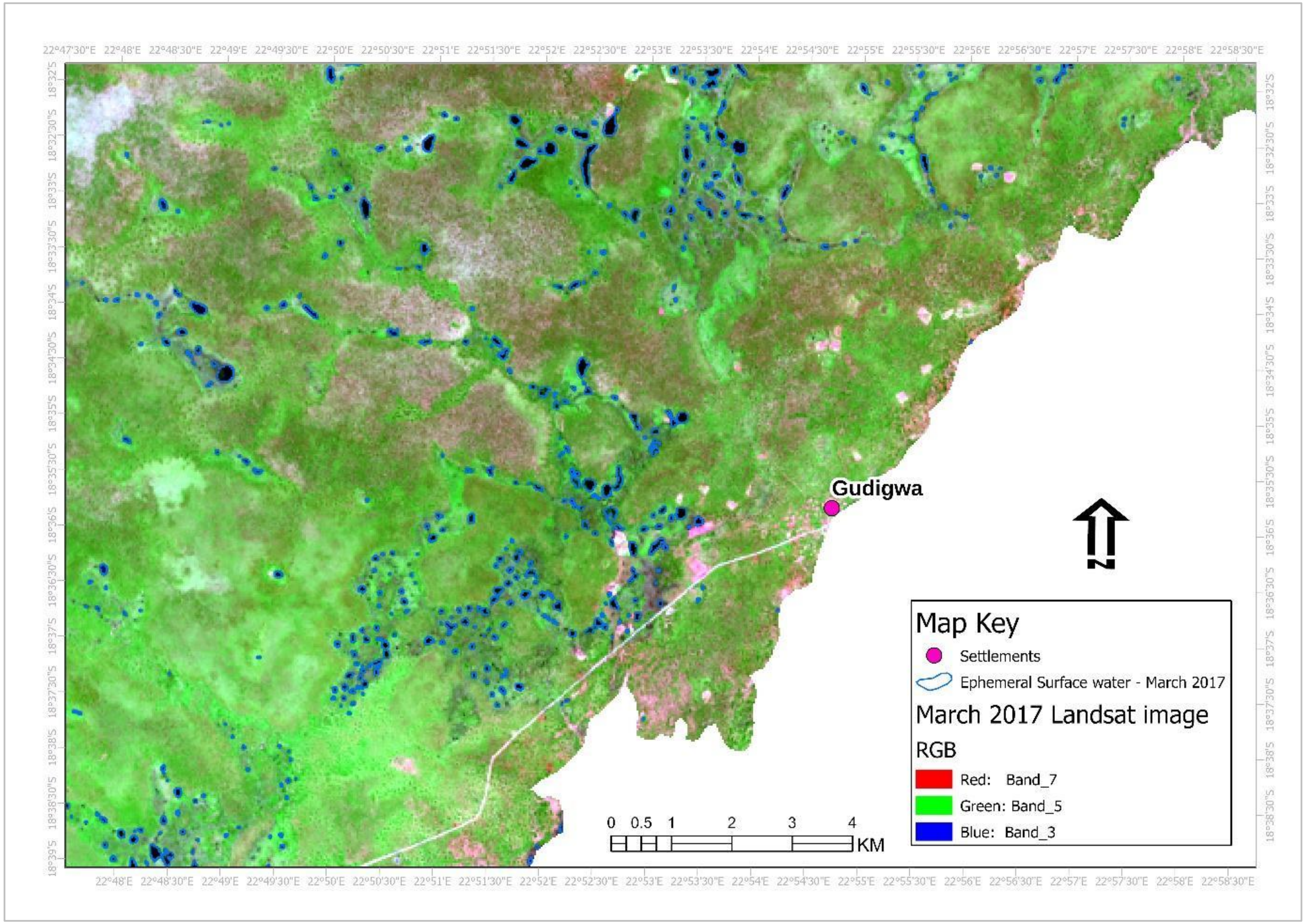
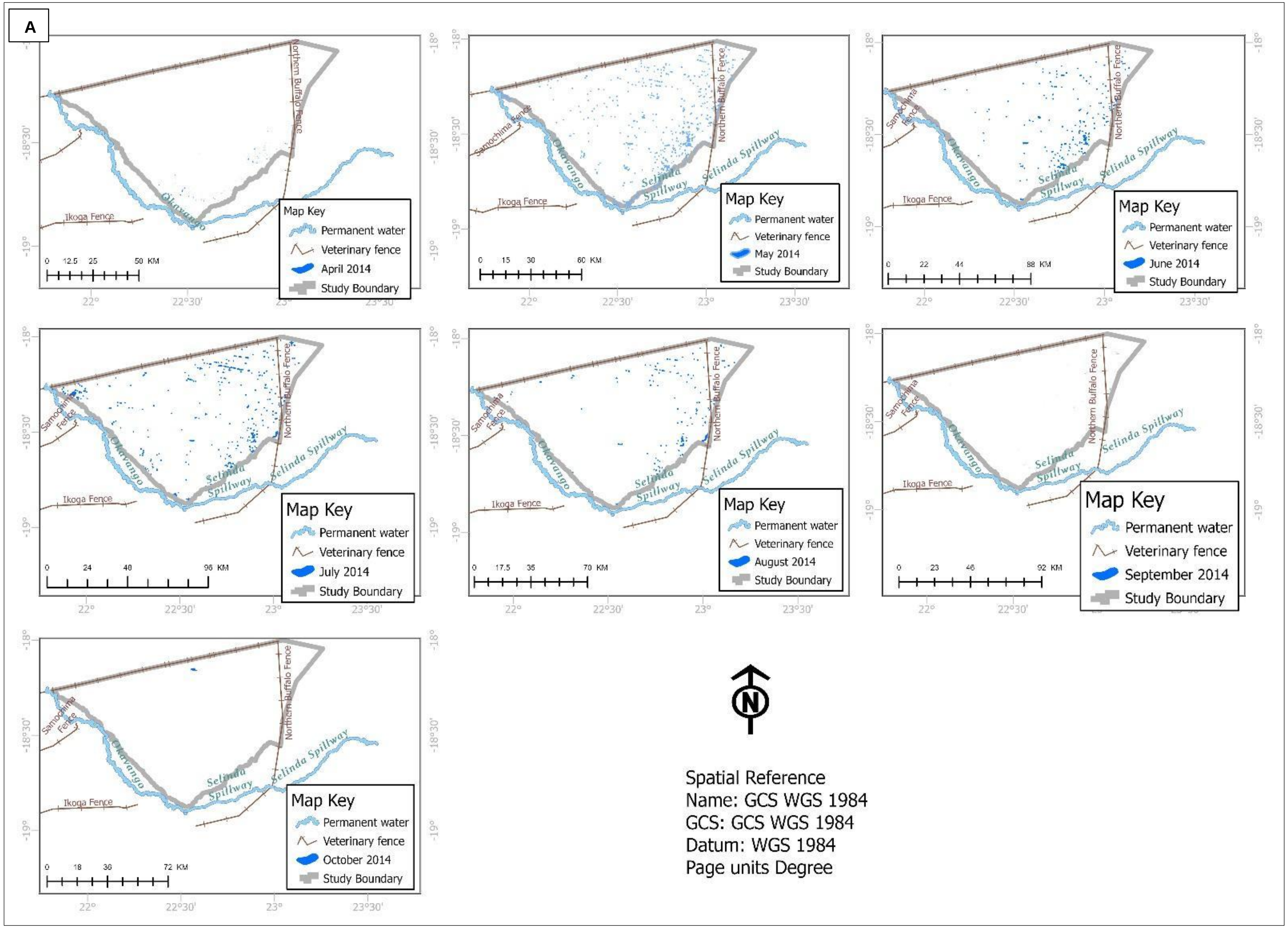
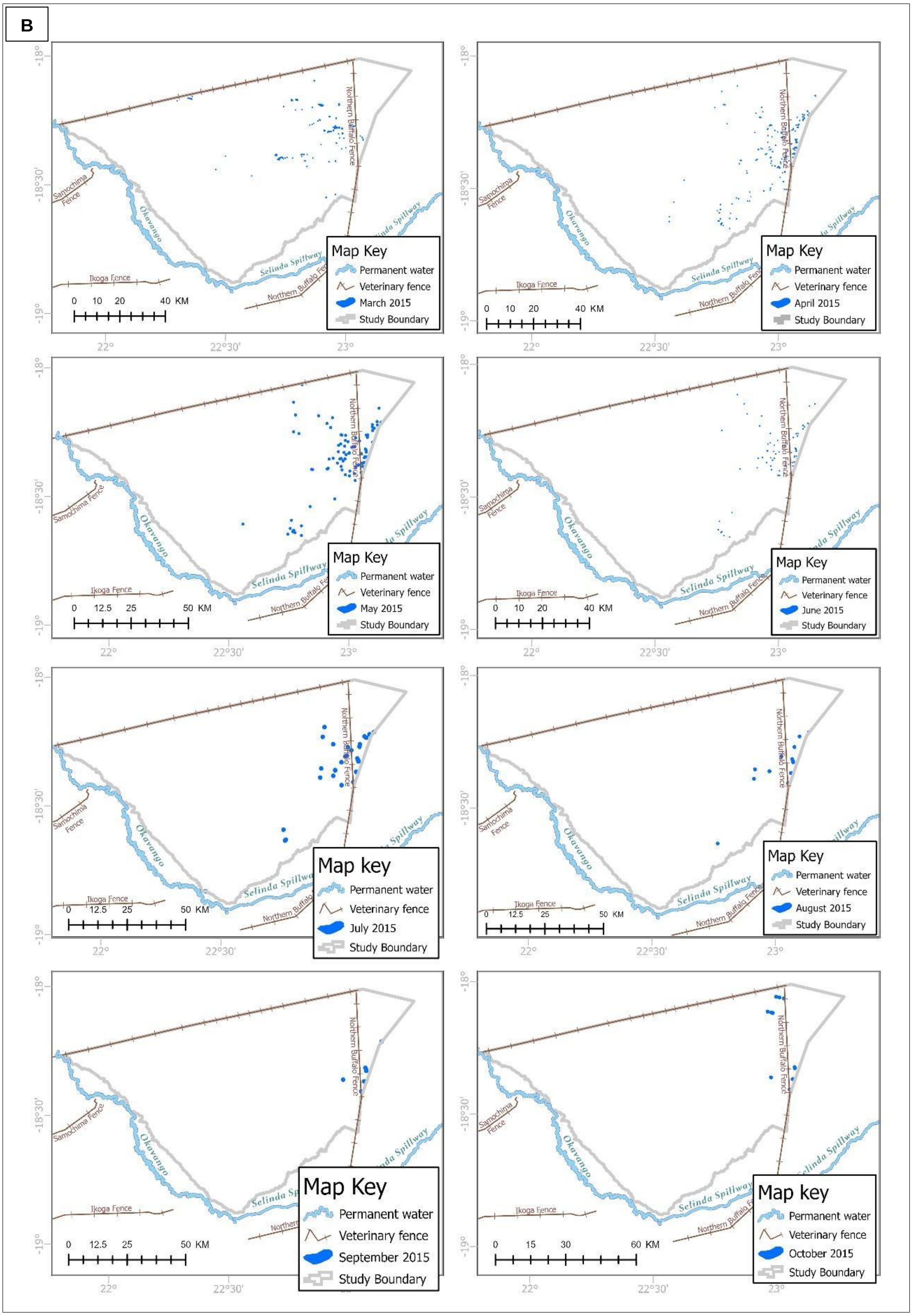


Figure 16. showing a Landsat 8 result of March 2017 using the AWEI index in mapping ephemeral surface water. Band combination 7:5:3 showing false color image with good atmospheric penetration depicting green vegetation and water features in black. Blue polygons surrounding small ponds of ephemeral surface water. The pink circle showing Gudigwa village in the eastern Okavango.


A
Map Key
Permanent water
Veterinary fence
April 2014
Study Boundary
Northern Buffalo Fence
Ikoga Fence
Okavango
0 12.5 25 50 KM
Map Key
Permanent water
Veterinary fence
May 2014
Study Boundary
Samochima Fence
Selinda Spillway
0 15 30 60 KM
Map Key
Permanent water
Veterinary fence
June 2014
Study Boundary
0 22 44 88 KM
Map Key
Permanent water
Veterinary fence
July 2014
Study Boundary
0 24 40 96 KM
Map Key
Permanent water
Veterinary fence
August 2014
Study Boundary
0 17.5 35 70 KM
Map Key
Permanent water
Veterinary fence
September 2014
Study Boundary
0 23 46 92 KM
Map Key
Permanent water
Veterinary fence
October 2014
Study Boundary
0 18 36 72 KM
-18°
-18°30'
-19°
22°
22°30'
23°
23°30'
N
Spatial Reference
Name: GCS WGS 1984
GCS: GCS WGS 1984
Datum: WGS 1984
Page units Degree


B
Map Key
Permanent water
Veterinary fence
March 2015
Study Boundary
Map Key
Permanent water
Veterinary fence
April 2015
Study Boundary
Map Key
Permanent water
Veterinary fence
May 2015
Study Boundary
Map Key
Permanent water
Veterinary fence
June 2015
Study Boundary
Map key
Permanent water
Veterinary fence
July 2015
Study Boundary
Map Key
Permanent water
Veterinary fence
August 2015
Study Boundary
Map Key
Permanent water
Veterinary fence
September 2015
Study Boundary
Map key
Permanent water
Veterinary fence
October 2015
Study Boundary
Northern Buffalo Fence
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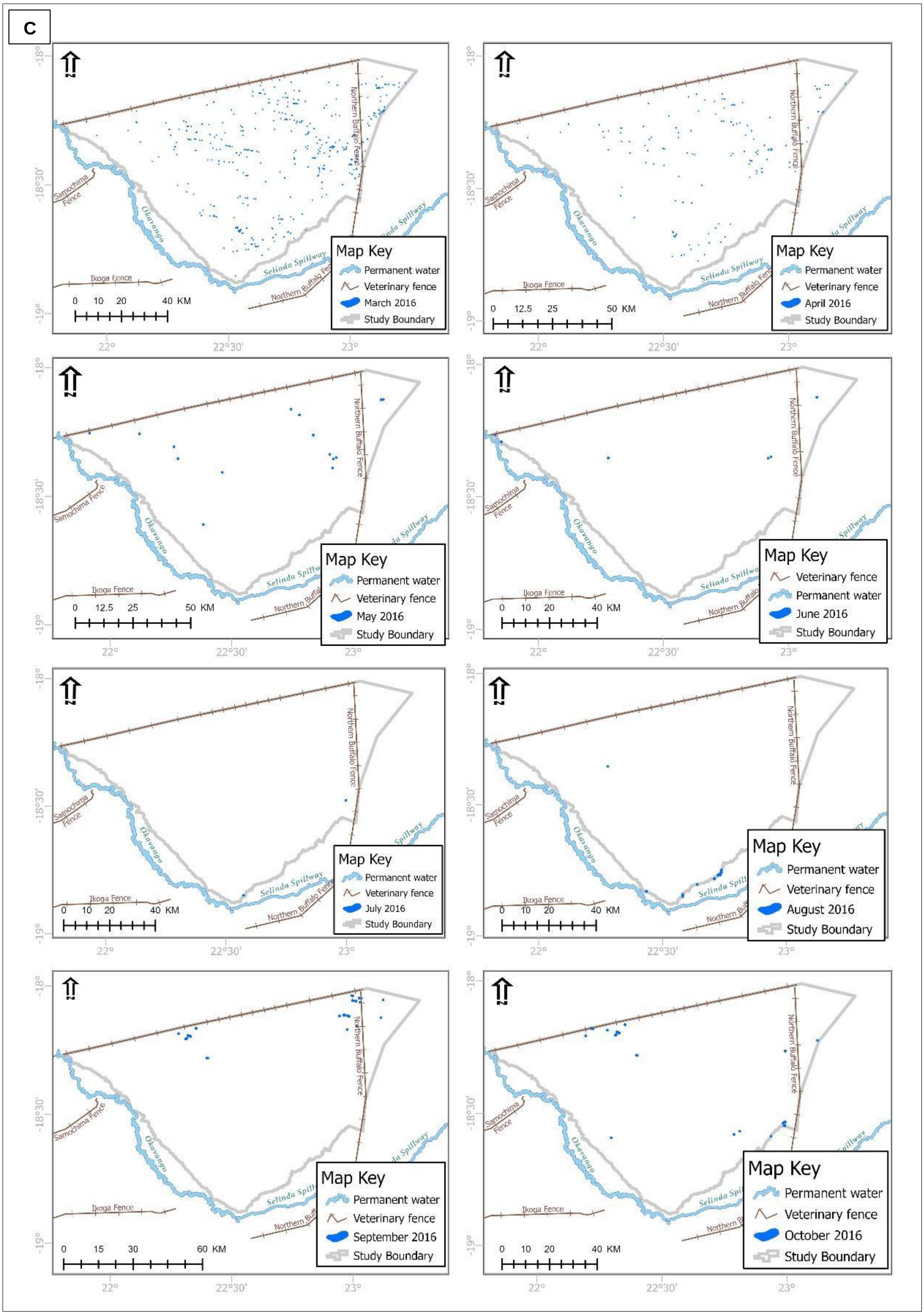
Okavango
Selinda Spillway
Ikoga Fence
-18°
-18°30'
-19°
22°
22°30'
23°


C
Map Key
Permanent water
Veterinary fence
March 2016
Study Boundary
Map Key
Permanent water
Veterinary fence
April 2016
Study Boundary
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Permanent water
Veterinary fence
May 2016
Study Boundary
Map Key
Veterinary fence
Permanent water
June 2016
Study Boundary
Map Key
Permanent water
Veterinary fence
July 2016
Study Boundary
Map Key
Permanent water
Veterinary fence
August 2016
Study Boundary
Map Key
Permanent water
Veterinary fence
September 2016
Study Boundary
Map Key
Permanent water
Veterinary fence
October 2016
Study Boundary
Northern Buffalo Fence
Samochima Fence
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Okavango
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-19°
22°
22°30'
23°

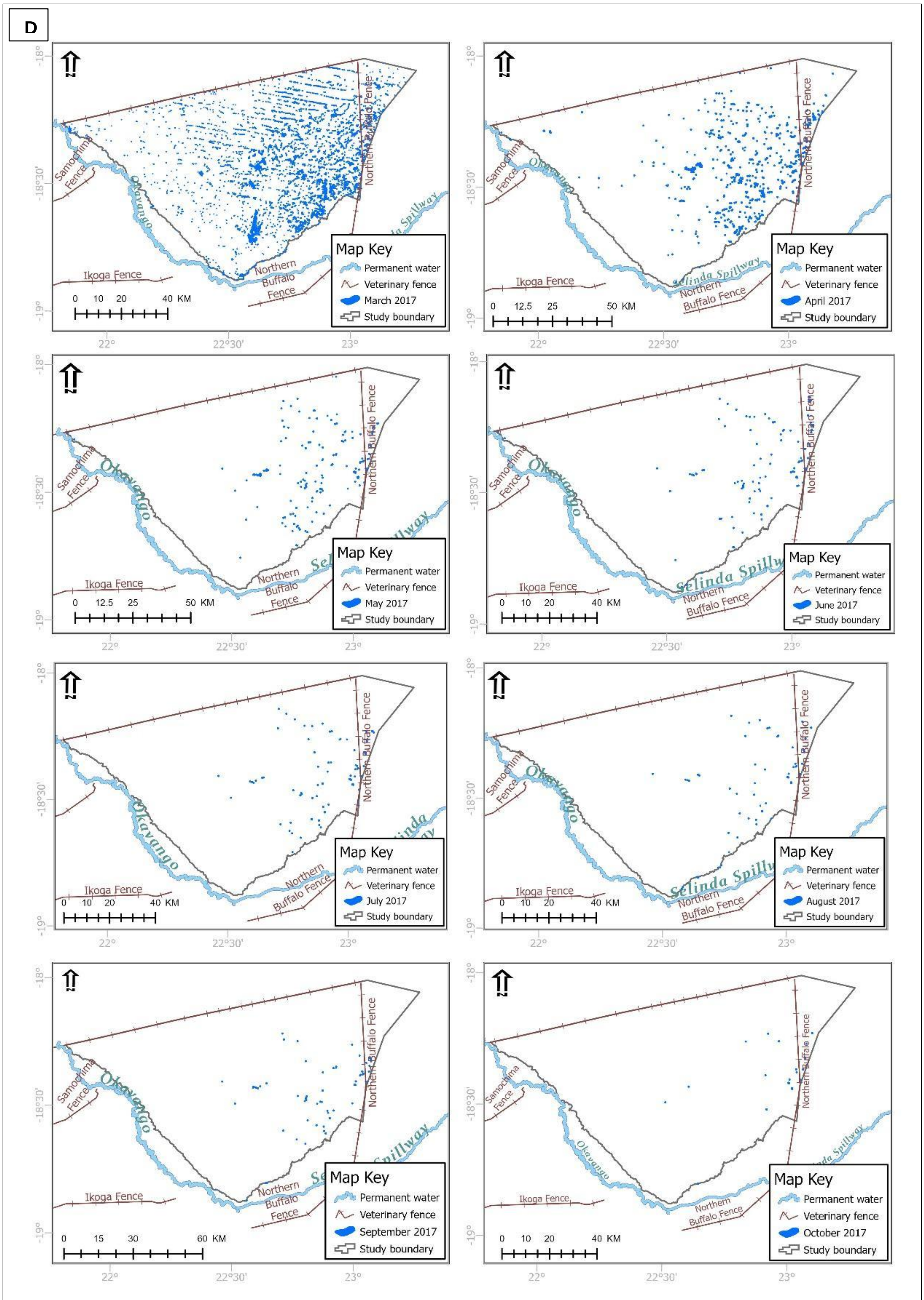
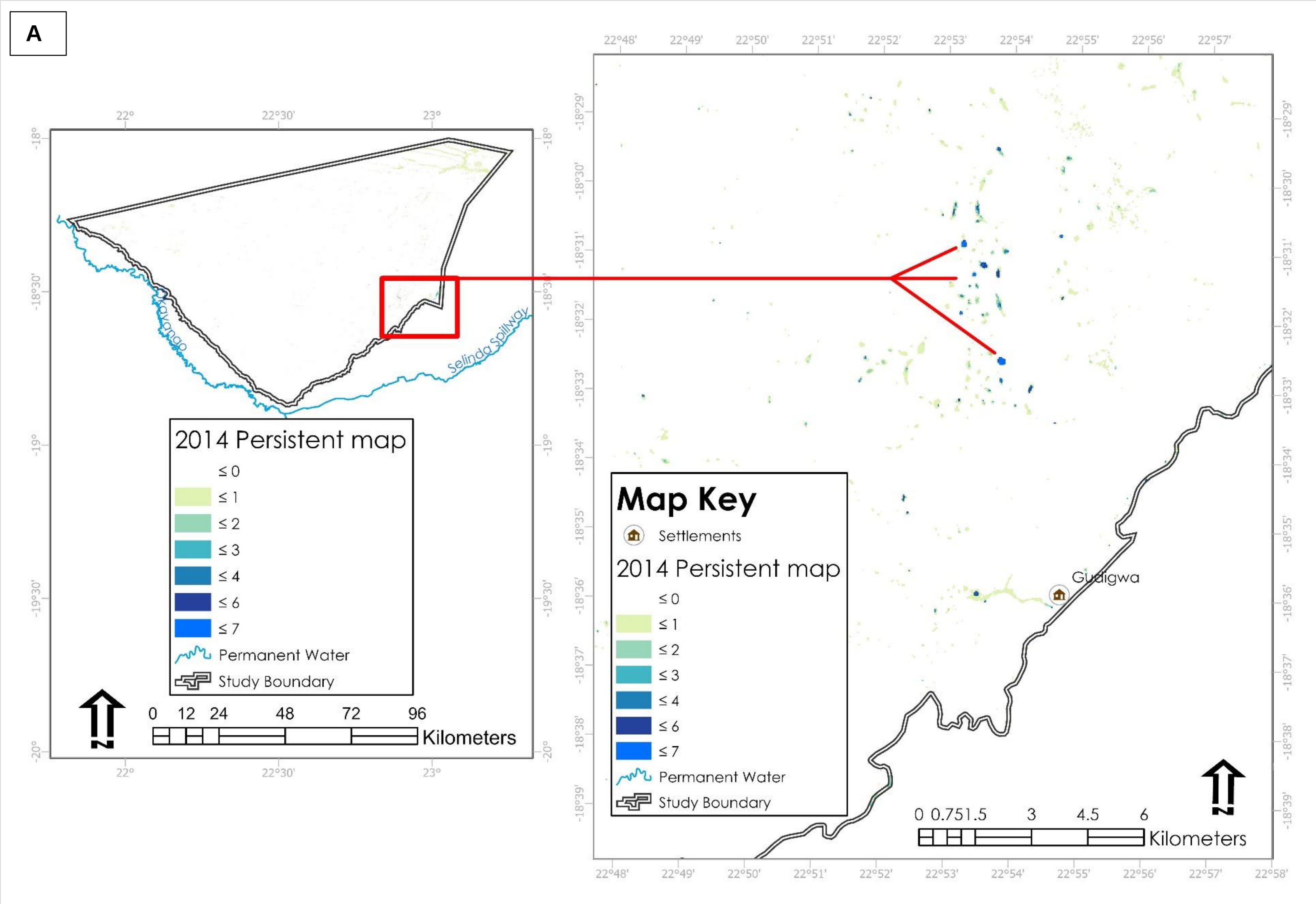
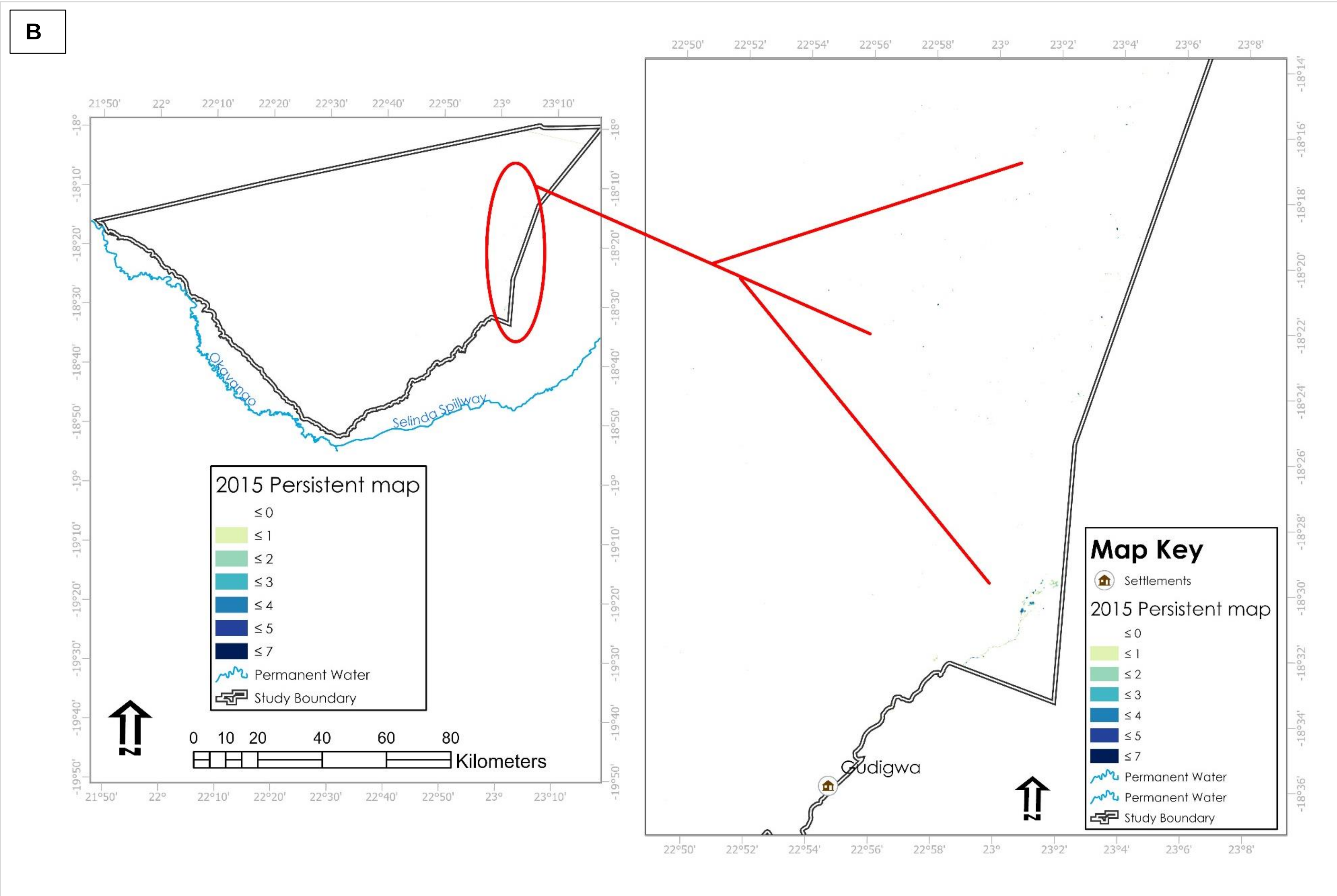


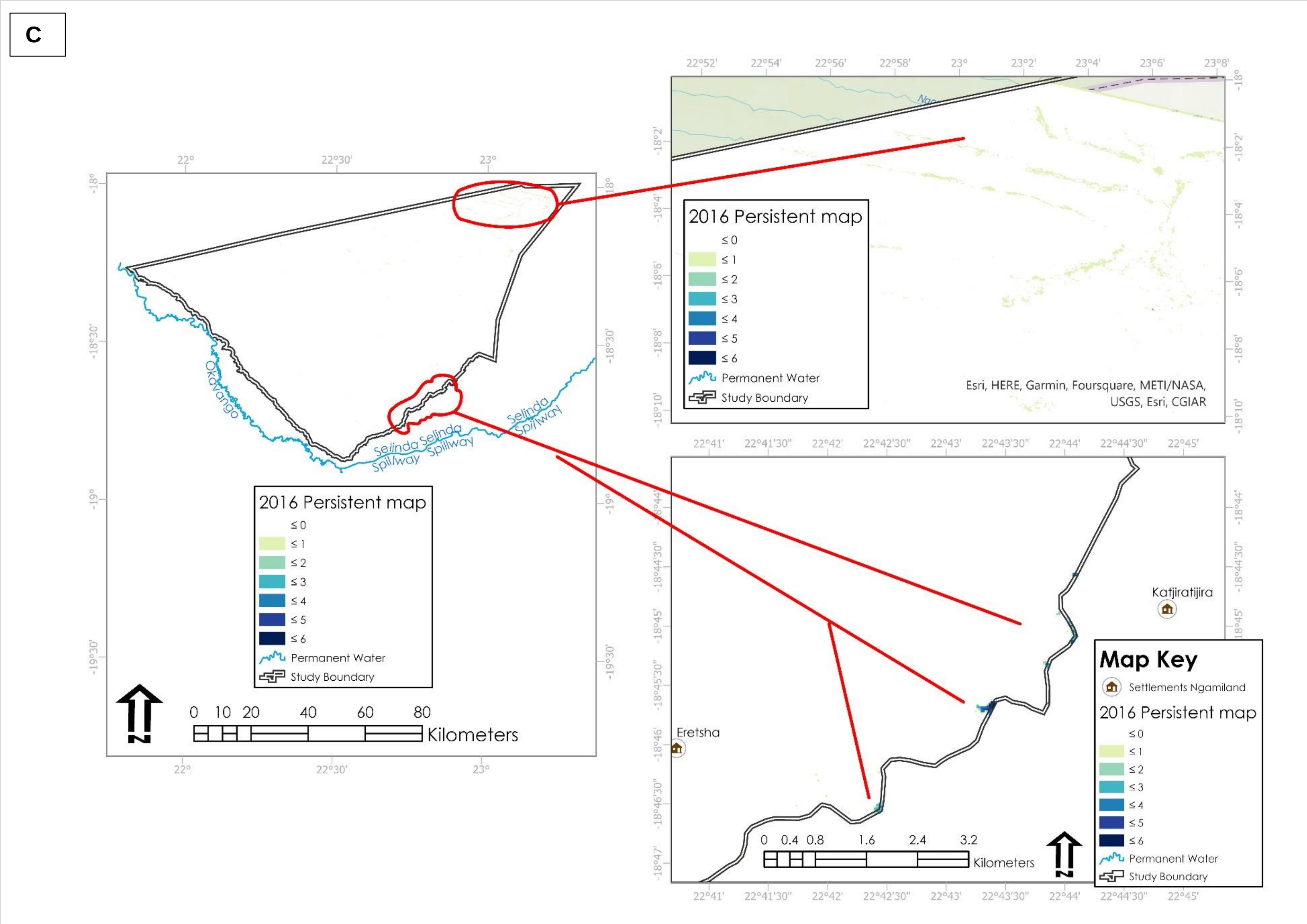
Figure 17a-d. 17A-D shows ephemeral surface water distribution for 2014-2017 in the eastern Okavango. The blue denote a specific month mapped. Surface water derived from using a spectral index – AWEI method to discriminate water features; grey boundary showing the study extent of NG11 and NG13 (in the dryland) of eastern Okavango, blue polygon displaying surface water, light blue line depicting the permanent Okavango River, as well as Selinda spill way.

2.4.2 Persistence ephemeral waterholes

The results from persistent maps showed that waterholes that hold water more than once in a month are found east of the study area where there are sand dunes and fossil rivers coming from Namibia. My study also found more persistent ephemeral waterholes near Gudigwa, southeast of the study area which hold more water every year see figure 18A-D showing yearly (2014-2017) and occurrent ones in figure 19 (A-B).


A
Okavango
Selinda Spillway
2014 Persistent map
≤ 0
≤ 1
≤ 2
≤ 3
≤ 4
≤ 6
≤ 7
Permanent Water
Study Boundary
0 12 24 48 72 96
Kilometers
Map Key
Settlements
2014 Persistent map
≤ 0
≤ 1
≤ 2
≤ 3
≤ 4
≤ 6
≤ 7
Permanent Water
Study Boundary
Gudigwa
0 0.751.5 3 4.5 6
Kilometers


B
Okavango
Selinda Spillway
2015 Persistent map
≤ 0
≤ 1
≤ 2
≤ 3
≤ 4
≤ 5
≤ 7
Permanent Water
Study Boundary
0 10 20 40 60 80
Kilometers
Gudigwa
Map Key
Settlements
2015 Persistent map
≤ 0
≤ 1
≤ 2
≤ 3
≤ 4
≤ 5
≤ 7
Permanent Water
Permanent Water
Study Boundary



C
2016 Persistent map
≤ 0
≤ 1
≤ 2
≤ 3
≤ 4
≤ 5
≤ 6
Permanent Water
Study Boundary
Okavango
Selinda Spillway
0 10 20 40 60 80
Kilometers
Esri, HERE, Garmin, Foursquare, METI/NASA, USGS, Esri, CGIAR
Katjiratijira
Eretsha
Map Key
Settlements Ngamiland
0 0.4 0.8 1.6 2.4 3.2
Kilometers

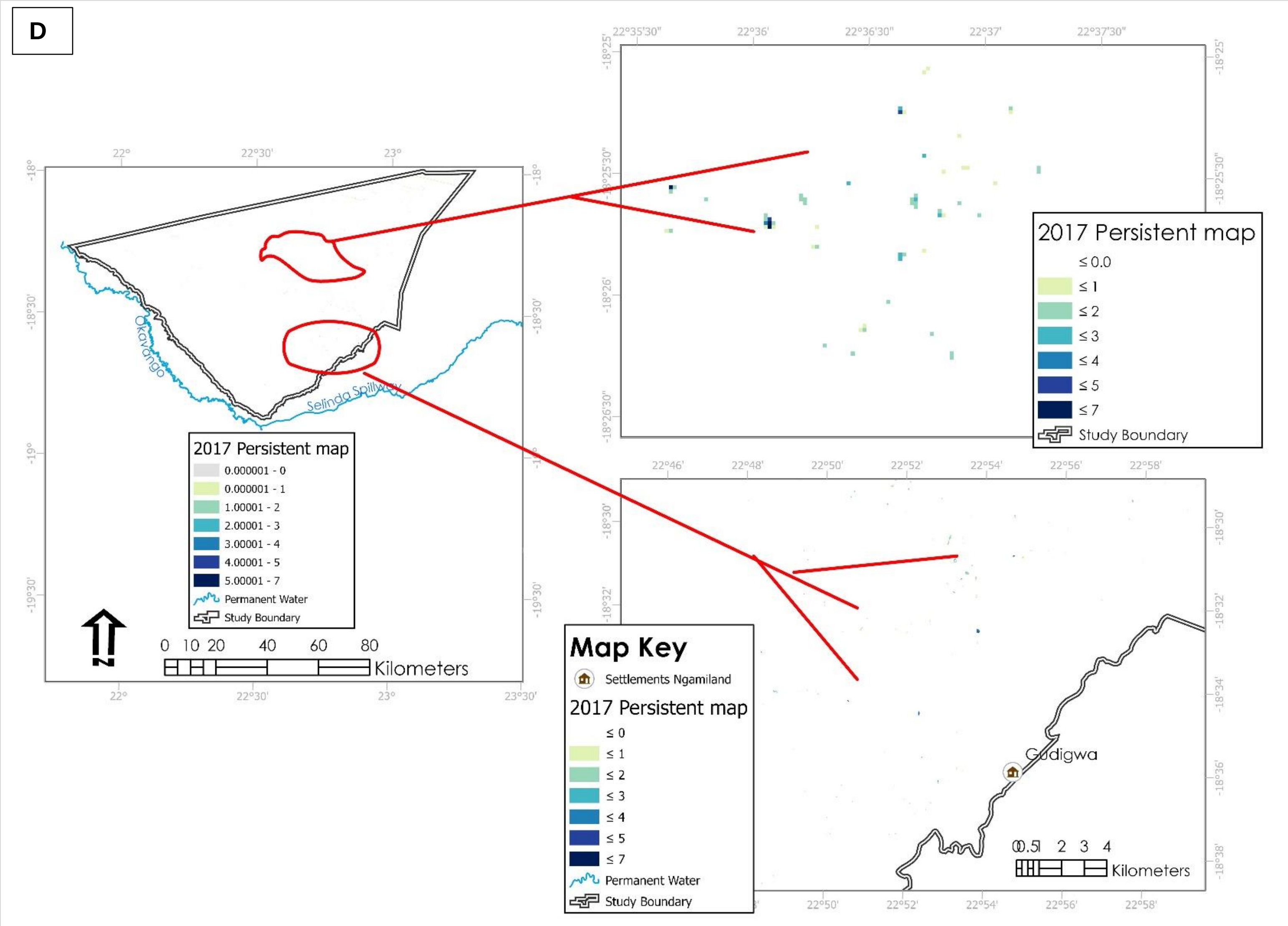
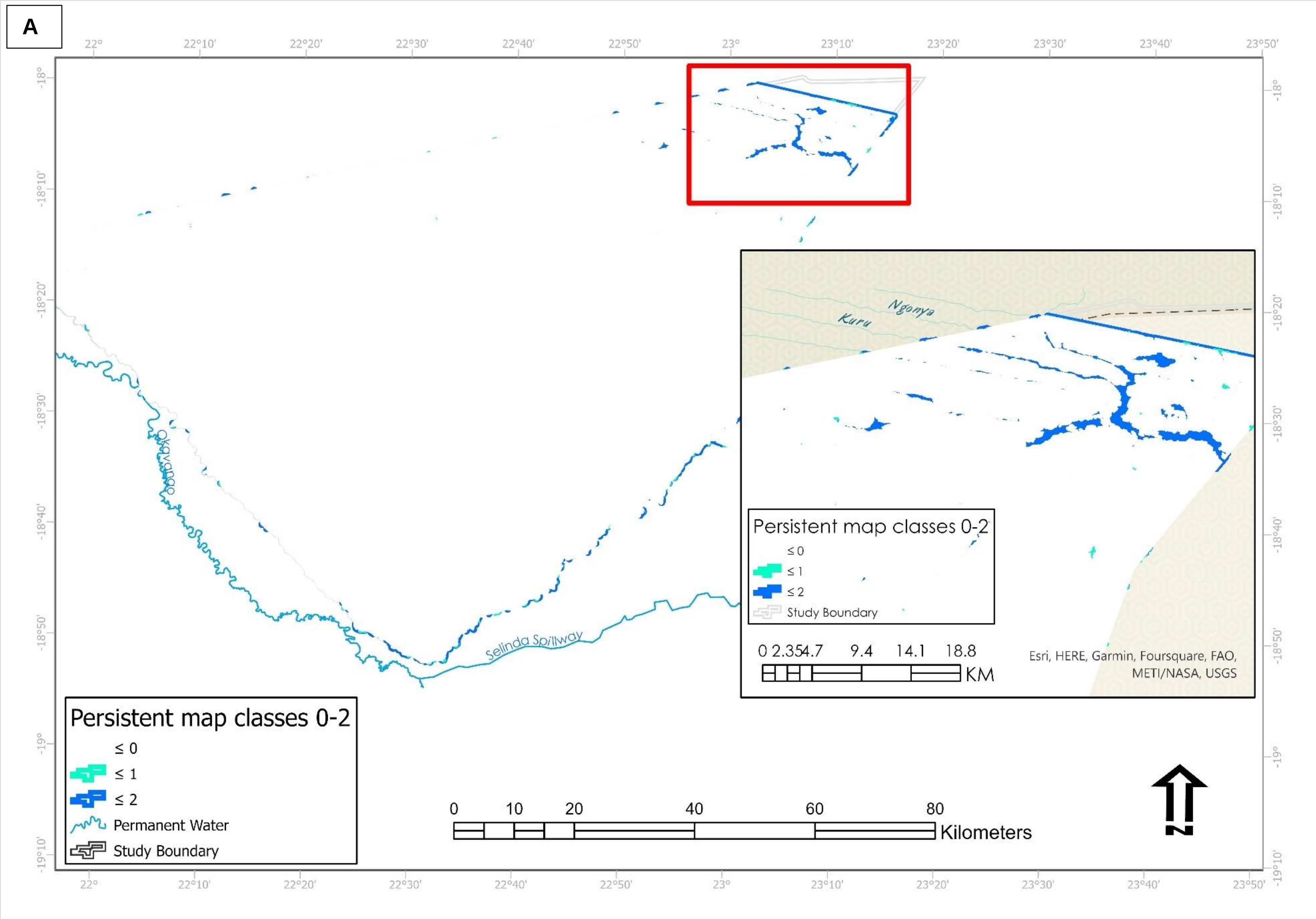


Figure 18a-d. Persistent maps for the period 2014-2017.A: 2014, B:2015, C:2016, D:2017


A
Okavango
Selinda Spillway
Kuru
Nganya
Persistent map classes 0-2
≤ 0
≤ 1
≤ 2
Permanent Water
Study Boundary
0 10 20 40 60 80
Kilometers
0 2.35 4.7 9.4 14.1 18.8
KM
Esri, HERE, Garmin, Foursquare, FAO, METI/NASA, USGS
N

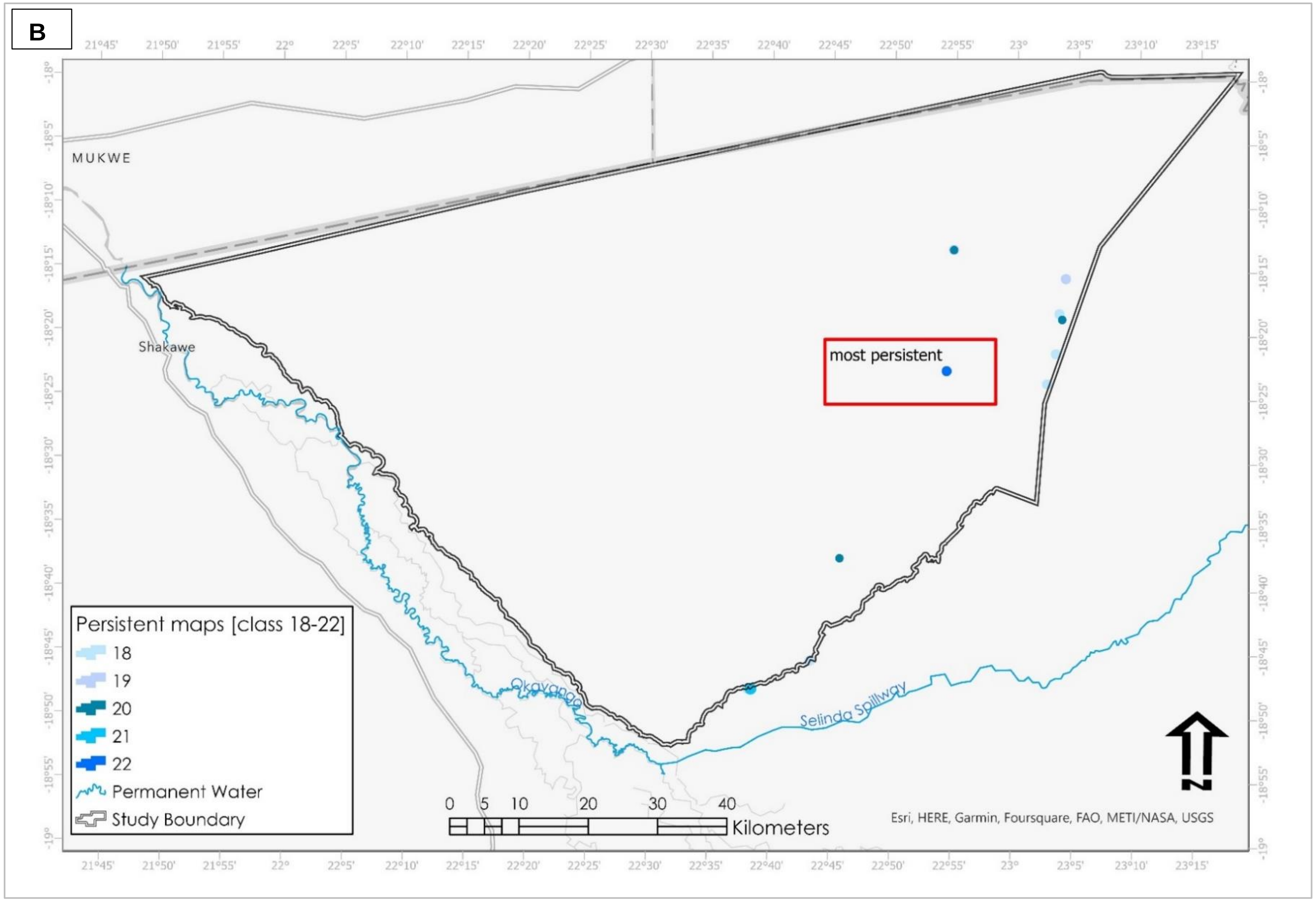


Figure 19a-b. Identified Persistent ephemeral waterholes in eastern Okavango Panhandle Botswana, A showing the northern side of the study area; B: ephemeral waterholes found in the southeast of the study

2.5 Discussion

Ephemeral surface water is a crucial resource for humans, animals, and cattle in dry and semi-arid areas (Chamaille-Jammes et al., 2007, Smit and Grant, 2009). The remote position and dispersed form of these water bodies hinder traditional techniques of monitoring, such as using gauges. Remote sensing provides a rapid and cost-effective means of detecting ephemeral surface water extent in these isolated places on a regular basis. Ephemeral surface water is a rain fed source of water and therefore in low rainfall years and in other areas it can be difficult to map such waterbodies. My study used the AWEI spectral index to delineate ephemeral surface water and showed that this is a useful technique to use in areas such as the eastern Okavango Panhandle because there are small waterholes found in that area. Persistent waterholes were easily identified after stacking. This approach has employed a simple and systematic strategy of strengthening class separability without the need for additional data (Feyisa et al., 2014). AWEI is not only a simple approach, but it has also been demonstrated to be resilient under a variety of environmental circumstances and for various sorts of water bodies.

Previous studies, such as (Zhai et al., 2015, Masocha et al., 2018) have also demonstrated the efficacy of the AWEI technique in mapping surface water, although in some cases a problem with some spectral indices were found due to specific sensors (Zhou et al., 2017). Alternative techniques have been tried in other studies to map surface water e.g., (Feyisa et al., 2014, Mustafa et al., 2017, Sarp and Ozcelik, 2017), for example using Landsat imagery in remote sensing to delineate surface water has shown positive results, however, there were significant sources of classification inaccuracy in certain terrain i.e. high mountainous places, where heavy shadow cast by the topography (Feyisa et al., 2014). Similarly, Pekel et al. (2016) found that the small waterholes are harder to spot when global datasets were used.

The AWEI reduces shadow and dark surface noises, which are frequently important sources of misclassification in surface water mapping (Worden and de Beurs, 2020), this approach employs a simple and systematic strategy of strengthening class separability without the need for additional data (Feyisa et al., 2014). AWEI is not only a simple approach, but it has also been demonstrated to be resilient under a variety of environmental circumstances and for various sorts of water bodies. I recommend this technique for future mapping of ephemeral surface water in the Okavango Delta as a whole because of the ability and robustness to capture small waterholes of the size of 30m. Compared to other spectral indices like NDVI, MNDWI and others the AWEI performed better showing stability especially when doing the thresholding. For future studies, I would recommend to mask out non water pixels after mapping and to do accuracy assessments, which unfortunately was not possible in this study due to lack of ground truth data. Additionally, I find the method effective because it was able to pick waterholes which were otherwise missed by global portals such as that used by Pekel et al. (2016).

Distribution of the water

At NG11 and NG13 ephemeral surface water is spread out the whole study area during the late wet season. Based on results, during the beginning of the early dry waterholes are mostly found in the middle or southwards of the study area near Seronga area. Different pattern is found during the late dry season, ephemeral water is mostly found in the southeast of the study in close proximity to Gudigwa. Waterholes that hold water more than once are also found in the same area. Waterholes differed in size, some were very small and others were quite bigger and prominent to see. It important to note that availability of these ephemeral waterholes influence HEC in the area. Around March-May when rainwater decreases elephant tend to move from the north of the study area NG13 down to the Okavango River and during this time as they move towards river they come across fields and trample on crops and in some instances kill people. HEC escalates during this period March-May when available wild forage and ephemeral water sources become limited, and elephants move and congregate around the Okavango River where farmers crop fields also occur. Potential areas to place artificial waterholes can be north of the study area so that elephants stay up there and in that way conflict will reduce in the area. There is a series of human settlements, linearly arranged along the banks of the Okavango River, and their rapid growth in the recent past,and expansion of agricultural fields have gradually closed up the known elephant movement corridors, hence restricting elephant pathways to and from the Okavango river, thereby worsening HEC.

2.6 Conclusion

The primary goal of this chapter was to use satellite images to map ephemeral surface water in the dryland of the eastern Okavango Panhandle. The Automatic Water Extraction Index (AWEI) method was utilized using Landsat 8 data. The findings of My study shows that existing global surface water portals are insufficient to map surface water, whereas $AWEI_{nsh}$, demonstrated good results in picking small turbid water and had very stable thresholds, demonstrating their suitability for monitoring changes in the area of surface water in the eastern Okavango Panhandle. AWEI index considerably and efficiently identifies surface water, particularly in locations where shadows and other dark surfaces (such as fire scars) are the primary sources of classification errors. I, therefore, recommend AWEI as a method to extract water information from places with noisy results due to the presence of shadows and built-up surfaces. This approach is also ideal for surface water change detection research because it identifies edge pixels with high accuracy and a stable threshold.

3 EXPLORING SEASONAL VARIATION IN ELEPHANT HOME RANGE SIZE, FACTORS AFFECTING HOME RANGE SIZE AND DAILY DISTANCE MOVEMENTS

SUMMARY

Herbivore habitat utilization varies seasonally in response to resource availability. Home ranges, migratory habits, and habitat choices are influenced by seasonal variations in resource distribution and availability. An area regularly travelled by an individual animal for activities such as eating, resting, reproduction, and shelter-seeking (Burt, 1943), and is big enough to supply adequate resources to meet its energy requirements is referred to as a home range (Damuth, 1981). For this chapter seasonal variation in home range size and daily movements were quantified for 15 elephants (n = 5 males and n= 10 females) in the eastern Okavango Panhandle, Botswana between 2014-2017. Home ranges were larger in the early and late wet than early and late dry season. Male elephants had larger home ranges than females. Seasonal variation in food and water resources were likely to be important drivers of elephant space use. The highest daily average distance moved was recorded in the early wet season, implying that elephants were not restricted because both forage and water were everywhere. A similar trend was found in the early dry and late dry season compared to the late wet seasons which recorded shortest distances travelled.

3.1 Introduction

The management and conservation of wildlife populations worldwide relies on informed decision-making (Sitati et al., 2003, Fernando et al., 2008). Important information on current threats, emergent threats, opportunities as well as underlying environmental conditions are needed (Ropert-Coudert et al., 2019). It is also critical to understand the behavioral ecology of animal species, which includes reproduction, foraging, and movement patterns and processes (Wittemyer et al., 2019). The movement ecology of a species focuses "*on the relationship between organism movement and environment (biotic and abiotic*)" (Nathan et al., 2008) and provide information on the underlying factors that impact resource selection (Signer et al., 2019). Investigating how features in the landscape such as vegetation biomass, water sources and anthropogenic activities drive the distribution of animals can also help to understand and predict movement patterns (Boettiger et al., 2011). Furthermore, information on movement provides a window into linking underlying environmental and physiological conditions with observed threats and implications for wildlife ecology, such as identifying physical barriers to movement (Naidoo et al., 2022a), areas of heightened human wildlife conflict (Songhurst et al., 2016, Buchholtz et al., 2019), or areas of high levels of poaching e.g., (Chase and Griffin, 2009b). Studies on movement ecology can also identify migration routes of animals, such as intercontinental birds (Technitis et al., 2015) ungulates in east Africa (Sinclair and Arcese, 1995), marine species (Quinn and Brodeur, 1991), blue wildebeest (*Connochaetes taurinus*) of the Central Kalahari (Williamson et al., 1988) and the longest transboundary migrations of zebra (*Equus quagga*) in Botswana/Namibia (Naidoo et al., 2016).

Large herbivores such as African elephants (Loxodonta africana) move across a mix of heterogeneous landscapes in search of available resources such as food and water (Chamaille-Jammes et al., 2007, Duffy et al., 2011). These resources in semi-arid environments are spatially heterogeneous and animal movement is usually guided by the animals' own instinct, spatial memory of resource distribution, predation risk, and intraspecific and interspecific competition (Valeix et al., 2007, Harris et al., 2008). Different approaches have been employed to determine the underlying environmental factors influencing animal movement patterns and gain an understanding of why, where, and how animals move in relation to resources vital for their survival and propagation. Previous studies have focused on a variety of species, including elephants (Loarie et al., 2009, Wittemyer et al., 2008, Polansky et al., 2015, Tsalyuk et al., 2019, Vogel et al., 2020, Chibeya et al., 2021); birds ; (Nichols et al., 2018, Siddharthan et al., 2019, Reading et al., 2019); lizards (Glaudas et al., 2019); ungulates (Levey et al., 2016, Owen-Smith and Traill, 2017, Fu et al., 2017, Grilo et al., 2018, Cushman et al., 2005, Pitlagano, 2007), and carnivores (Van der Weyde et al., 2017). The distribution of animals across landscapes is influenced by how resources are distributed in space and time (Matthiopoulos, 2003). Animals tend to use resources in the same places, which leads to the development of a home range, defined as "an area used by an animal in its daily activities of foraging, mating and caring for young" (Burt, 1943: 351). Factors that determine home range size include sex specific behavior, proximity to surface water, forage availability, seasonal parameters, and competition avoidance (Adams et al., 2021). Processes that affect animal space use/distribution differ depending on the scale of analysis (Fryxell et al., 2008, van Beest et al., 2011) so a multiple scale approach can potentially improve our understanding of how animals use their environment (van Beest et al., 2011).

African elephants are water dependent species and cannot exist in arid conditions without access to drinking water (Gaugris and Van Rooyen, 2010, Dunkin et al., 2013). The spatial distribution of waterholes influences the movement and distribution of wildlife such as elephants (Dzinotizei et al., 2018), and therefore an understanding of the trends and distribution patterns of water availability is important for the management of elephants

(Chamaillé-Jammes et al., 2007, Branco et al., 2019). Elephant home ranges can vary in size, ranging from 10 km^2 (Douglas-Hamilton, 1972, Douglas-Hamilton et al., 2005) to as large as 8700km^2 (Lindeque and Lindeque, 1991). Studies in east and west Africa have shown that there are patterns in the seasonal size of elephant home range, with wet season ranges often larger than dry season ones (De Villiers and Kok, 1997, Leggett, 2006). There also appears to be sexual variation in home range size, with male elephant home range sizes often found to be larger than those of females (De Villiers and Kok, 1997, Leggett, 2006), except for one study in a closed population in Addo Elephant National Park (AENP), South Africa (Whitehouse and Schoeman, 2003), who found that Female home ranges are larger, possibly because larger areas are required to meet the nutritional needs of their young. Elephant home range sizes are affected by an interaction of factors, including temperatures and rainfall (van Beest et al., 2011) human disturbances and landuse (for example farms, settlements, and fences (Ngene et al., 2017). They May also be influenced by anthropogenic factors such as human-elephant conflict e.g., (Pozo et al., 2018), barriers to movement e.g., (Naidoo et al., 2022a), war and poaching pressure (Schlossberg et al., 2018). . Other factors include fires (Morrison et al., 2016); forest cover (Songer et al., 2016); climate (Kupika et al., 2017, MacFadyen et al., 2019, Dejene et al., 2021).

The advent of new technologies such as improved Global Positioning System [GPS], satellite collars and advances in remote sensing have enabled the remote collection of animal location data (Kays et al., 2015, Fieberg et al., 2021), and driven development of new methods for modelling animal movement and linking individuals to their environments (Fieberg et al., 2021). Recent advances in nanotechnology have enabled researchers to track organisms as small as a millimetre (Qu et al., 2013). This technique began in the early 2000s because tracking devices were too heavy in marine settings, leading them to move abnormally. Large amounts of data can now be collected on movement in space and time for large terrestrial and marine mammals (Hebblewhite and Haydon, 2010, Tomkiewicz et al., 2010). Such studies have made use of these technologies to answer scientific questions on animal movements and relate them to environmental variables/covariates (Hooten et al., 2017). Similarly, cheaper and freely available software, open data (including imagery), and processes have greatly facilitated the consumption and use of data generated to provide opportunities for information generation at depths and rates previously unseen. Machine learning and deep learning techniques can uncover wildlife and improve conservation efforts (Ongsulee, 2017, Christin et al., 2019) because big data sets can be analysed.

Many variables influence animal space usage, including environmental circumstances (seasonality). Distinguishing patterns in large datasets based on how they interact helps to expose patterns that would otherwise be unknown. In a circumstance where one must deal with a large dataset, GPS collar data, in this case home range size, can be employed as a dependent variable as a function of the interaction relationship between seasons. Linear mixed-effects models are effective tools for analyzing complicated datasets containing repeated or clustered observations, which are prevalent in ecology and evolution (Schielzeth et al., 2020). Ecological studies have applied them to explore relationships about factors affecting home range size of buffalos (Loveridge et al., 2009); elephants (Mills et al., 2018, Hahn et al., 2022); zebras (Courbin et al., 2016), and impalas (Matson et al., 2007).

My study aims to explore the elephant home range size and daily movement patterns in the eastern Okavango Panhandle. This area is a hotspot for human elephant conflict and is a key part of the Kavango Zambezi Transfrontier Conservation Area (KAZA TFCA) Kwando Wildlife Dispersal Area (KWDA). GPS collar data from 15 elephants were used to conduct home range analysis and calculate average distance travelled from 2014 – 2017.

3.2 Hypotheses

- Elephant seasonal home range size will be bigger during the early and late wet seasons than during the early and late dry seasons because of more plentiful resources in the wet season.
- Male home ranges will be larger than females because the latter care for their dependent young who cannot cover large distances.
- Elephants will cover shorter daily distances during the early and late wet than early and late dry season due to resource availability

3.3 Methods

Elephant fixes were extracted using Microsoft Excel and R statistics version 4.0.1 (R Core Team, 2013b) from raw datasets. I identified four seasons according to rainfall and temperature patterns (Batisani and Yarnal, 2010): early wet (onset of rains and forage sufficient for daily survival; November to January), late wet (precipitation higher than dry seasons but lower than early wet; February – April), early dry (beginning of dry season and temperatures are moderate; May- July) and late dry (temperature are high and low water availability in seasonal waterholes; August – October; Fig.20). Mean annual rainfall, occurring seasonally between Dec-Mar, ranges from 360 to 500 mm, (Ramberg et al., 2006, Songhurst et al., 2015). Mean annual temperature ranges between 26.1 – 35 °C.

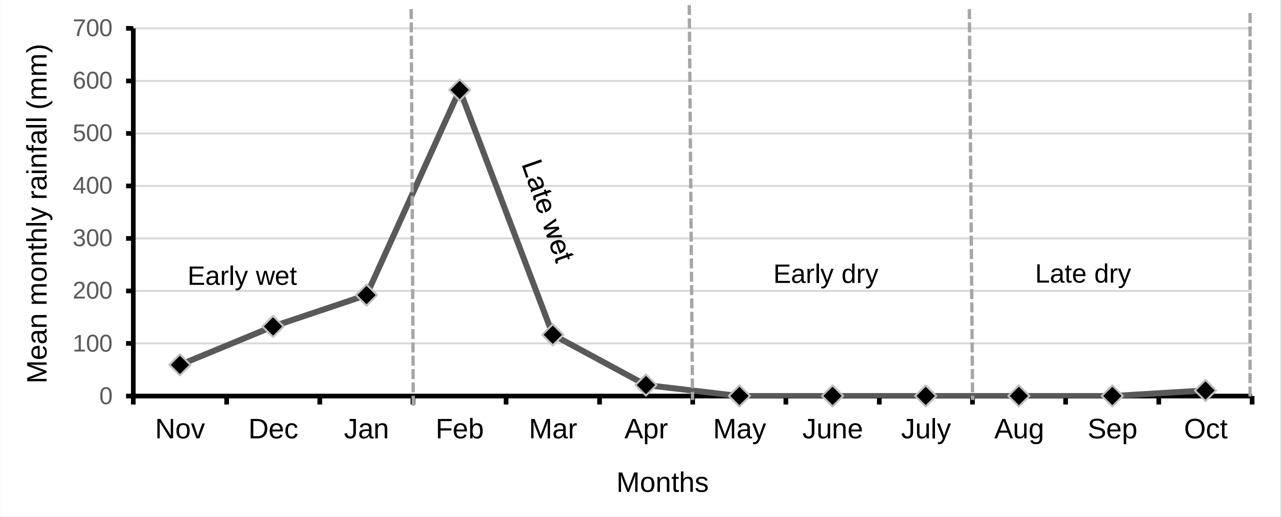


Figure 20. Mean monthly rainfall in the eastern Okavango Panhandle, Botswana (2014-2017). Rainfall data obtained from (Center for Hydrometereolohy and Remote Sensing, 2020)

3.3.1 Elephant collar data

I used GPS collar data from 15 elephants (5 males, 10 females) collared by Ecoexist Trust in Wildlife Management Areas (NG11, 12 and NG13) in the eastern Okavango Panhandle. . Elephants were collared from April 2014 – December 2017, during which time the collars recorded GPS fixes every hour, generating 10518 –30609 fixes per animal. Animals were darted by an experienced wildlife veterinarian with permission from the Government of Botswana under research permit EWT 8/36/4 XVII (79) and immobilization permit 2014 WP/RES 15/2/2 XXIII 169 (Songhurst, 2014). The data were cleaned by deleting rows without XY coordinates and data that were transmitted prior to deployment (Songhurst, 2014). The 'getDuplicatedTimestamps' function was used in the 'move' package to delete duplicates using R version 4.0.3. (Kranstauber et al., 2020) .This process left a total dataset of 333,319 fixes across 15 animals (Table 4 and fig. 20).

Table 4. Information relating to GPS fixes obtained from 15 African elephants in the eastern Panhandle of the Okavango Delta, Botswana, between April 2014 – December 2017.

NAME	ID	Deployment / Tracking period	SEX	AGE	No. fixes
Mbamba	14653	25 Apr. 2014 – April 2017	FEMALE	20+	30260
Mpule	14650	24 Apr. 2014 – April 2017		25	27791
Nare	14649	22 Apr. 2014 – April 2017		25	18361
Pille	14648	22 Apr. 2014 – April 2017		20+	30609
Rain	14654	24 Apr. 2014 – April 2017		20	17395
Amantle	14664	23 Apr. 2014 – April 2017		20	10518
Koo	14660	23 Apr. 2014 – April 2017		20	29492
Ann	14656	23 Apr. 2014 – April 2017		20	14861
Ebby	14659	24 Apr. 2014 – April 2017		16-20	29977
Whisper	14661	25 Apr. 2014 – April 2017		25	11866
Chan	14652	25 Apr. 2014 – April 2017	MALE	36+	20734
G	14657	23 Apr. 2014 – April 2017		40	19266
Howard	14646	23 Apr. 2014 – April 2017		40+	21543
The Bachelor	14658	24 Apr. 2014 – April 2017		30	20502
Whiskey	14662	25 Apr. 2014 – April 2017		30	30144

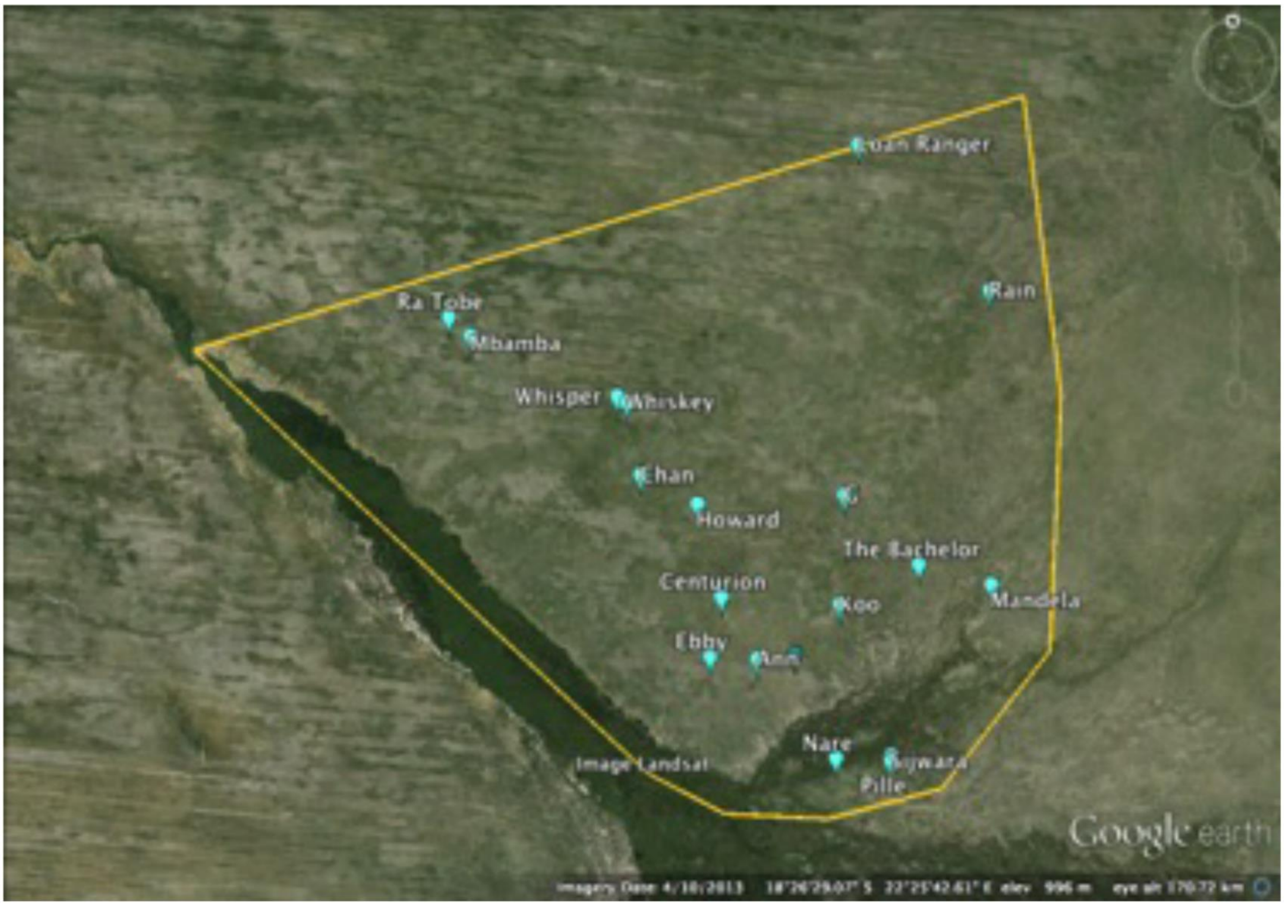


Figure 21. Collaring locations of elephants collared in the eastern Okavango Panhandle, Botswana used for analysis (males: n=5 and females: n=10

Data source: (Ecoexist, 2015b)

3.4 Data analysis

3.4.1 Home range size

The 95 % kernel utilisation distribution (UD) for each elephant was derived with the kernel density estimation (KDE) method (Van Winkle, 1975, Fieberg and Kochanny, 2005), from the ‘adehabitat’ package in R version 4.0.3 (Calenge, 2006) to allow a comparison of home range sizes between seasons (Benhamou, 2011). The reference smoothing parameter (h_ref) (Worton, 1987, Viana et al., 2018) was used to calculate home ranges and 95% contours (Börger et al., 2006). The smoothing parameter h_ref was chosen over Least Square Cross Validation (LSCV) which is widely used because the latter did not converge with my dataset. Kernel home range estimators were also selected over Minimum Convex Polygon (MCP) estimators since the MCP do not reveal the real outline of the home range but consider areas that are infrequently visited identically to those that are often visited. Kernels give estimations that are comparable to LoCoH (Getz et al., 2007). However, LoCoH were not used for My study because the data couldn’t converge. Kernels differentiate intensively used locations more precisely (Worton, 1987). From these HRs, seasonal HR size were extracted for every collared individual elephant.

3.4.1.1 Factors affecting HR size

GPS collar data were segmented into four seasons as previously defined on figure 15. I only used data from collars that had recorded GPS fixes for a full 3-months season to generate home ranges sizes (HRs). After removing obvious relocation errors, I had a total of 316,353 fixes for all animals in four seasons for the HR analysis (Figure 24a-c). In the HR analysis, fixes included in 2014 included early and late dry season (August – October) and the subsequent years fixes used were from early wet (November – Jan) and late dry season (August – October) as well because deployment started in the end of late wet (February-April) towards the end of April.

The data failed the assumptions of normality after a Shapiro-Wilk test and I log-transformed them, after which data followed a normal distribution (W= 0.99191; p value = 0.2977). The effects of season on home range size were analysed using a linear mixed-effects model (LMM) in R (lmer package; (Bates et al., 2015) with the log of HR size as the dependent variable, fixed effects predictors variables were the interaction between season and sex, and individual animal and year as the random effect. The dredge function in the ‘MuMIn’ package were used to run models with all possible combinations of the predictors and identified the most parsimonious models based on AIC values (Akaike, 1974). When more than one model was competitive (ΔAIC<2), models were averaged using the ‘model.avg’ function from the ‘MuMIn’ package version 4.0.3 (Zeugner and Feldkircher, 2015, Barton, 2010).

3.4.2 Daily movement distances

Distance travelled or moved is one of the most often calculated variables from animal tracking data because it provides activity patterns (Noonan et al., 2019). . For this analysis four seasons were used similar to the home range size analysis. Using the 'geodesic distance' as a function in Python, location data from elephant collars were used to compute daily distance moved for each individual elephant (Karney, 2013). The effects of season on daily distance movements were investigated using linear mixed models (LMMs) in R (lme4 package after (Bates et al., 2015) using a log link function for the data (Bates et al., 2015). Daily distance was used as the dependent variable, fixed effects predictors variables were the interaction between season and sex and the individual animal and year as random effect variable. The dredge function in the ‘MuMIn’ package was used to run the model with all possible combinations of the predictors and identified the most parsimonious global models based on AICc values (Akaike, 1974, Barton, 2009)

3.5 Results

3.5.1 Home range size

The mean seasonal home range size from the 15 (10 female and 5 male) collared elephants recorded over 4 years was 1246.80 km^2 (sd 1050.901), ranging between 95.04 and 6998.96 km^2 (Table 5).

Figure 24a-c shows that the collared female elephants predominantly used areas southeast of the study area (NG11and 12) during the year 2014; the year however had 2 seasons (Fig. 22a-c). During 2015, 2016 and 2017 the movement was more widespread in the area for both male and females. The results also indicate that in the early-late wet season they occupied NG13 (Fig. 22a-c).

Table 5. Descriptive statistics for male and female elephants home range size in the eastern Okavango Panhandle, Botswana between 2014-2017.

sex	***season***	***mean***	***standard deviation***	***minimum***	***maximum***
male	early wet	2026.2	1197.216	473.4	3875.4
	late wet	2010.1	944.4828	607.7	4121.4
	early dry	632.84	452.9682	95.04	1922.52
	late dry	865.8	720.6907	224.8	2590.2
female	early wet	2551.8	1377.347	962.8	6999
	late wet	1242.2	675.0773	292.7	3029.1
	early dry	709.7	470.0866	164	2045.7
	late dry	727.6	390.2525	118.8	1794.8

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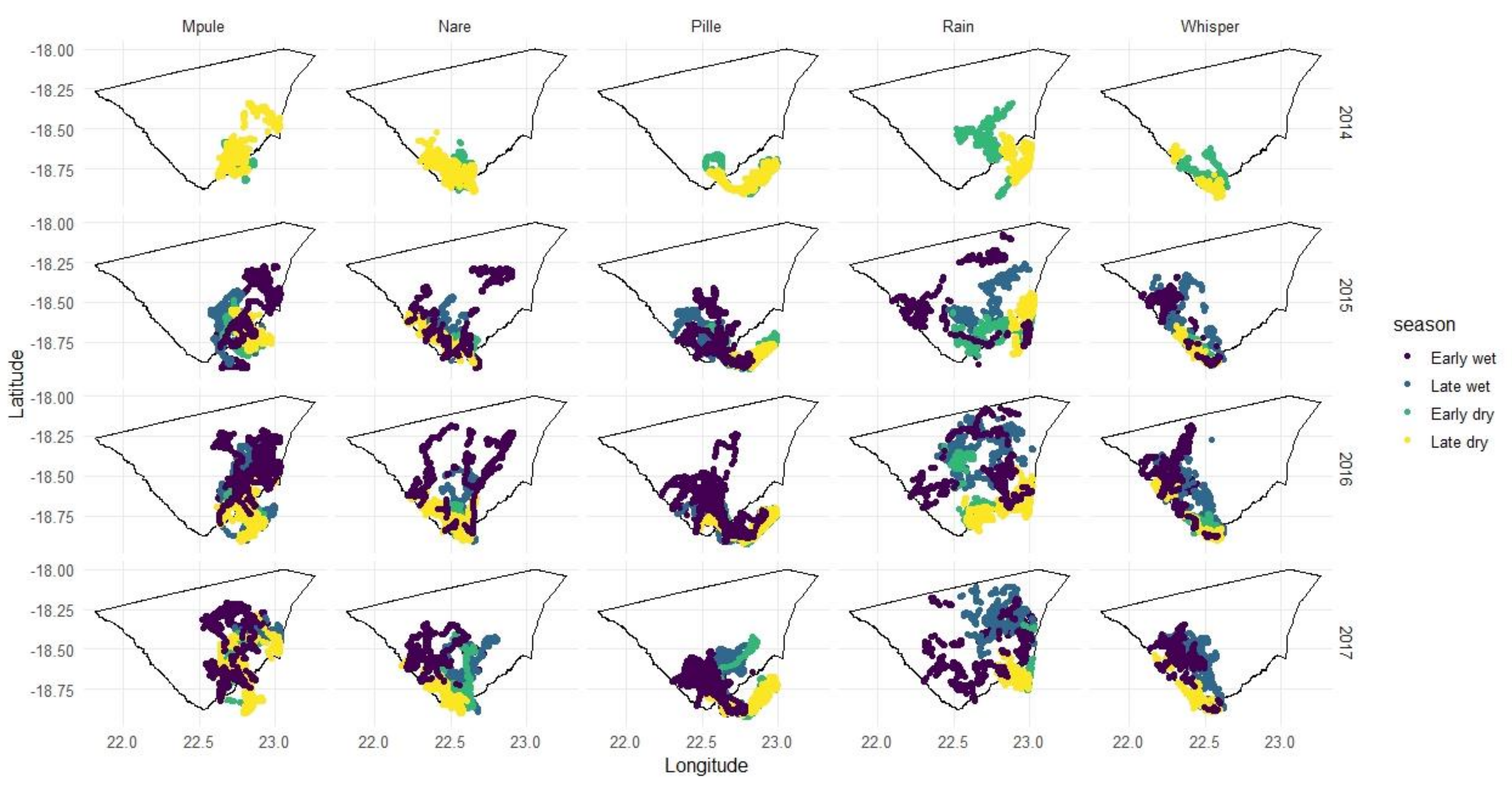

Mpule
Nare
Pille
Rain
Whisper
-18.00
-18.25
-18.50
-18.75
2014
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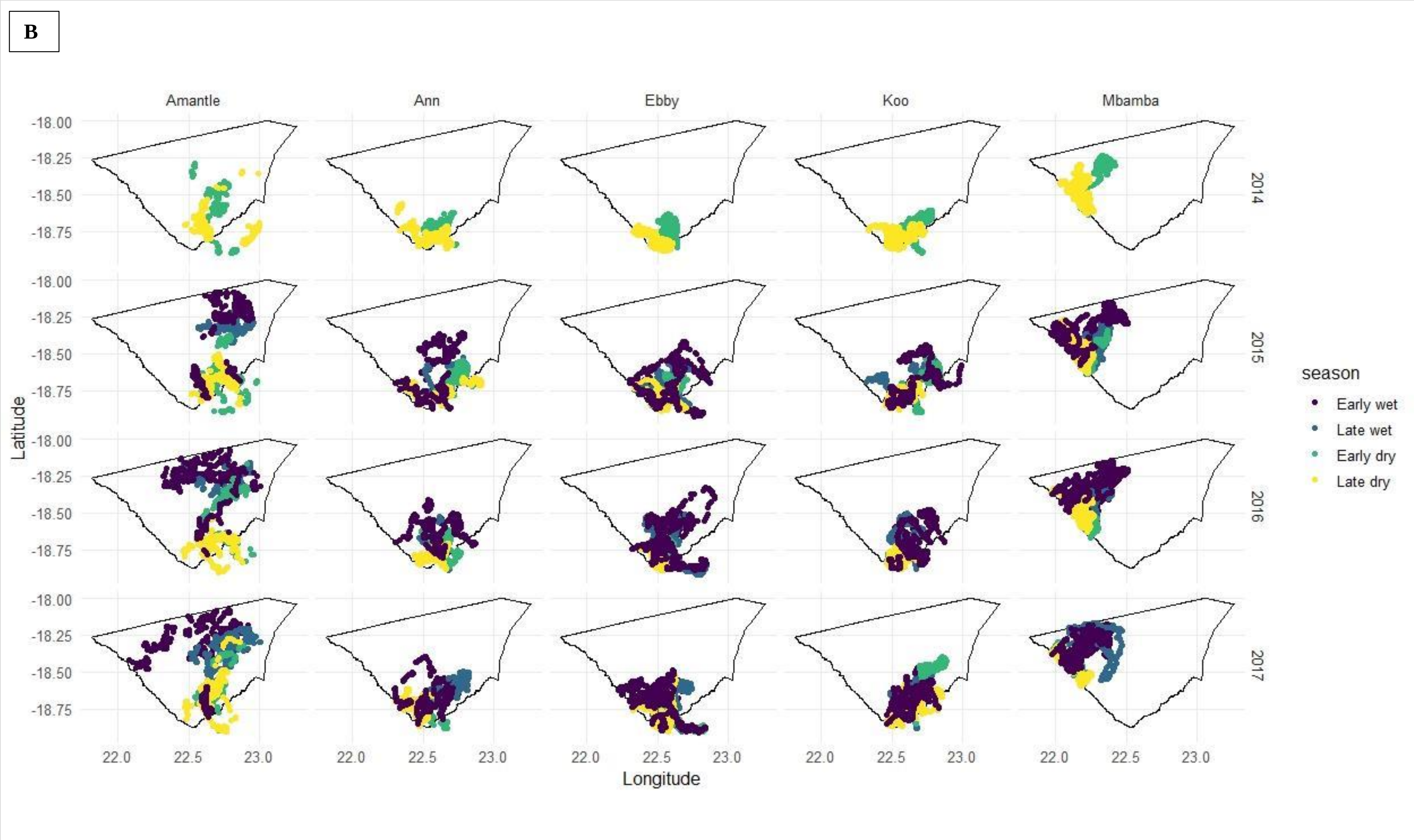
Early wet
Late wet
Early dry
Late dry


B
Amantle
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Ebby
Koo
Mbamba
2014
2015
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2017
-18.00
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Longitude
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Early wet
Late wet
Early dry
Late dry

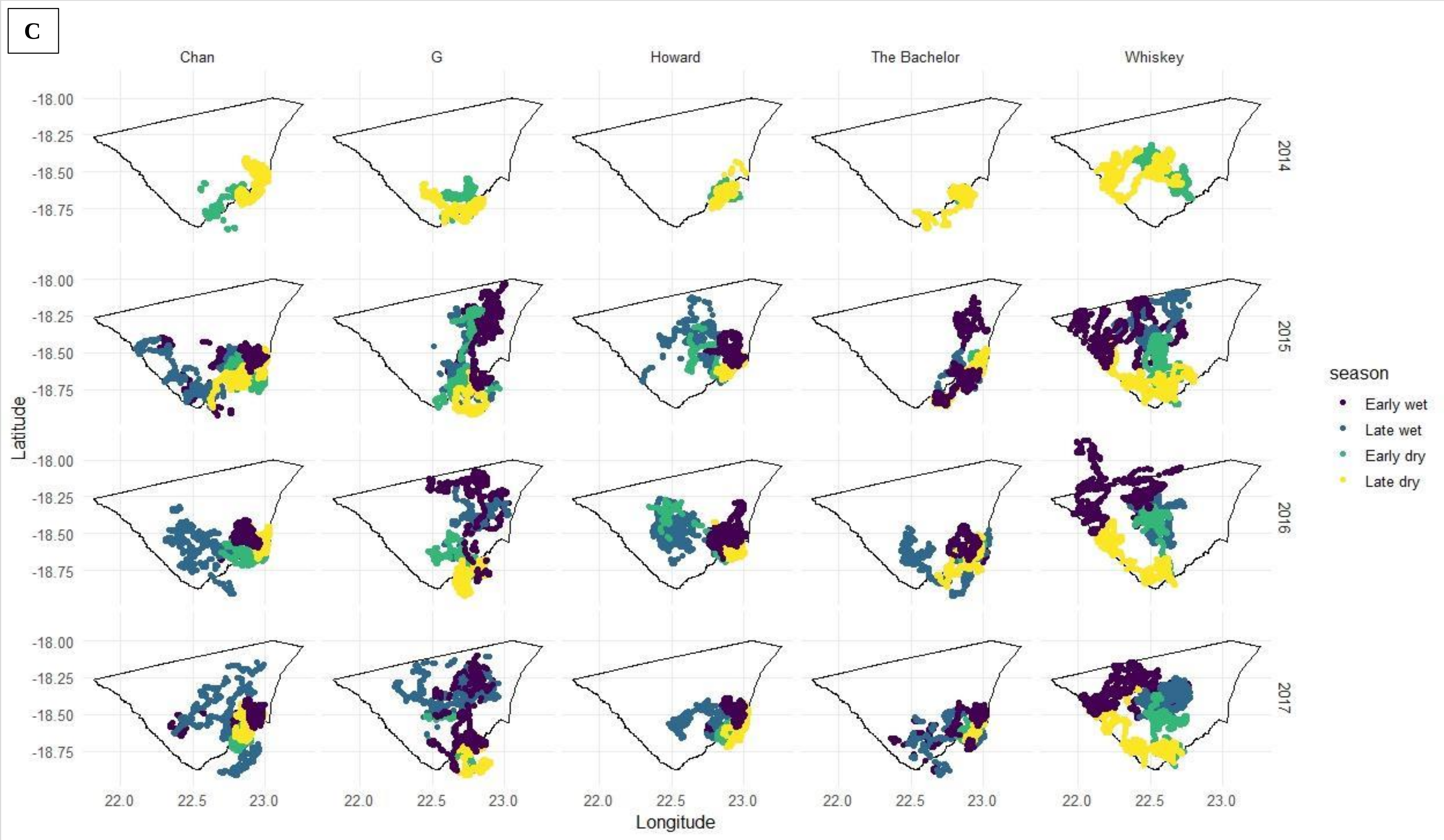


Figure 22a-c. Seasonal movements of female (A&B) and male elephants (C) between 2014-2017 in the eastern Okavango Panhandle, Botswana. Dark-blue dot represent early wet, light blue dot showing late wet, the green dot depicting early dry and yellow dot representing late dry season. The map was derived from using R statistics version 4.2.1

3.5.1.1 *Factors affecting HR size*

The most parsimonious model included the interaction between season and sex (AICc=384.9, AIC_w=0.573); but the model with only the fixed effect of season was also competitive (AICc=385.8, AIC_w=0.359) signifying that the effect of season was also important, (Figure 23 and table 6 & 7). Variation in HR size was observed between early wet, late wet, and dry seasons, however the HR sizes were more consistent in the dry season (early and late). Early wet season HRs were larger than late wet season HRs and early dry season home range size were larger than late dry season home range size.

Table 6. Candidate models of the effects of season, sex and their interaction on home range size in African elephants in the eastern Panhandle, northern Botswana, between 2014-2017

Model	(Int)	Season	Sex	Season: Sex	df	LogLik	AICc	delta	Weight
12	7.727	+	+	+	10	-181.89	384.89	0.00	0.573
2	7.612	+			6	-186.706	385.8	0.93	0.359

Table 7. Model averaged parameter values explaining seasonal variation in HR size for elephants in the eastern Okavango Delta, Botswana.

	PARAMETER	ESTIMATE	STANDARD ERROR	CONFIDENCE INTERVAL
SEASON	**late wet**	**-0.6389**	**0.1885**	**-1.00940387; -0.2684446**
	early dry	**-1.3373**	**0.1218**	**-1.57739619; -1.0970965**
	late dry	**-1.2327**	**0.1332**	**-1.49500344; -0.9703475**
SEX	male	-0.2114	0.2630	-0.85406726; 0.1660383
	late wet: sex [male]	0.5264	0.4555	0.39520306; 1.3181172
	early dry: sex [male]	0.0966	0.1879	-0.27446333; 0.5888438
	late dry: sex [male]	0.2257	0.2478	-0.06432794; 0.7989792

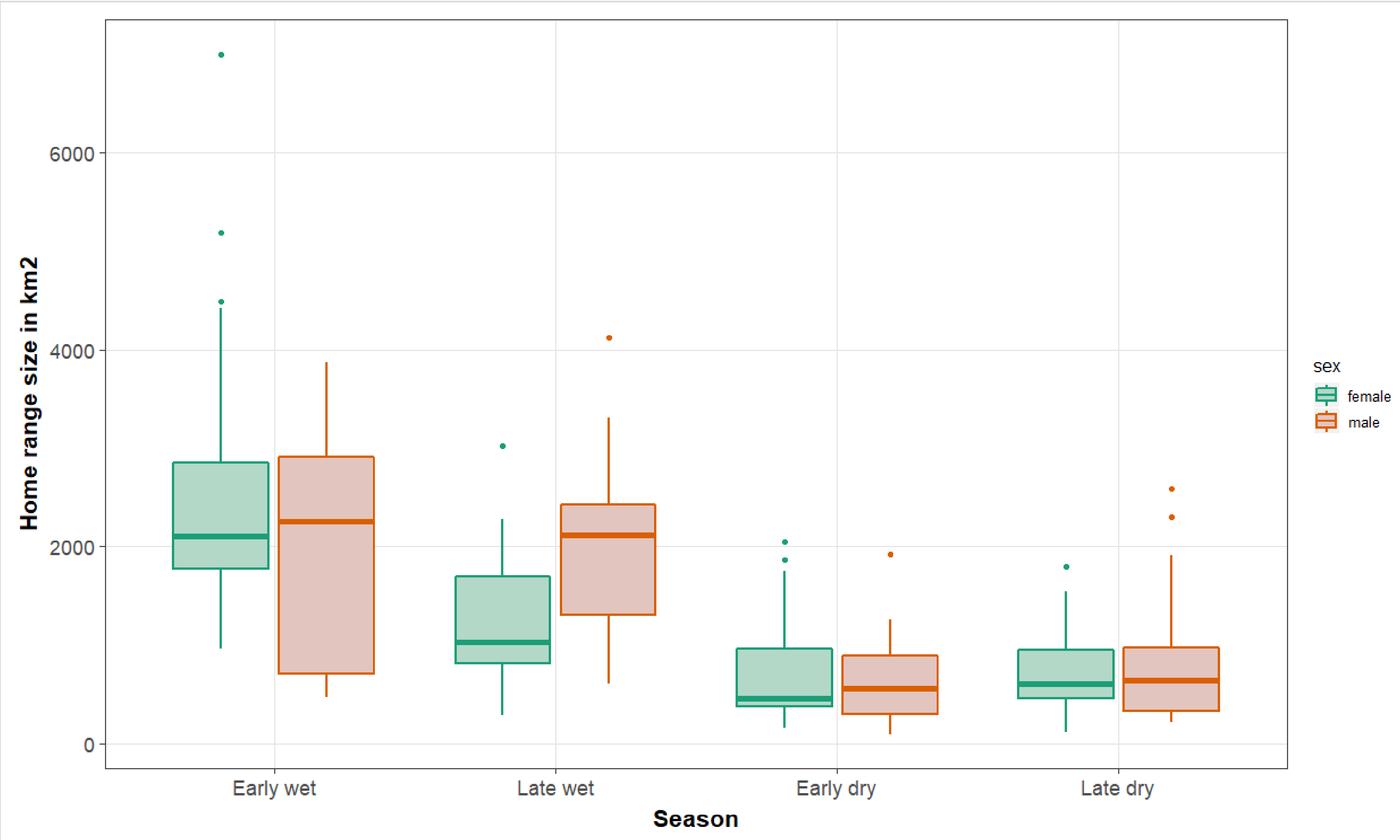


Figure 23. Seasonal home range sizes for male and female elephants in the eastern Okavango Panhandle, Botswana between 2014-2017. Home ranges derived from Kernel density estimation using R Statistics version 4.2.1

Home ranges were larger in the early and late wet seasons than in the early and late dry seasons (Fig. 23); HR sizes were also more variable in both wet seasons, particularly in the early wet season. Male and female elephants had HRs of similar sizes for most of the year, but males occupied larger HRs than females in the late wet season.

3.5.2 Daily movement distances

The most parsimonious model of factors influencing daily distance included an interaction between season and sex (AICc= 488238.4, AIC_w =1), no other model was competitive. There were significant variations in the distance covered by the elephants between seasons (early wet (t = -0.04529), late wet (t = -0.07785 and late dry (t = 0.01475).-The early wet, early dry, and late dry seasons elephants covered larger distances than in the late wet season. The mean daily distance traveled between 2014-2017 was 6.3 km, this varied seasonally with the largest in early wet and late dry seasons (6.8km), and the early dry (6.4km) and the smallest in the late wet season about (5.1km), see figure 24.

Male elephants covered largest distances in the early wet, early dry and late dry seasons whilst female elephants covered largest distances in the late wet season (see figure 24).

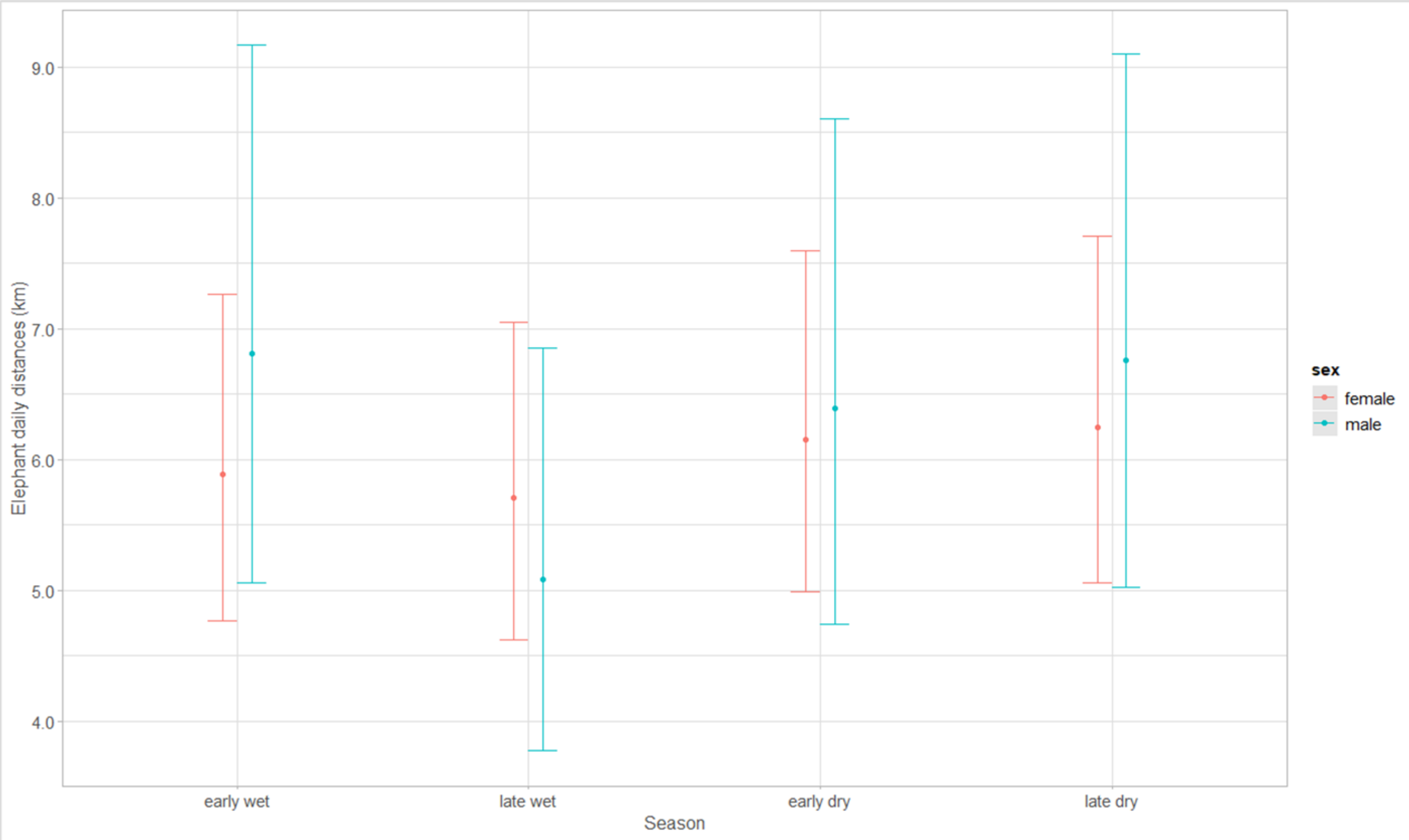


Figure 24. Elephant seasonal daily distance movement in the eastern Okavango Panhandle, Botswana from 2014-2017. Error bars represent ± 1 standard error. Distances derived using 'geodesic distance' package in Python

In the early wet, early dry, and late dry seasons both female and male elephants had larger daily distances than in the late wet season (fig. 24). The male elephants covered the daily distance of 6.8km in the early wet, 6.4km in the early dry and 6.8km in the late dry season whereas in the late wet season the distance was about 5.1km. The daily distance travelled by females was consistently lower than the daily distance travelled by males except for the late wet season where females covered a longer distance.

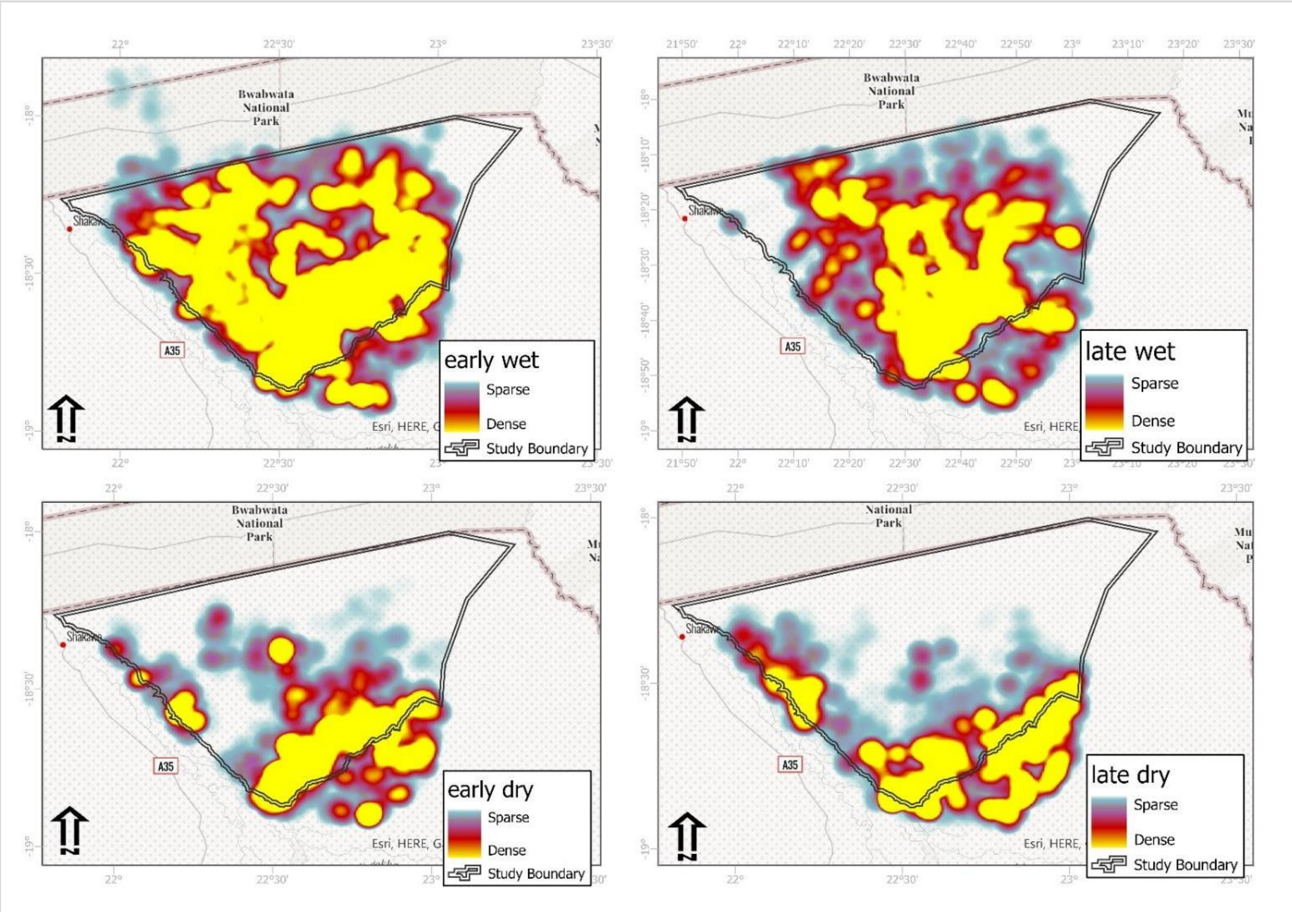


Figure 25. Seasonal movements shown using heat map in eastern Okavango between 2014-2017. A = early wet; B = late wet; C = early dry and D = late dry, Heat maps derived using ArcGIS Pro 3.0.

Elephant movements were mostly restricted to riverine and delta resource areas (e.g., water) during the dry season (near the permanent waters). These areas are also closer to settlements and farms, due to the ribbon-like development along the Okavango River and Delta. Elephants dispersed further into the dryland areas during the wet season when resources such as forage and surface water were available across the landscape, figure 25.

3.6 Discussion

My study investigated the effects of season on home range size during the early and late wet (when there is abundant food resources) and the early and late dry season when surface water and forage are limited across the landscape. I had predicted that elephant home range size would be larger in the wet than in the dry season because in the wet season resources are plentiful, and elephants are not restricted to a few areas with localized resources. My results show that seasonal home ranges for elephants ranged between 1,500 – 2,500 km^2, with larger ranges significantly observed in the wet season (see appendix 1). These results support the hypothesis that elephant home range size would be larger in the wet than in the dry season. The early and late wet seasons had bigger home range sizes when compared with early and late dry seasons. The elephants were observed to be widely distributed in the wet season than in the dry season suggesting that when resources are plentiful and widespread elephants will maximize their utilization of the available landscape than restricting themselves to certain locations.

Surface water and forage availability are key determinants of elephant movement and home-range size (De Beer and Van Aarde, 2008, Loarie et al., 2009, Cushman et al., 2010), and in the dry season when these resources are in short supply elephants will not travel far from resource-rich areas. Elephants are water dependent, and they drink regularly to maintain their body water requirements and facilitate thermoregulation (Hidden, 2009).

Studies carried out in other areas of northern Botswana (Chase, 2007, Adams, 2016) and other countries have observed larger home range sizes for elephants in the wet season than in the dry season (Western and Lindsay, 1984, Osborn and Parker, 2003, Galanti et al., 2006, Kikoti, 2009, Ngene et al., 2017, Mlambo et al., 2021). However, seasonal home range sizes observed in the Okavango Panhandle were larger >1500 – 2500 km^2 than those reported in other parts of northern Botswana which ranged between 149.68-685.81 km^2 (Adams, 2016). Larger home ranges in the eastern Okavango Panhandle could be due to the vast openness of the area, wide availability of surface water and limited human developments in the area that could restrict elephant movement (see appendix 2). Resource availability is critical in influencing home-range sizes (Cumming et al., 1997, Van Aarde et al., 2006). During years with extended dry seasons and droughts, such as the ones experienced between 2014-2017 (see chapter 1), elephants travelled long distances and exhibited larger home ranges, a behaviour that is uncommon in normal dry season periods. These large home ranges in the drier seasons were associated with the need to search for sufficient forage and water over a wider landscape to meet energy and other physiological needs. Young et al. (2009) and others also observed larger home range sizes for elephants in the dry season, and this is attributed to poor rainfall and reduced vegetation productivity in the preceding wet season which exacerbated the conditions in the current dry season. Diminishing amount of forage and water can also trigger seasonal migrations which reduces intra-specific competition for limited resources (Stokke and Du Toit, 2002), and these migrations usually occur at the beginning of the dry season, or the onset of the early wet season to move to areas with better forage quality and quantity. The early wet season migration would explain the increase in home range size observed at this time of the year. In the Okavango Panhandle larger home range sizes were observed in the early wet season, and this suggested the increasing availability of surface water and food resources.

Human presence and developments can also influence elephant movement, distribution and home range sizes. Elephants have large home ranges and the size of these home ranges can be restricted by the human activities and developments surrounding the elephant habitats (Theron et al., 2013). Such developments may include cordon fences, fenced agricultural farms and homes and industries e.g. (Naidoo et al., 2022b). Some of these developments may have impermeable boundaries that constrain elephants within small areas, and where semi-impermeable boundaries exist, elephants are pushed away by constant killing, poaching and use of other repellents. Elephants in wildlife areas that are enclosed or fenced may also fail to exhibit dispersal behaviour that free-ranging elephants demonstrate. For example, the smaller elephant home range sizes observed in Pongola Game reserve in South Africa in the wet season than in the dry season (Shannon et al., 2006) could be attributed to the confinement and restriction of movements by the fences around the study area, and the possibility that food resources and water availability in the enclosed habitats were sufficient enough to support the relatively few elephants that were in the study area. Sex of the elephants can also have an influence in the home range sizes (Perry, 1953, Purdon and Van Aarde, 2017). Female elephant would tend to have localized movements to care for the newly born calves which may not be fit enough to travel long distances (Purdon and Van Aarde, 2017).

The effect of sex on elephant home range size over the different seasons was also investigated in My study. It was predicted that male home range sizes would be larger than those of female elephants because the latter usually does not travel long distances when they are caring for the young calves that cannot cover large distances. My results showed that male and female elephants had HRs of similar sizes for most of the year, but males occupied larger HRs than females in the late wet season. Male home ranges sizes may be influenced by competition over resources and mate searching (Archie et al., 2007, Allen et al., 2020). Competition between males causes wide ranging movement in search of new territories

(Archie et al., 2007). On the other hand, female movement behaviour is limited by their young and also the fact that they usually move in groups and slower than the lone male counterparts. The smaller home range sizes in the late wet season for female elephants may also be explained by the fact that during this period, the female elephants would be still walking their calves. The breeding season is associated with the onset of the wet season (Perry, 1953). This is time young ones are born, hence likely limit the home range size in late wet season due to lower movement ranges (Purdon and Van Aarde, 2017). Also, elephant families move in large groups comprising juveniles and sub adults which limit the distance that could be covered in a day. This is different with male elephants which are normally lone males or bachelor herds, which are not restricted in their movements by young ones. Male elephants generally travel longer distances than female elephants in search for new spaces or breeding herds (Stokke and Du Toit, 2002, Chase and Griffin, 2007, Kikoti, 2009, Ngene et al., 2017). One collared male elephant in the Okavango Panhandle, named "Whiskey", travelled long distances to the neighbouring coutries of Namibia and Angola and returned to the study area in the following season.

However, some studies showed contrasting findings, for example in the Addo Elephant National Park in South Africa, larger home range sizes were observed for female elephants than males (Roux and Bernard, 2009). The authors attributed their findings to the need for female elephants to move longer distances in search for resources to satisfy the nutritional requirements of their young calves. Whitehouse and Schoeman (2003) attributed the larger home ranges found for female elephants to minimal human disturbance and unrestricted resource availability. Habitat type can also influence elephant home range sizes (Moses et al., 2015). Elephant may behave differently depending on the habitat structure and composition they live in (Schulte, 2000). Another possible reason for the differences observed between the present study and other studies might be variations in local environmental factors e.g., terrain (Bohrer et al., 2014).

Management strategies can also have significant influence on elephant movements and home range sizes. For example, artificial water provisioning at strategic locations within the elephant range like in Amboseli and Kruger National Park (Smit et al., 2007a, Chamaille-Jammes et al., 2007). The provision of artificial waterholes increases sedentary behaviour, intensifies resource use, and alters elephant space use (Purdon and Van Aarde, 2017). In situations where resources are managed or provided, elephants might not need to move widely in search for these resources. Elephants in the eastern Okavango Panhandle are not managed and no artificial water is provided.

The effect of season on elephant daily distance movements was investigated. The seasons were divided into 4 seasons to determine variations that might arise as the weather and environmental conditions change as the year transits through different seasons. The study hypothesized that elephants would cover shorter daily distances during the early and late wet than early and late dry season. Elephants moved shorter distances in the late wet season than during the early wet and early & late dry seasons. The early wet season however was not significantly different with the early and late dry seasons, hence the hypothesis not fully supported by the results on distance travelled on the seasons.

Elephants travelled longer distances during early wet, early and late dry seasons. Shorter distances moved in the late wet season suggest that resources were either localized or were adequately available within the wet season range therefore discouraging long distance movements beyond their normal daily home ranges in the late wet. Shorter distances in the late wet would likely mean that there might be competition for resources, i.e., conflict between elephants and communities because crop harvesting occurs during this time in the eastern Okavango Panhandle (Mosojane, 2004, Songhurst et al., 2015). During the early wet season, surface water and forage become widely available over a large landscape and elephants have the option of conserving their energy by making only local movements around surface water sources. When forage and water are abundant, especially in the wet season, family elephant herds, with young calves, may not travel longer distances for the sake of the young ones who are still at a critical stage of growth (Lee, 1987). However, at the onset of the dry season when surface water and forage resources become scarce, elephants start to move out and cover long distances to areas with these resources (see fig. 26 and 27). Additionally, longer distances recorded in the Okavango Panhandle could have been influenced by the vast, uninhabited landscape within the study area where elephants spend most of their time and movements to and from the permanent river sources (i.e., the Okavango River) when ephemeral water holes dry up at the end of the wet season and onset of the dry season.
The average distance recorded by elephants in My study are similar to those found by (Leggett, 2010), who recorded distances of approximately 6km travelled in the wet season for elephants collared in semi-arid Namibia (wet season), which has similar climatic and environmental conditions as eastern Okavango, Botswana. Comparable results of elephants moving long-distances in the wet season were found elsewhere (Loarie et al., 2009, Purdon et al., 2018). However, in very wet seasons elephant movements have been found to be restricted to within a radius of 3km (Loarie et al., 2009, Purdon et al., 2018).

Mating season may also explain the longer distances travelled by bull elephants in search for mating partners (Barnes, 1982). In the study area of this research elephant mating occurs during periods of high rainfall (November-January), and disturbances normally associated with mating may cause some long-distance movements as males wander around in search for mating partners (Moss, 1983, Poole and Granli, 2009). Some long-distance movements can be regular and occur at certain times of the year such as seasonal migrations observed in some large herds of herbivores (Alerstam et al., 2003, Purdon et al., 2018). In elephants, partial migrations have been reported and are highly driven by spatio-temporal variability in resources (Purdon et al., 2018). The variability in resources is common in semi-arid savannas where climate is the main driving force (Jacobson, 1995). Elephant movements are linked to the availability and variability of these essential resources (Leggett, 2006). Between 2014 and 2017, the eastern panhandle experienced dry spells which might have influenced partial migration or long-distance movements out of the study area (see appendix 6 and chapter 1 on climate). The drying up of ephemeral waterholes in the eastern Okavango panhandle between April-June triggers elephants to move from the core area of the study area to the Okavango Delta in the south where permanent surface water is available (Pozo et al., 2018, Songhurst, 2012b). At the beginning of the wet season in semi-arid environments, the erratic nature of rainfall can also on the other hand trigger local movements within the core area of the elephant range or cause cross-boundary movements depending on where the first few drops of rains fell that caused the emergence of flush vegetation and attracted the elephants and other herbivores (Viljoen and Bothma, 1990).

3.7 Conclusion

I found that elephant home ranges were larger in the early and late wet season than in the early and late dry season. Males were more responsive to seasonal changes than females, and male elephants had larger home ranges than females. Seasonal variation in food and water resources were important drivers of space use by elephants in the Okavango Panhandle. In the wet season elephants ranged widely during the early and late wet season and in the dry season (early and late) they were largely confined to areas with permanent surface water such as Selinda spillway and areas in close proximity to the Okavango Delta. Elephants travelled longer distances in the early wet season and early/late dry season than in the late wet season when they covered smaller distances. The above observation suggests that seasonality and resource availability were key factors influencing elephant home range size and their distance travelled.

4 ELEPHANT RESOURCE USE IN THE EASTERN OKAVANGO PANHANDLE

SUMMARY

Chapter 2 explored the availability of ephemeral surface water within the study area and Chapter 3 investigated the spatial use of the area by elephants in relation to season or resource availability. In this chapter, I aimed to bring these findings together to determine the influence of environmental factors (season, vegetation, and water availability) on the distribution and resource use by elephants in the study area. The utilization distribution (UD) parameter was used as a proxy for elephant resource use. Generalized Linear Mixed Models (GLMMs) were used to model actual and random points of elephants in the eastern Okavango Panhandle. Resource Selection Function (RSF) were then used to determine whether the actual GPS points were closer than random points to ephemeral surface water, and whether this effect changed with season. Results indicate that both sexes occupied areas closer to water with high NDVI values, and this preference was stronger in males than females. It is likely that both sexes selected sites which were closer to water and have high NDVI values than areas that are further away in order to conserve energy. This observation was consistent throughout the period of the study.

4.1 Introduction

Elephants are megaherbivores that need to consume a large quantity of vegetation (grasses, fruits, and roots) and drink water (<20 gallons) each day (Burton, 2000, Owen-Smith and Chafota, 2012). They need to visit water regularly for drinking but also for mud bathing and thermoregulation (Dunkin et al., 2013, Purdon and Van Aarde, 2017). Environmental factors that influence elephant movements include water sources, human settlements, fences, forage and distance to rivers (Loarie et al., 2009). Although, several factors have been identified that determine elephant movement and space use, water is among the leading factor (Chamaille-Jammes et al., 2007). Indeed, surface water availability has been shown to be the most influential environmental factor influencing elephant resource use in both Asia and Africa, for example in China (Dzinotizei, 2019), Ghana (Ashiagbor and Danquah, 2017), Tanzania (Kioko et al., 2015), Zimbabwe (Chamaille-Jammes et al., 2007), South Africa (Smit et al., 2007a), and Namibia (Smit et al., 2007a, Tsalyuk et al., 2019). It has also been found that when forage and/or water are scarce, elephants widen their ranges (Western and Maitumo, 2004) and access to seasonal rain filled ephemeral waterholes affects range expansion for elephants and other herbivore species in southern Africa (arid) ranges, (Redfern et al., 2003).

Upon reaching maturity male elephants are known to range widely in search of new territories. These individuals tend to also form the majority problem animals in areas outside their home ranges. At times these lone bulls aggregate to form bachelor herds. On the other hand, female elephants are always found in matriarchal herds which include juveniles and sub adults.

Understanding how elephants use their landscape in response to the habitat composition is crucial for applied ecology. It is necessary to describe distributions and abundance of resources to investigate interactions between organisms and their environments. Resource Selection Functions (RSFs) may be utilized from a population viewpoint to make statistical inferences about the relationships between environmental factors, as well as understanding the complex and dynamic interactions between species and their environment (Boyce et al., 2002, Schick et al., 2008, McLoughlin et al., 2010). RSF models are multivariate functions which account for natural variations in the habitat such as predation and within-species competition (McLoughlin et al., 2010), and human activities, including cumulative effects of human developments (Houle et al., 2010). They compare used and available resource units to estimate the relative probability of occurrence, based on the resource characteristics (Manly, 2002), providing a quantitative description of the resource use and the analysis using both categorical and continuous variables. The selection of areas closely associated with surface water is a reflection of preference by animals. The principle of resource selection thereby recognises this behavioural variability as well as resource necessity that can manifest in heterogenous landscapes (Boyce et al., 2002). RSF models are useful for informing decisions made by conservation managers since they provide spatial information as well as probabilities of species occurrence in time and space (Johnson and Onwuegbuzie, 2004).

Differences between resource selection behaviour vary between individual, populations, and landscapes. Numerous studies have used RSFs and offer ecological insights (Loarie et al., 2009, Wadey et al., 2018, Bastille-Rousseau et al., 2020). In Namibia, Tsalyuk et al., (2019) used RSF to explore temporal variation in resource selection in elephants and test how they respond to information of where they have been. They found that elephants prefer to stay near water sources, and fences. In the eastern Okavango, (Buchholtz et al., 2019) used RSF to model resource use by elephants and people, and where they are sharing natural resources.

I used RSF to investigate the link between where elephants were and the resources they use, for example, ephemeral surface water and NDVI as a proxy for forage.

4.2 Hypotheses

- Elephants, particularly females, will occupy spaces closer to surface water during the early and late wet season
- Elephants, particularly females, will occupy areas with the highest relative greenness throughout the year, indicative of nutritious abundant and nutritious forage.

4.3 Methods

4.3.1 Elephant collar datasets

GPS collar data were used from 15 elephants (5 males, 10 females) to calculate monthly home ranges in this chapter. Data was cleaned (see chapter 3) before RSF analysis. Elephant fixes were extracted using both Microsoft Excel and R Statistics version 4.0.1 (R Core Team, 2013a) from raw datasets. The early wet season was excluded from this analysis because high cloud cover prevented the use of remote sensing to identify surface water. Remote sensing and elephant GPS data from the late wet, early, and late dry seasons from 2014-2017 were included in the analysis.

4.3.2 Remote sensing datasets

While the lack of a complete vegetation map for this area prohibited the current study from analysing the effect of vegetation structure in animal space use, NDVI serves as an indicator of vegetation greenness within the elephant range as well as a predictor of forage availability for elephants (Borowik et al., 2013). NDVI time series may be calculated using a variety of Earth-orbiting remote sensing datasets. The Landsat 8 sensors deployed in 2014-2017 were used, they offer data at a 30m resolution and images collected every 16 days of frequency at no cost (USGS, 2013). NDVI is obtained from the red/near-infrared reflectance ratio [NDVI = (NIR RED)/(NIR + RED)], where NIR and RED are the quantities of near-infrared and red light reflected and recorded by a satellite's sensor, respectively (Pettorelli et al., 2011, Duffy and Pettorelli, 2012). The NDVI index detects and quantifies the presence of live green vegetation using this reflected light in the visible and near-infrared bands (Guerschman et al., 2009).

Same images (Landsat 8) utilised for surface water mapping were used to compute NDVI for the study area. NDVI was calculated using the below formula;

$$\text{NDVI} = \frac{NIR-Red}{NIR+Red} \qquad (7)$$

Where the NIR (near infrared is band 5 and Red is band 4).

4.4 Data analysis

4.4.1 Utilization distribution for each elephant at a monthly scale

The GPS data were delineated into 3 seasons: late wet (slight rains; Feb- April), early dry season (May-July) and late dry (high temperatures and no rains; (August-Oct), due to the timeframe of movement data available from collared elephants (appendix 6 & 7). The 95 percent kernel utilisation distribution (UD) for each animal were derived with the kernel density estimation (KDE) method (Van Winkle, 1975, Fieberg and Kochanny, 2005), from the 'adehabitat' package in R version 4.0.3 (Calenge, 2006). One UD per animal per month was derived, in order to analyse the relation to the ephemeral surface water data. The 'spsample' function from the sp. package (Pebesma and Bivand, 2005) was used to generate 10 random points per actual GPS fix (Manly, 2002, Johnson et al., 2006) also bounded within the respective KDE home ranges (see figure 29). The reference smoothing parameter (h_ref) (Worton, 1987, Viana et al., 2018), was used to calculate UD and 95% contours (Börger et al., 2006). It is important to note that the h_ref was chosen over LSCV because the latter couldn't converge for the dataset.

4.4.2 Distance to ephemeral surface water

Using ArcGIS Pro 2.8 and ENVI 5.4.1 applications surface water maps were generated. ENVI was used to pre-process the raw Landsat images. The pre-processing involved among other things radiometric calibration to convert digital numbers into surface reflectance and geometric corrections to reduce distortions. ArcGIS Pro 2.8 was used conversion of rasters into vectors files (this was to allow mapping and visualizations of the mapped surface water with other shapefile files. Distances from each recorded actual and random point to the nearest ephemeral surface water were computed using the 'near analysis' tool in ArcGIS Pro 2.8 (Environmental Systems Research Institute, 2021). A resource selection function was run to determine whether the recorded actual point was closer than random points to ephemeral surface water, and whether this changed with season: late wet (Feb–April); early dry (May-July) or late dry (August – October) as individuals were in the late wet or early dry as well as late dry or year (2014-2017). The RSFs employ logistic regressions, which are commonly used as robust estimates of an animal's chance of using a resource (Boyce et al., 2002).

4.4.3 Exploring environmental factors affecting elephant utilisation distribution

To analyse the effects of environmental variables on elephant distribution, a Generalized Linear Mixed Models (GLMMs) in R with a binomial error distribution (lme4 package; (Bates et al., 2015) were used to model binary data represented by '0' and '1', Zero signified random

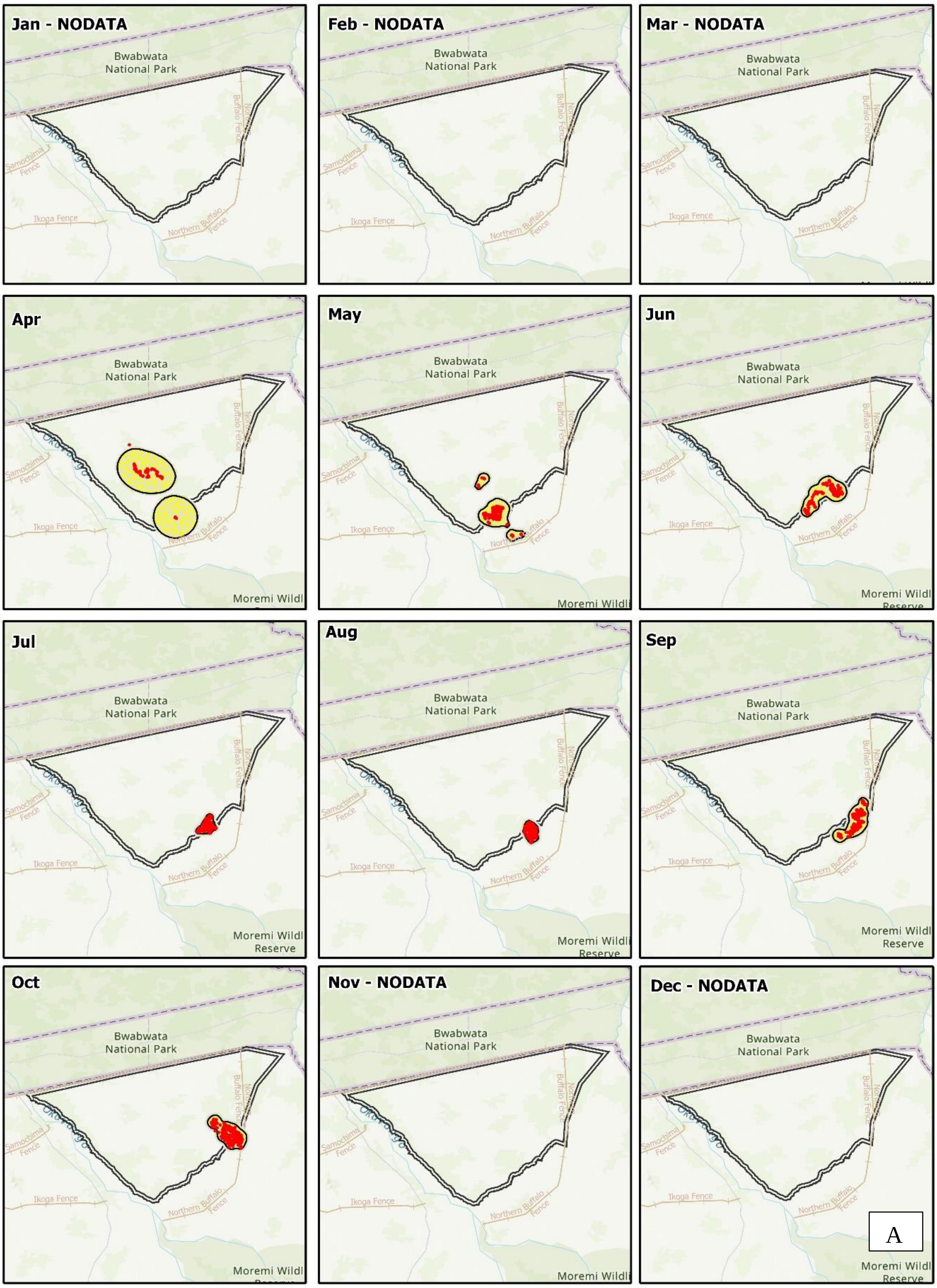
GPS points and ‘1’represented actual points. I used vegetation productivity (NDVI) and distance to ephemeral surface water as explanatory variables. The analysis considered monthly movements for each individual animal. The model was specified with fix type as the dependent predictor variable; to account for these repeated observations among individuals, random effects were month, year and individual animal allowing them to vary. The fixed effects predictors were the interaction among distance to water, NDVI and sex, and another two-way interaction among distance to ephemeral surface water and season. The ‘dredge’ function from the ‘MuMIn’ package was used to identify all possible candidate models with ΔAIC<2. AIC values from each model were extracted and compared to identify the most parsimonious model (Akaike, 1974).

4.5 Results

4.5.1 Utilisation distribution for each elephant

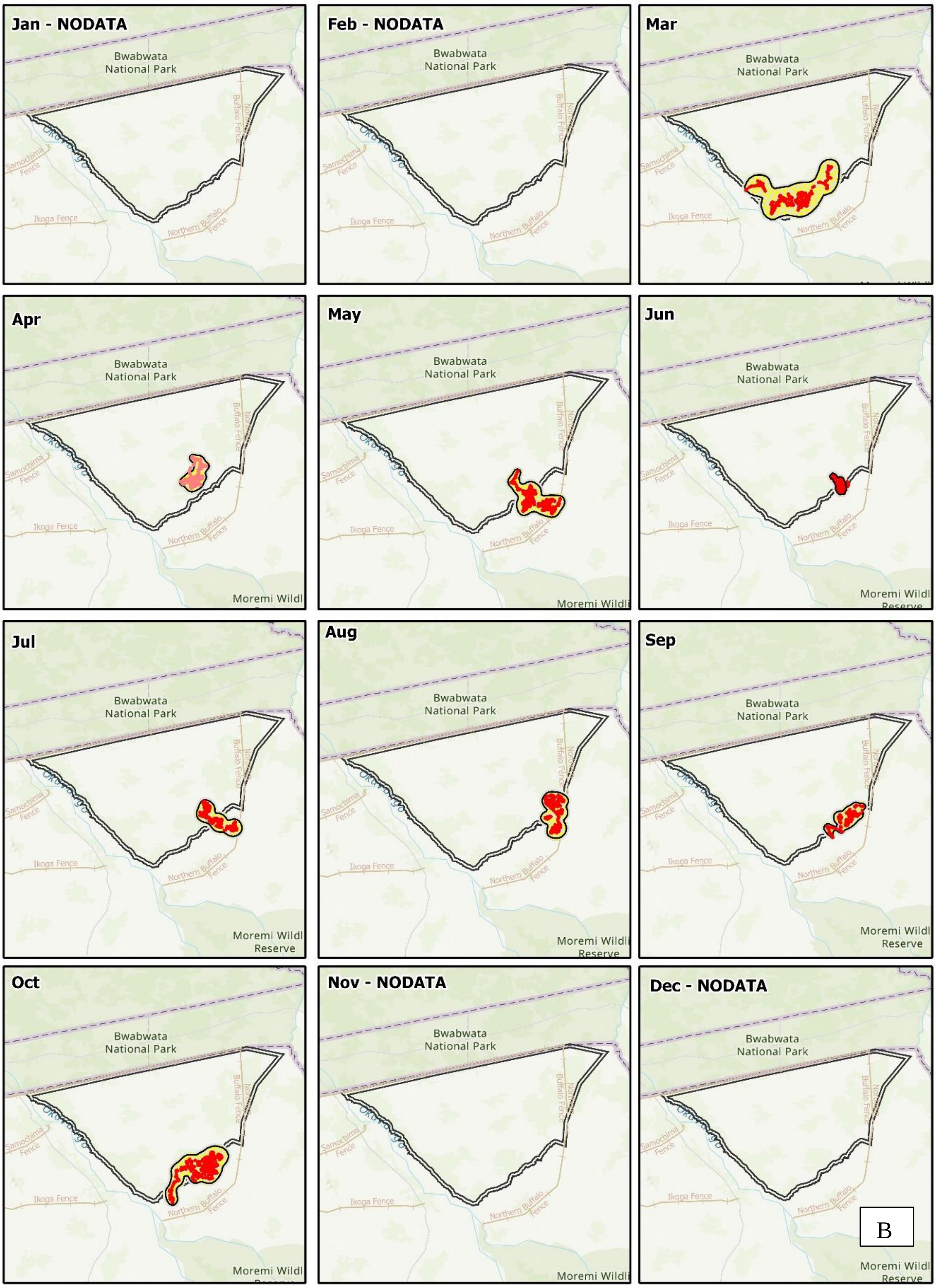
Monthly fixes of elephants show different utilization distributions throughout the study period. For example, one collared elephant (Chan) was closer to the Seronga area in April and May 2014-2017 and the home range was smaller in size. in June - August 2014-2017, when resources are patchy its home range increased, overlapping into NG12 near Selinda spill way and not far from Gudigwa where there are permanent water sources. Between September - October 2014-2017, it had moved closer to the Okavango River near Mokgacha and Mawana settlements (see figure 26 (A-D) and the appendix 7-8 for more elephants). Results showed on Fig.26 only one elephant as an illustration of utilisation distribution, other elephants are found in the appendix 7-8. In other study individuals’ movement patterns varied widely; in the early and late wet season they were found at NG/12, NG/13 and permanent waters of the Okavango Delta in the early and late dry season.

Chan in 2014



Jan - NODATA
Feb - NODATA
Mar - NODATA
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov - NODATA
Dec - NODATA
Bwabwata National Park
Okavango
Samochima Fence
Ikoga Fence
Northern Buffalo Fence
Buffalo Fence
Moremi Wildl Reserve
A

Chan in 2015



Jan - NODATA
Feb - NODATA
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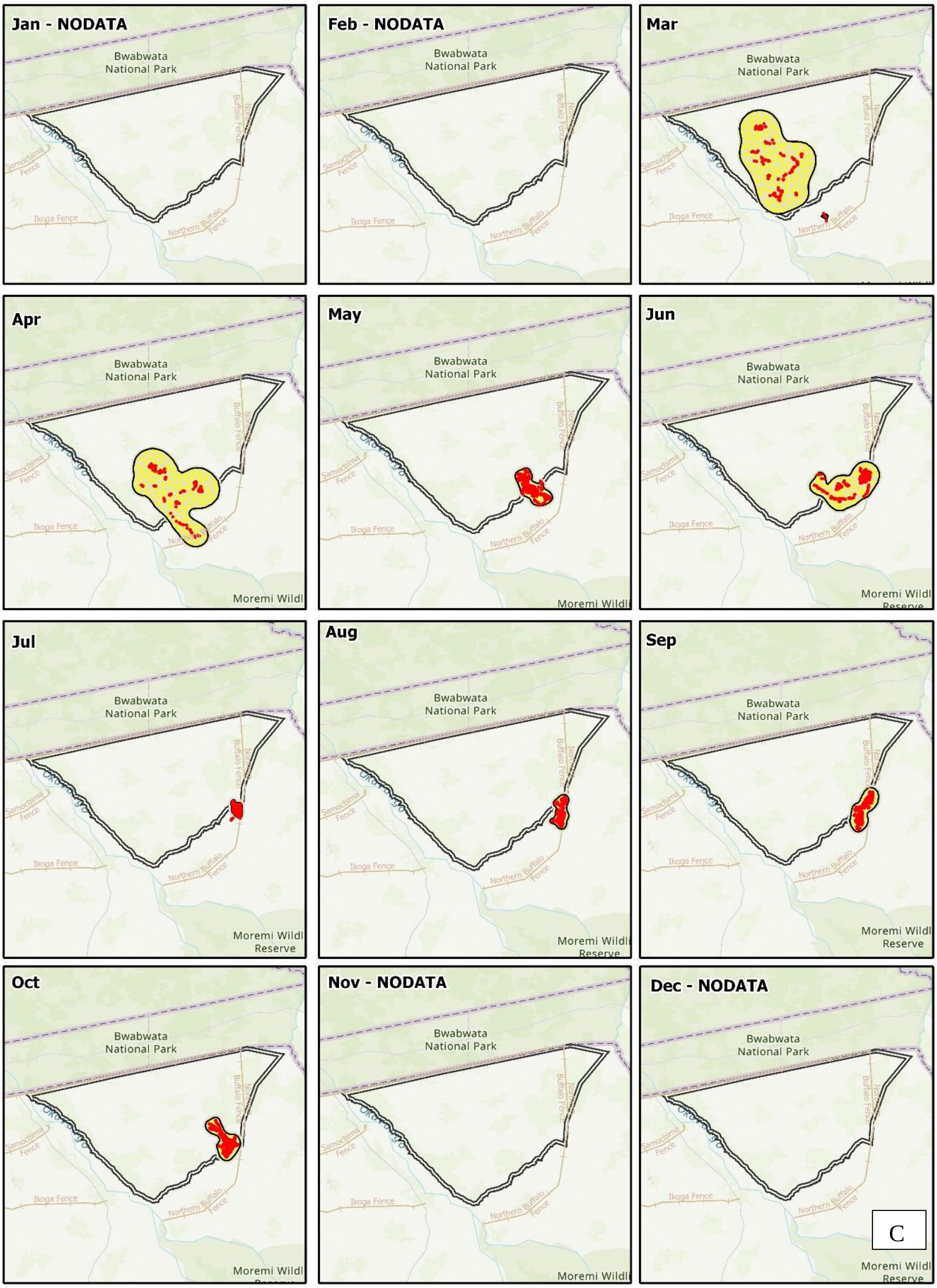
Oct
Nov - NODATA
Dec - NODATA
Bwabwata
National Park
Buffalo Fence
Okavango
Samochima Fence
Ikoga Fence
Northern Buffalo Fence
Moremi Wildl
Reserve
B

Chan in 2016


Jan - NODATA
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Bwabwata National Park
Okavango
Samochima Fence
Ikoga Fence
Northern Buffalo Fence
Buffalo Fence
Moremi Wildl Reserve
C

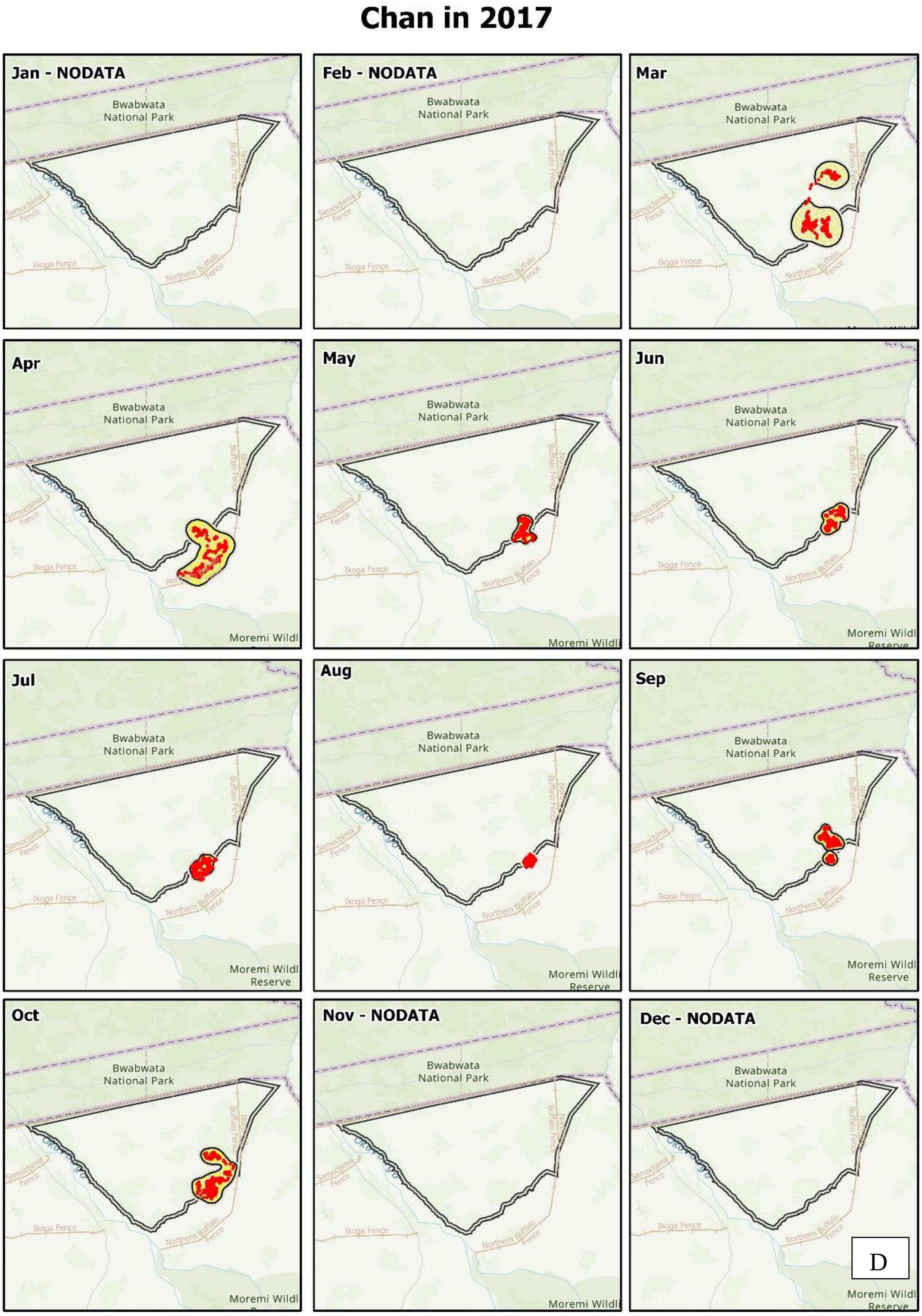


Figure 26a-d. an example of fixes to show how data was prepared for Resource selection function for Chan between 2014-2017 A-D). Red dots denote to actual fixes whilst the yellow dots indicate random fixes over a month for example in 2014 (April-October) and from 2015 -2017 home ranges were generated from March - October. Months with no data are also shown.

4.5.2 Distance to ephemeral surface water

My results showed that smaller distances to ephemeral surface water occurred between March to August and distances increased in the drier season, hotter months of September and October for the entire 2014-2017 study period. Elephants use of areas beyond 25000m (25km) from water increased during the hottest months of September-October and decreased during the cooler months of May, June and August (Figure 27). Throughout the late months of the year, elephants spent less and less time in close proximity to ephemeral waterholes, as shown in Fig. 27.

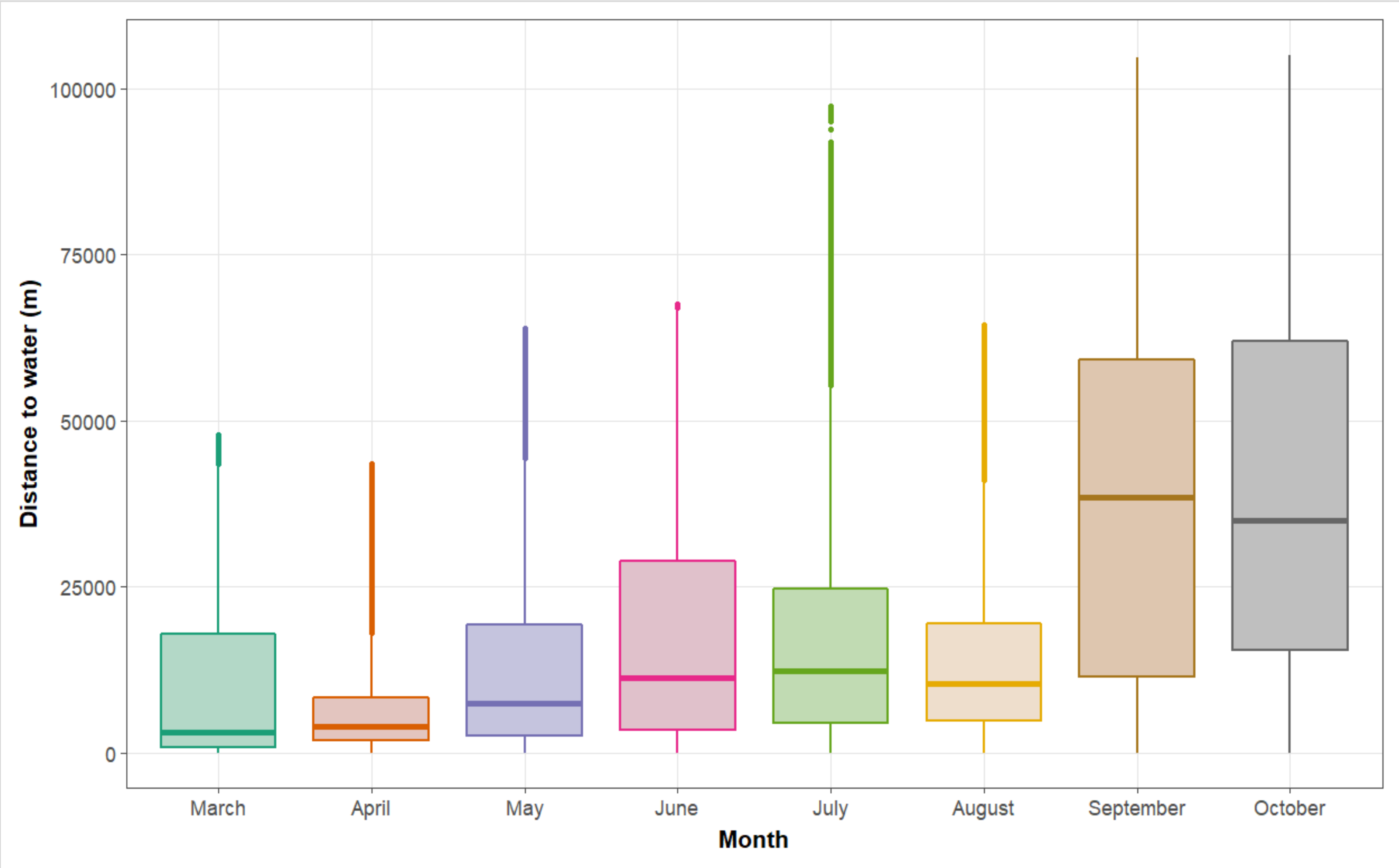


Figure 27. Distribution of elephant utilization according to distance to water by month. Box plot ranges from the 25th to 75th percentile, including the median (horizontal line). Distances were derived using ‘st_distance’ R statistics

4.5.3 Environmental factors affecting elephant utilisation distribution

The mean lowest NDVI recorded was 0.3659 for entire sampled period ranging between the maximum of 0.8005 and minimum -0.7057. A seasonal breakdown of this is indicated in **Error! Reference source not found.**. Throughout the years (2014-2017) from November-April vegetation is green whlist May-October there are very few areas with healthy green vegetation (**Error! Reference source not found.**).

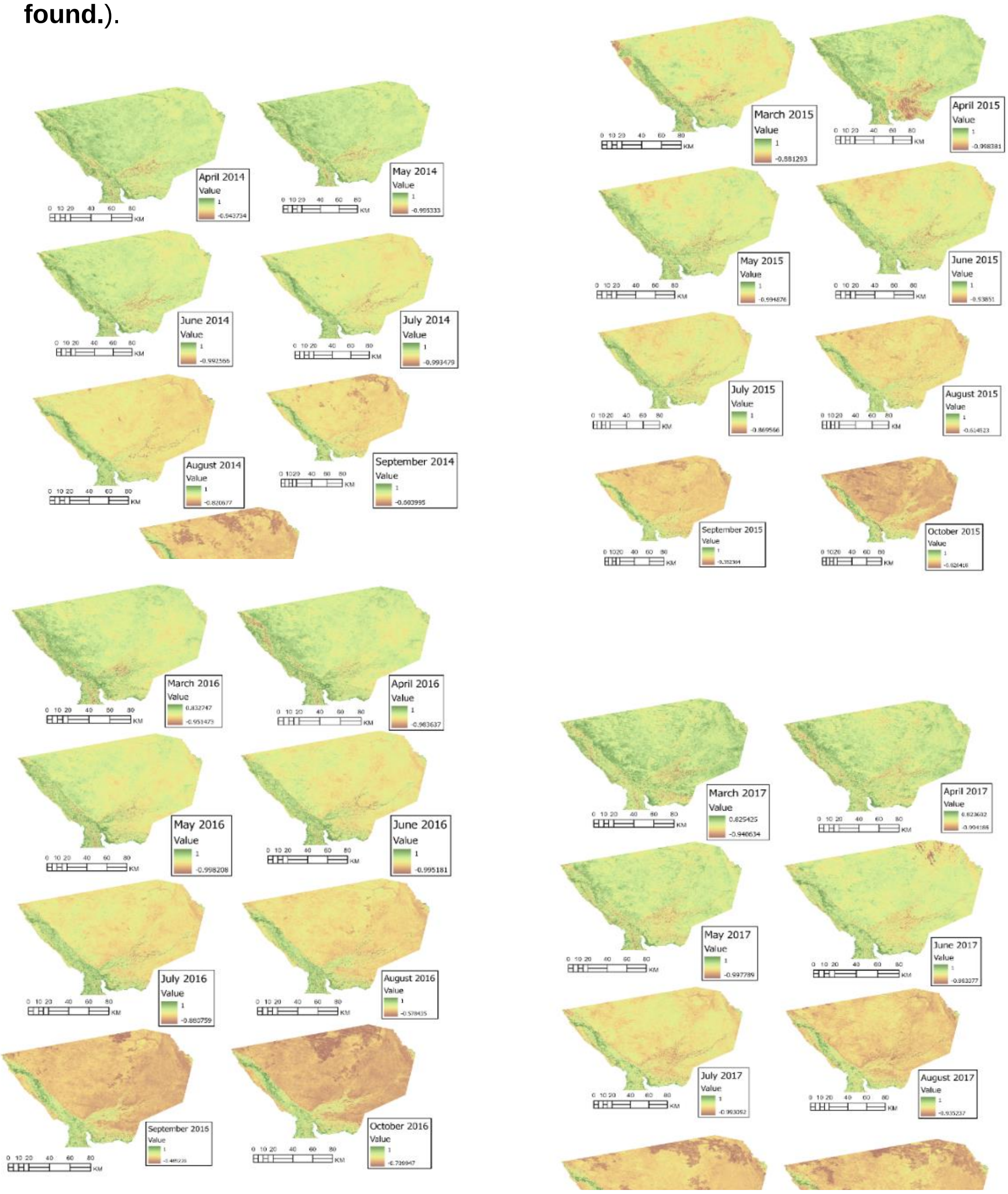
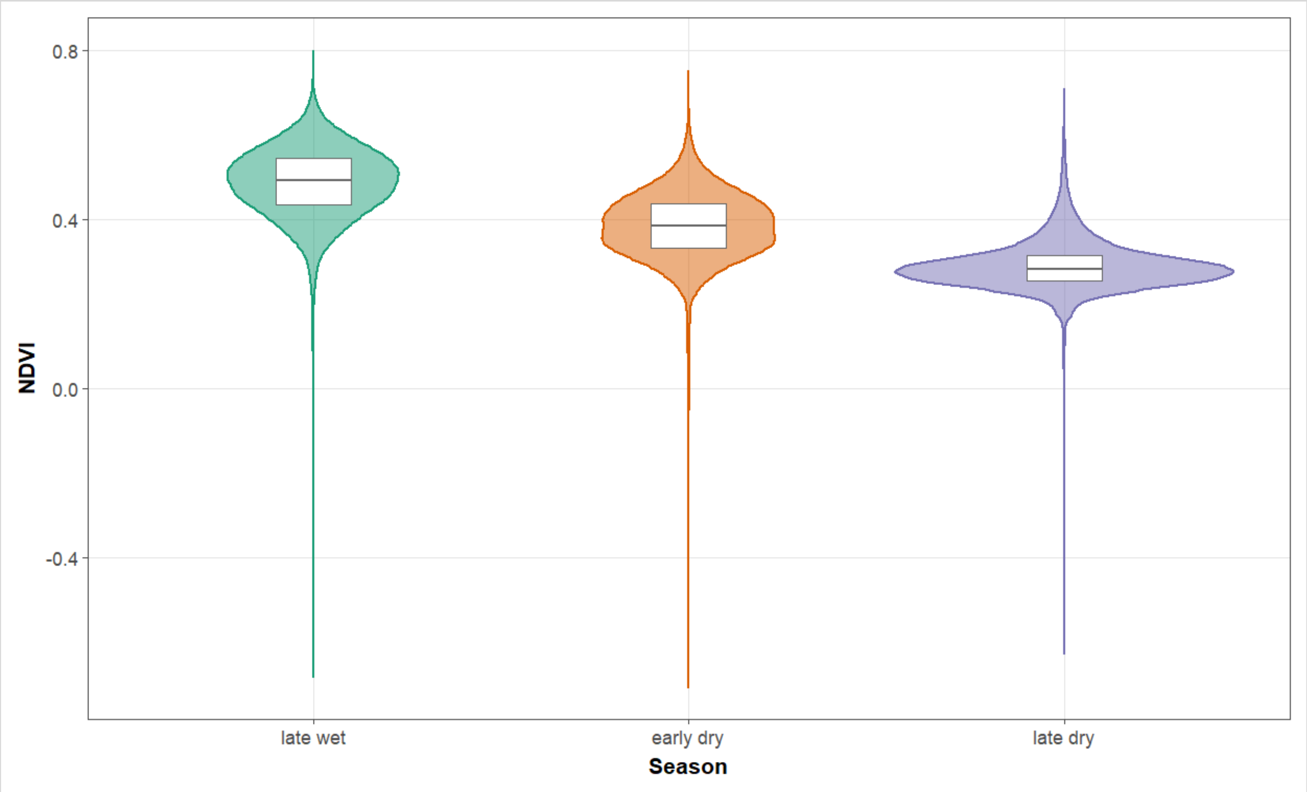


Figure 28. Normalized difference vegetation index (NDVI) data used to assess elephant utilization of vegetation along the eastern Okavango Panhandle, Botswana. The top left row shows the 2014 images from April-October. Subsequent rows top right shows the NDVI for 2015 from March-October, bottom left and right showing NDVI maps for 2016 and 2017. NDVI values derived by using Landsat 8 images and NDVI ranges from −1 to +1. Positive values closer to 1 shows healthy green vegetation and negatives signify non vegetative areas



The GLMMs showed that a combination of distance to water, NDVI and sex of elephant had a significant effect on elephant utilization distribution in the eastern Okavango Panhandle. The most parsimonious model was a 3 – way interaction among distance to water, NDVI, Sex, with (AICc=1436722, AICw=0.999); no other models were competitive (see figure 29). The orange-coloured curve represents high values of NDVI (closer to 1) or dense vegetation whilst values less than 0.5 (sparse or no vegetation) are represented by purple (=<0.4); green (=< 0.3); blue (=<0.2) and red (=<0.8) curves respectively. Negative values represent water or cloud cover features.

The illustration on figure 30 shows that both sexes were more likely to occupy areas closer to water with high NDVI values, and this preference was stronger in male than female elephants. As distance from ephemeral surface water increased and greenness of vegetation decreased.

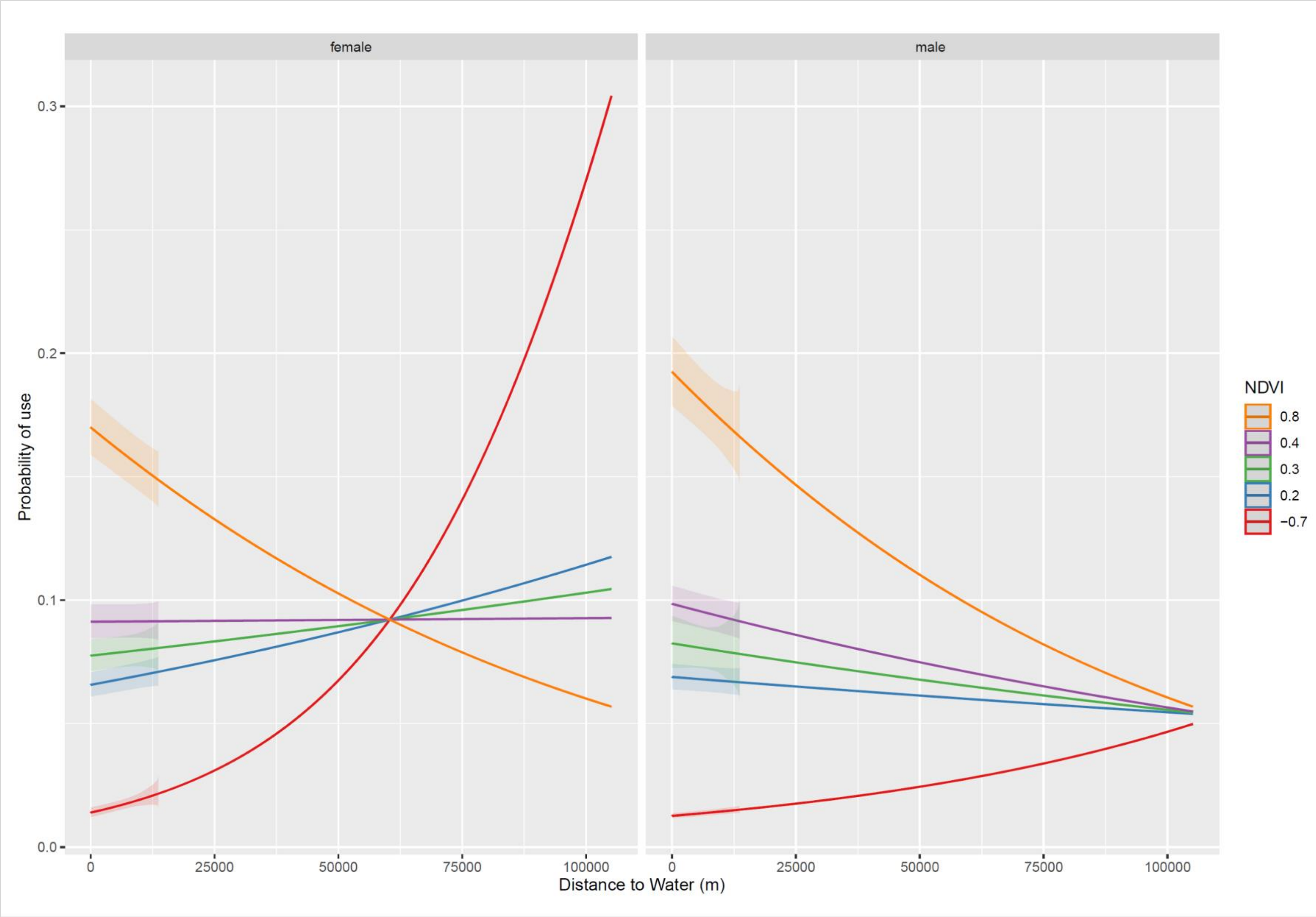


Figure 29. Probability of use in relation to distance to water NDVI and sex in the eastern Okavango Panhandle, Botswana, for elephants (males: n=5 female: n=10). Probability of use was derived by comparing GPS locations from collared elephants with an equal number of locations generated randomly within monthly home ranges through resource selection functions

4.6 Discussion

To survive, ungulates must adapt their geographical distribution to changing resources throughout time (Tsalyuk et al., 2019). Most animal species, notably elephants, need frequent water intake and must move between forage locations and watering points to satisfy their energy and water requirements (Stokke and Du Toit, 2002). By merging high temporal resolution telemetry data with satellite images, my study shows the importance of seasonal temporal variations in African elephant resource use and their responses to landscape variables.

Surface water and forage are key resources in elephant populations. I investigated the effects of environmental variables on elephant resource use, and hypothesized that elephants, particularly females, will occupy spaces closer to surface water during the early and late wet season when surface water is abundant across the landscape because the movement of the herd is limited by young who cannot cover large distances. The findings reveal that both male and female elephants were closer to water during the early and late wet season, which supports this hypothesis.

The concentration of elephants around areas with surface water can be easily explained by the Optimal grazing theory which postulates that animals tend to conserve the energy they gain by reducing the cost associated with the search for a resource. Therefore, to achieve this, elephants in the Okavango Panhandle tended to conserve their energy by foraging in areas closer to water supply areas. Elephants were therefore spending less energy to get the maximum benefit from resources that are available, at the lowest cost. My results are consistent with other studies in Namibia (Tsalyuk et al., 2019), Tsavo National Park, Kenya (Wato et al., 2018), and Hwange National Park, Zimbabwe (Tshipa et al., 2017). Male elephants travelling alone, have been found to forage further from water and depleted river vegetation (Prins, 1996a) in order to maximise their intake of forage and water.

During my study period (2014 – 2017) there was a long drought period identified through low NDVI values (see fig. 28 and 29) and my results showed that elephants had to travel longer distances of over 100km from the ephemeral pans to areas with permanent surface water and other resources during this time. The reason they moved long distances could be a result of overutilisation of forage around the waterhole. Elephants have a good memory, and have been found to change their migratory routes during seasonal changes and resource availability (Loarie et al., 2009, Abrahams, 2013).

The second hypothesis of my study was that elephants, particularly females, occupy areas with the highest relative greenness throughout the year, indicative of productive and good quality forage. The basis of the hypothesis was that female herds travel shorter and select patches of high forage quality and quantity to satisfy the needs of the calves and other family members. My results support this hypothesis and show a positive relationship between the probability of resource use by female elephants and the distance they covered to reach ephemeral surface waterholes.

4.7 Conclusion

My study gave an overview of elephant resource use in the eastern Okavango Panhandle in Botswana. Water-adjacent sites were 50% more likely to be selected over distant sites. Areas closer to water with high NDVI were occupied which implies that elephants are water dependent species and prefer greener vegetation. Caution is needed in the interpretation of these results due to possible correlation between water and higher NDVI, further analysis is needed to determine such correlation versus causation. Accessibility between ephemeral water resources and the Okavango Delta is critical for elephants in the eastern Okavango Panhandle. Consideration of these needs and the critical elephant routes in the area is needed to ensure elephants can access the resources they need, especially through areas with human settlements and fields.

5 SYNTHESIS

My study investigated resource availability, elephant movement, and factors affecting elephant resource use in the eastern Okavango Panhandle, Botswana. I first gained an understanding of water availability throughout the study area, using the Automatic Water Extraction Index (AWEI) with Landsat 8 data. I found that existing global surface water portals were insufficient to map surface water, whereas $AWEI_{nsh}$, demonstrated good results in picking small turbid water and had very stable thresholds, demonstrating their suitability for monitoring changes in surface water in the eastern Okavango Panhandle (see chapter 2). I then investigated how elephants were using space in the eastern Okavango Panhandle through home range and daily movement analysis of 15 collared elephants. I found that elephant home ranges ranged between 1,500 – 2,500 km^2, with significantly larger ranges observed in the wet season. The elephants were observed to be widely distributed in the wet season than in the dry season suggesting that when resources are plentiful and widespread elephants will maximize their utilization of the available landscape rather than restricting themselves to certain locations. Collared elephants moved shorter distances in the late wet season than during the early wet and early & late dry seasons, which could be due to seasonal differences in water and vegetation resource availability (see chapter 3). To explore elephant spatial use further in the Okavango Panhandle and understand the role of ephemeral water availability and other resources in elephant distribution, I investigated the effects of environmental variables on elephant resource use using utilization distributions (UD) and Resource Selection Functions (RSF). I found that water-adjacent sites were 50% more likely to be selected over sites further from water and areas with higher NDVI that were closer to water were more likely to be occupied by elephants. Both male and female elephants were found closer to ephemeral water sources during the early and late wet season and average daily movement were within a distance of 6.4km in the late dry season, and 5.5km to ephemeral water in the late wet season.

The eastern Okavango Panhandle is an important area for elephants in northern Botswana and indeed the KAZA Transfrontier Conservation Area (KAZA TFCA). In this area, around 16000 people and 18000 elephants live and compete for shared resources like space, water and food (Ecoexist, 2015) and it is a hotspot for human elephant conflict (HEC), (Songhurst, 2017). In the early wet season when water is in the ephemeral waterholes and vegetation resources are plentiful, incidents of HEC are fewer, however elephants begin to move towards the Okavango and past fields and human settlements in larger numbers in the late wet season and early dry season when ephemeral surface water is reducing and they require additional food resources from the Delta, (Buchholtz et al., 2019, Velempini, 2021). This timing coincides with the crop harvesting season and crop raiding incidents occur during this time (March –

May), (Songhurst, 2017). Fields that are closer to elephant movement corridors have been found to be more likely to be raided by elephants in the Okavango Panhandle (Songhurst and Coulson, 2014) and my findings suggest that fields closer to ephemeral water could also be more vulnerable to crop raiding due to the increased likelihood of elephant presence close to ephemeral water. Current strategies for managing HEC in this area include both short term interventions, such as the use of chili pepper deterrents and scaring with noise deterrents, as well as longer term strategies such as improved land use planning, electric fencing at landscape levels and minimizing human development on known wildlife routes. One longer term strategy that has been proposed in this area involves provision of artificial water sources to influence elephant movements and keep animals away from fields during the cropping season. My study aimed to investigate the role of ephemeral surface water on elephant space use and movement in the eastern Okavango Panhandle, Botswana to help inform such management strategies. I found that ephemeral surface water has a significant role in influencing elephant spatial use in the area, particularly during the early and late wet season. As ephemeral pans dried and NDVI (vegetation greenness) decreased, elephants started to move closer to the Okavango Delta and consequently human settlements and fields. However, further investigations into the timing of movements away from ephemeral waterholes and the influence of other environmental factors on elephant movements in the area would be needed before any recommendations can be made regarding artificial water provision in this area.

5.1 Conservation Management implications

Ephemeral surface water has a significant role in determining elephant spatial use and resource distribution in the Okavango Panhandle. Climate also has an influence on elephant distribution. Elephants range widely during the early wet season and return towards the Okavango Delta and human settlements during the late wet (February – April) and early dry season (May – July). This is when there is a peak in HEC incidents, especially crop raiding (Pozo et al., 2017, Pozo et al., 2018), as elephants move south towards the Okavango Delta to access water and other resources. During this time, elephants move closer to human settlements and fields, which increases the chances of human-elephant encounters and crop raiding incidents (Songhurst et al, 2015). Current strategies for managing HEC in this area include both short and long-term interventions. These include strategies to help people and elephants share space and continue to access the resources they need, through informed land use planning and strategically placed mitigation techniques. My findings could contribute to assisting with one intervention being used to assist with improved land use planning in the area, the Land Use Conflict Information System (LUCIS). This system identifies areas of land suitable for agricultural development, settlement development and elephant corridors to help demarcate zones and reduce land use conflicts (Ecoexist, 2015a). Information from studies such as mine could be used to provide model input for the information system, thus informing ongoing HEC management in the area.

In NG11 and 13 the concentration of surface water is towards the southern ends and this is where there are higher concentrations of humans. Areas of higher surface water concentration tend to be preferred by elephants as well and this results in spatial overlap and competition of resources between humans and elephants (Songhurst, 2012) and a higher probability that human elephant conflict will occur in NG11 (Pozo et al., 2017, Buchholtz et al., 2019, Matsika et al., 2020). More research is needed to contribute to these discussions further.

The eastern Panhandle is an interesting study area, where elephants are limited in their movements out of the area due to the northern buffalo and Namibian-Botswana border fence (Songhurst, et al, 2014; Naidoo, et al 2022). During my study period 2014-2017 rainfall patterns were very low in the eastern Panhandle and temperatures were very high when there were no rains. Both extreme drought and above normal rainfall conditions may have negative outcomes for elephants and other wildlife, e.g., hundreds of elephants in the study area are reported to have died of toxic algae in water ponds in 2020 after good rainfall (van Aarde et al., 2021). Although a separate study by Veerman et al. (2022) could not confirm cyanobacteria as a trigger for the mass elephant die-offs it demonstrated that they experienced an exponential growth in cyanobacteria, possibly due to climate change induced temperature rises. Anthropomorphic interventions such as artificial water holes in a bounded area like NG 11 and 13 with an already increasing elephant population may only result in higher birthrates (due to perennial water availability) and degradation from higher animal concentration around water holes (Wato et al., 2016). In addition, a study in Hwange National Park, Zimbabwe observed drought induced increase in the predation rate of elephants calves (Loveridge et al., 2006). The authors argued that this vulnerability might be due to aggregation by large herds around limited resources resulting in wide ranging movement when seeking resources.

Timely provision of artificial water has been proposed as a management strategy to influence elephant movements in the eastern Okavango Panhandle and keep elephants away from fields during the cropping season. Artificial waterholes can influence elephant movements (Chammille-Jammes, et al., 2007), however, there are also negative implications in the provision of artificial water that need to be considered (Selebatso et al., 2018). Further research would be needed to determine the timing of ephemeral water drying up in relation to elephant movements close to human settlements and fields, before any recommendations regarding artificial water provision to alleviate HEC could be made. Elephants in the eastern Okavango Panhandle do move across international boundaries into

Namibia and Angola and actions in neighbouring countries can affect elephants in Botswana. For example, van Aarde et al. (2021) reported that elephants are cautious about crossing the border fence straddling Botswana's northern fence into Namibia, due to hunting on the Namibia side. The border fence itself has also been identified as a barrier to elephant movements, particularly females in this area (Naidoo et al, 2022). The transboundary nature of movements, therefore, calls for appropriate elephant management strategies that are multilateral in nature in order to facilitate elephants to freely move northwards out of NG11, 12 and 13, and reduce HEC in the area.

5.2 Implication of HEC

Results indicate that the seasonal resource needs of the elephants, their type, distribution and quality, most importantly how the elephants move around the landscape to satisfy their needs must be taken into account when carrying out land use planning around human settlements that are in proximity to elephant habitat and movement corridors. Therefore, stakeholder engagement in planning and any elephant management interventions is critical as communities living around elephants also need to be empowered with knowledge and reliance skills to co-exist with elephants. This is important when considering the semi-aridness of Botswana where rainfall is erratic, and resources variably distributed. It is critical also that human developments should be controlled and not encroach in areas reserved for wildlife management. Human developments should take cognisance of elephant movement corridors and while absolute separation may not be possible, intrusion into known elephant corridors must be legally prohibited in order to protect them from business interest along the Okavango River east bank. Further, elephant intrusion deterrents such as use cluster farming and electrify fencing, use of chilli pepper, crop-raiding resistant crops, and other mitigation measures should be used.

Artificial water provisioning is another effective management tool that can be used to influence elephant movements within their areas and reduce HEC. However, they can affect seasonal movements and resource use. The water pumping regime should be regulated to minimise habitat destruction and unintended animal die offs due to food shortage and waterhole pump faults. A provision of artificial water holes may have the effect of reducing HEC as a result of elephants being drawn away from human settlements, especially during the dry season. However, this is premised on the animals preferring the water holes rather than walking to the river. Further research investigating the temporal patterns of elephant movement and ephemeral water availability are needed to make recommendations on such management strategies.

The findings of my study also indicate long distance movements in the early dry and restricted movements in the dry season when water and resources only occur in abundance around the Okavango River. The conflict at Seronga is exacerbated by scarcity and competition for surface water especially during the dry season when the only source of surface water is the perennial Okavango River. There is a series of human settlements, linearly arranged along the banks of the Okavango River, and their rapid growth in the recent past, and expansion of agricultural fields have gradually encroached upon the known elephant movement corridors, hence restricting elephant pathways to and from the Okavango River, and excerbating HEC. HEC escalates in March-May when available wild forage and ephemeral water sources become limited, and elephants move and congregate around the Okavango River where farmers crop fields also occur.

5.3 Recommendations

1. Further research is needed on the timing of the drying and filling up of the ephemeral waterholes and the amount of time elephants spend away from these water sources when they are dry during the dry season.
2. Further research should also explore the importance of other environmental factors such as hunting across the international boarder, water provision, elephant corridors and the use of chilli fences by farmers in influencing the movement of elephants in the area.
3. Remotely collected data can have inaccuracies of variable magnitudes depending on the data acquisition tools and processing techniques used. Ground truthing is therefore often used as an additional undertaking to verify the remotely sensed data collected and improve its accuracy. This study was limited in embarking on field verification exercises for locations of ephemeral waterholes. Hence, it is recommended for future studies to incorporate ground truthing when processing and interpreting remotely sensed data in order to improve accuracy.
4. The methods employed for derivation and mapping of surface water can be tested further by other studies around the country in areas that experience HEC due to elephants (e.g., Linyanti, Boteti and Central Kalahari Game Reserve)
5. The methods used in this study and the data generated can serve as a baseline for further studies and decision making on land use and efforts to enhance human-elephant co-existence and sustainable conservation, especially where the common resource is surface water.
6. The study found out that elephants are characterised by large home ranges during the wet season (early and late), and that male elephants in particular cover longer distances in the landscape. Green forage and water are critical resources determining the sizes of the home ranges and distance covered. These observations have important implications on the utilization of space by elephants and people. The findings of this research may inform new land use policies that minimise human activities along known elephant movement corridors while promoting agricultural programs that encourage co-existence through timing of crop-production and harvesting activities with greater presence of elephants near water holes and away from human settlements.

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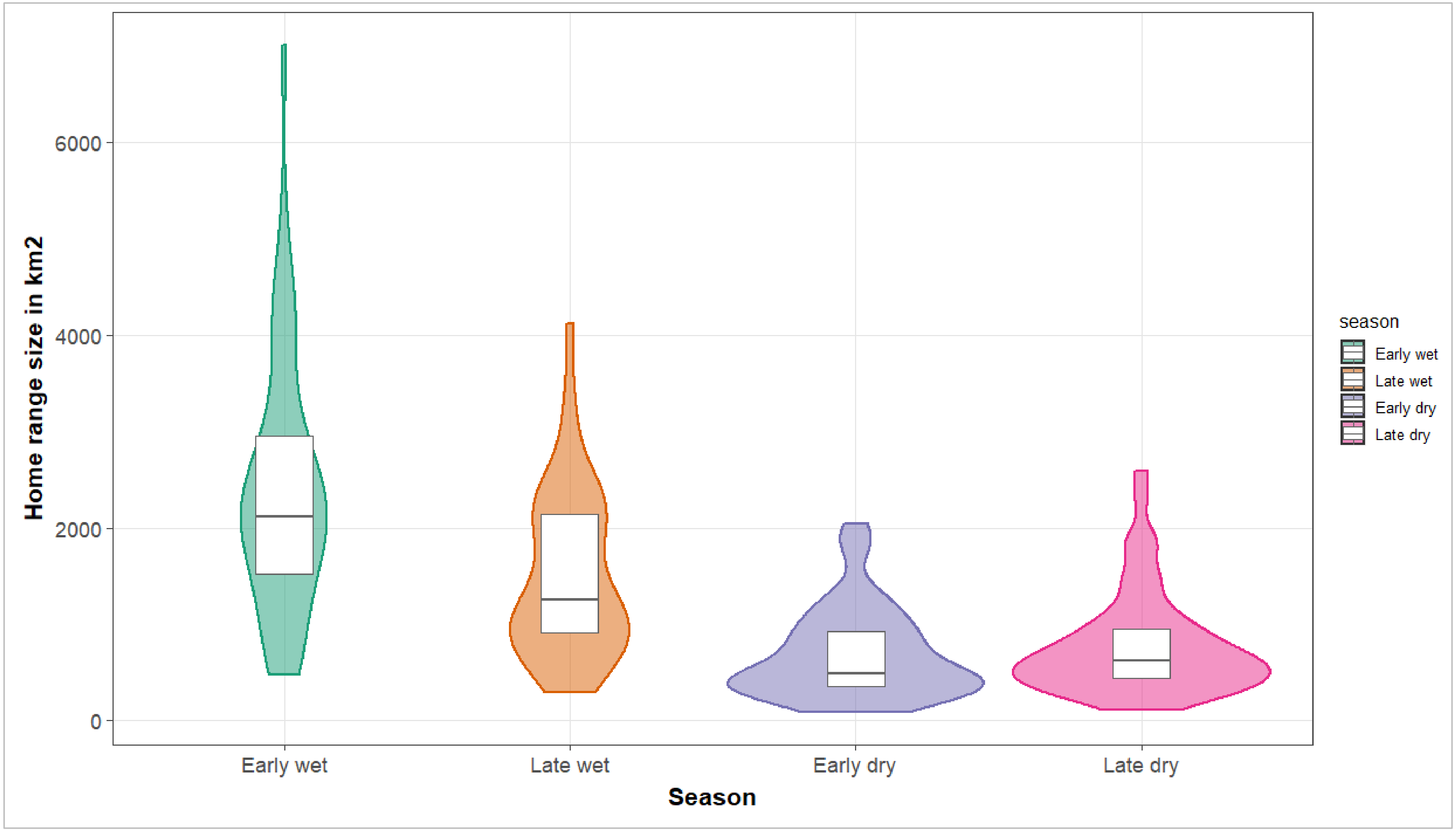
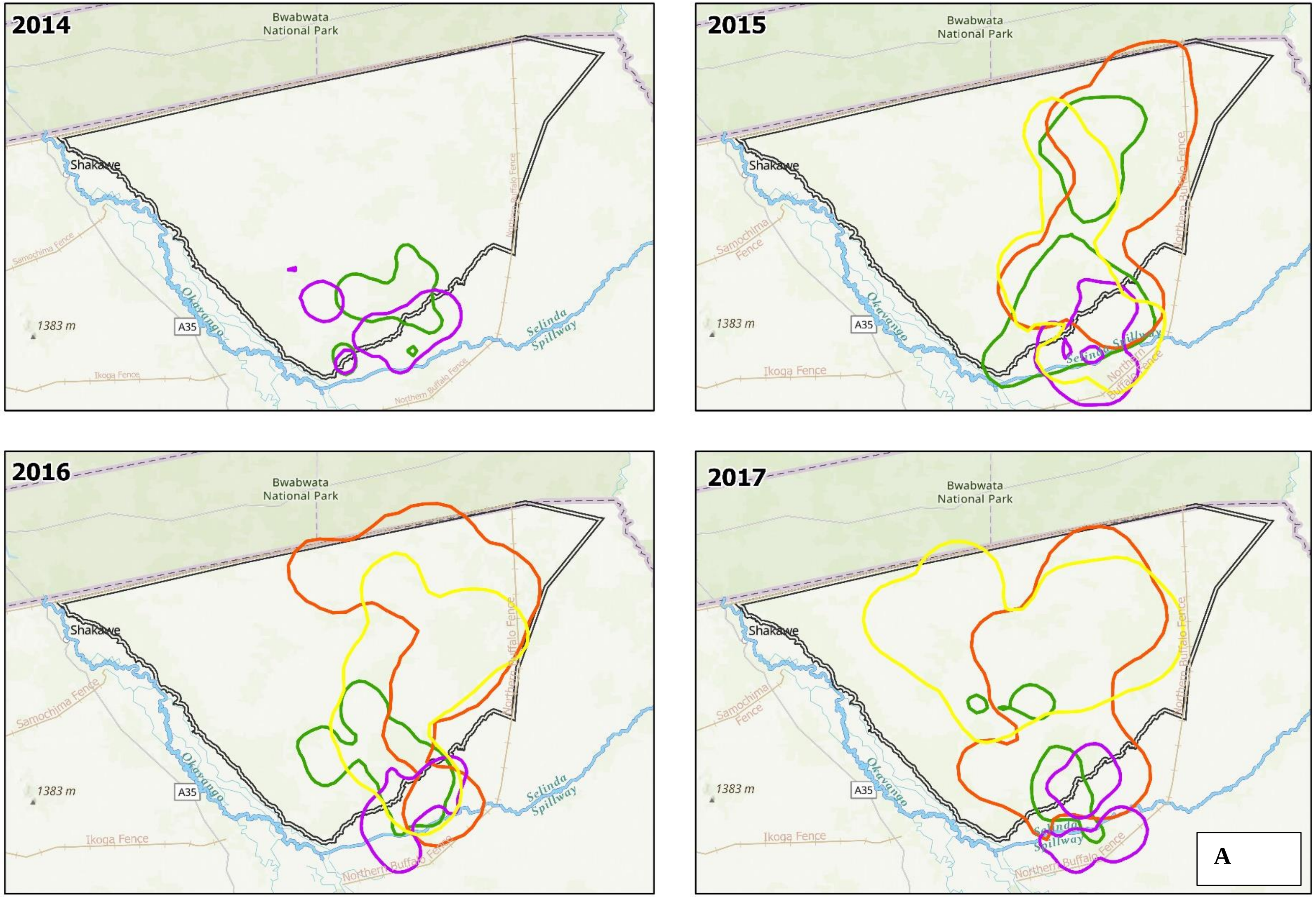
7 APPENDICES

Supplementary information for the thesis.



Appendix 1. Seasonal home range size for male and female in the early wet, late wet, early dry, and late dry in the Eastern Okavango Panhandle, Botswana

G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Ikoga Fence
Selinda Spillway
Northern Buffalo Fence
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Okavango
Ikoga Fence
Northern Buffalo Fence
2016
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Ikoga Fence
Selinda Spillway
Northern Buffalo Fence
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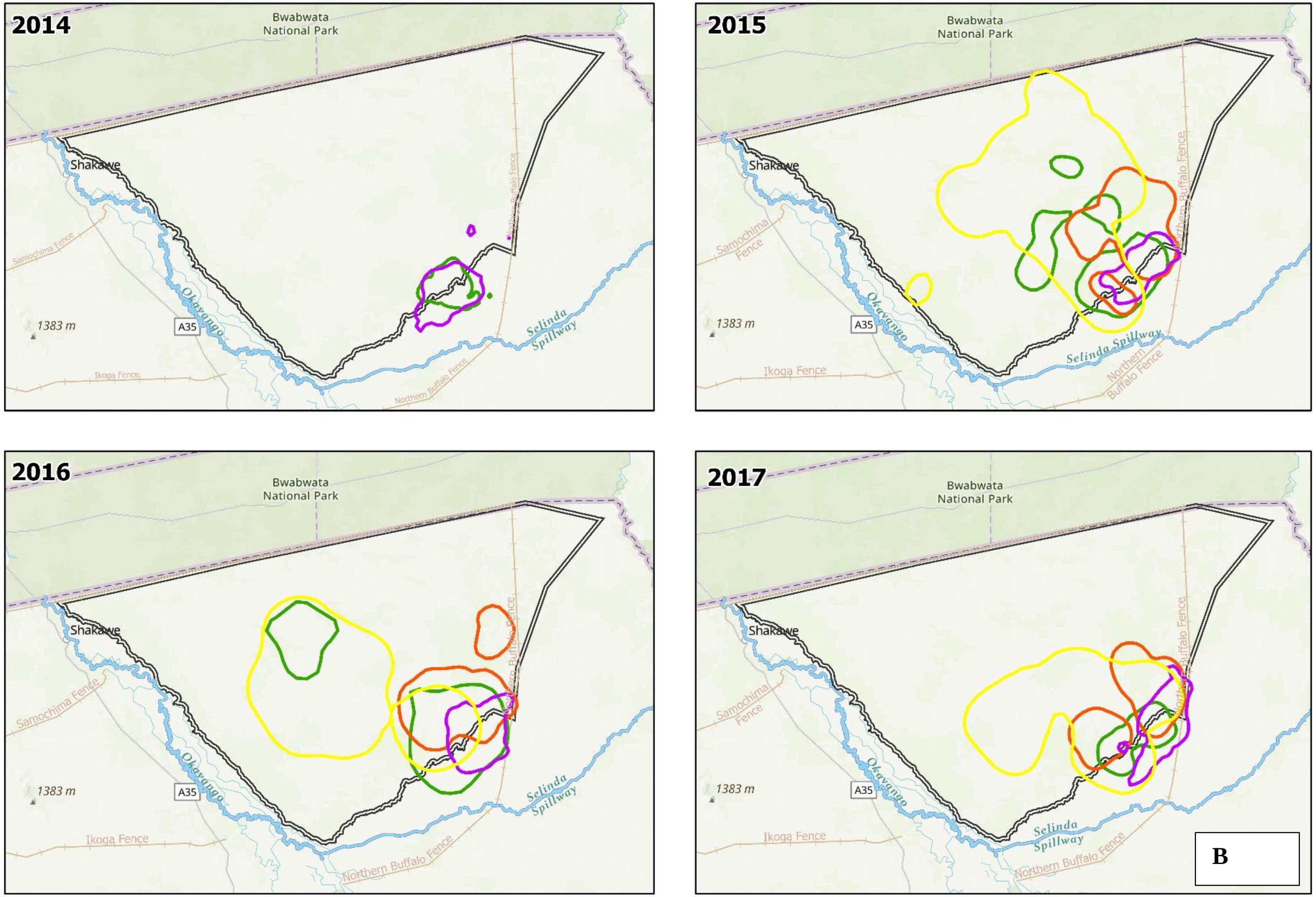
Okavango
Ikoga Fence
Selinda Spillway
Northern Buffalo Fence
A

Howard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Northern Buffalo Fence
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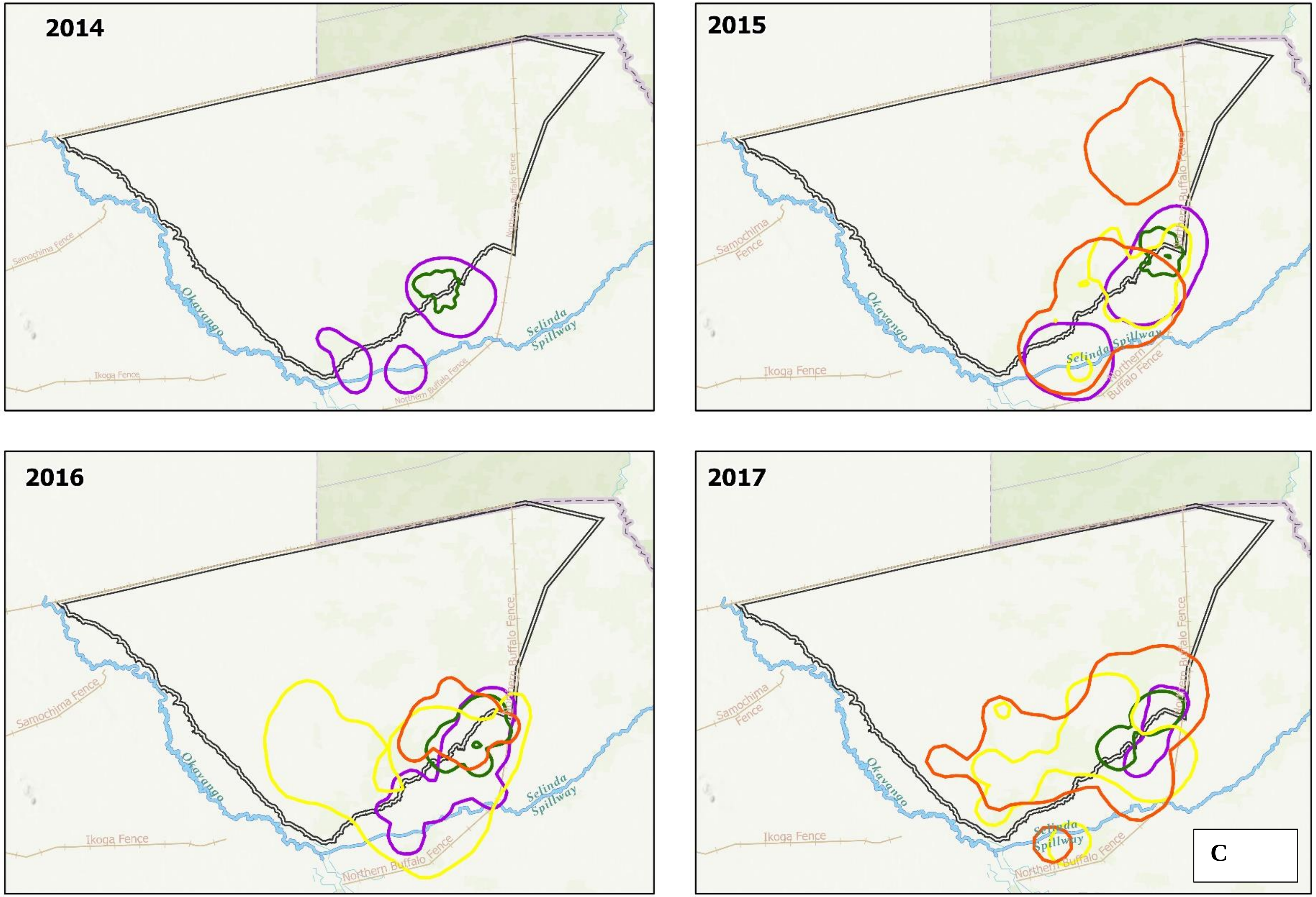
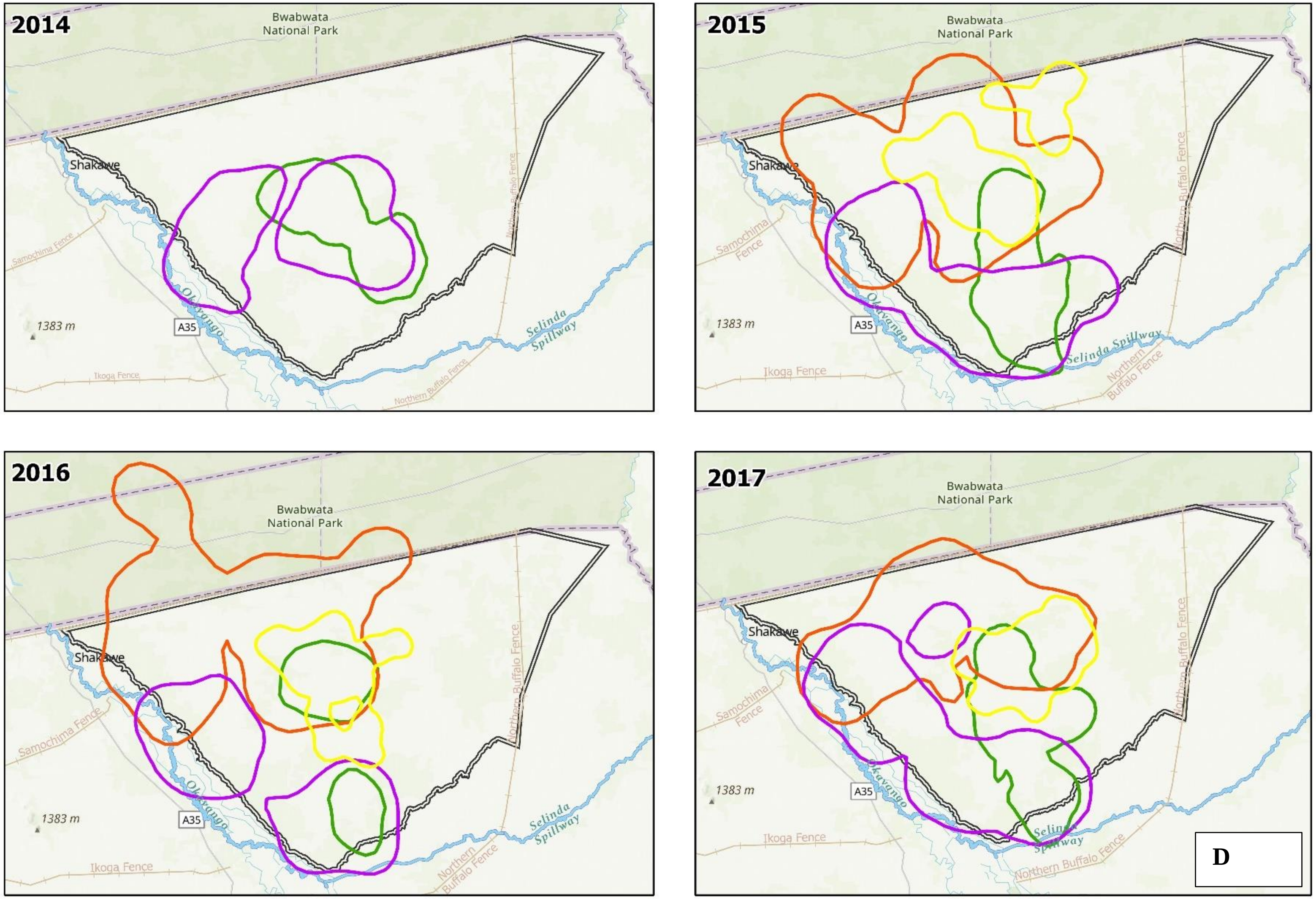
The Bachelor



Whiskey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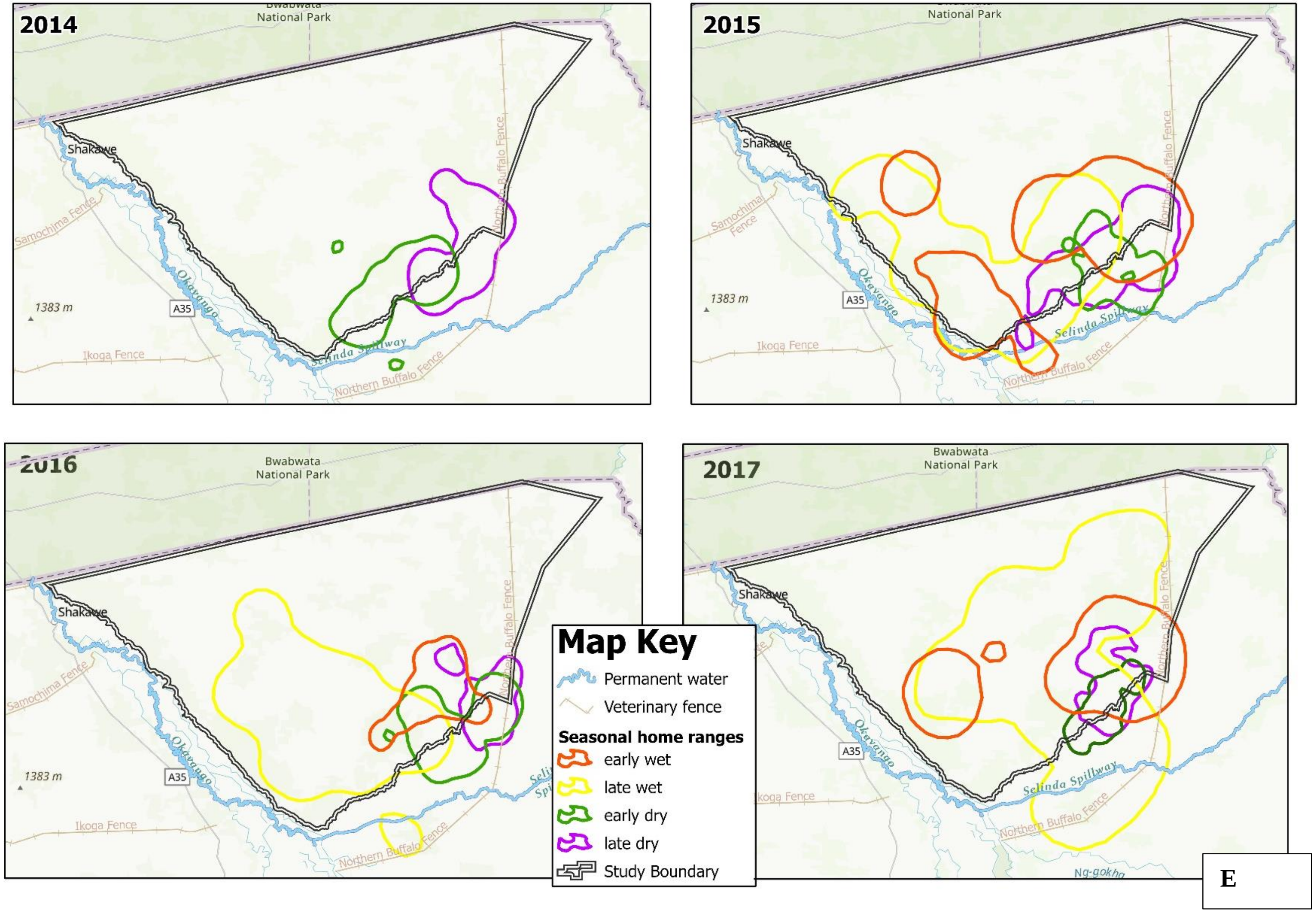
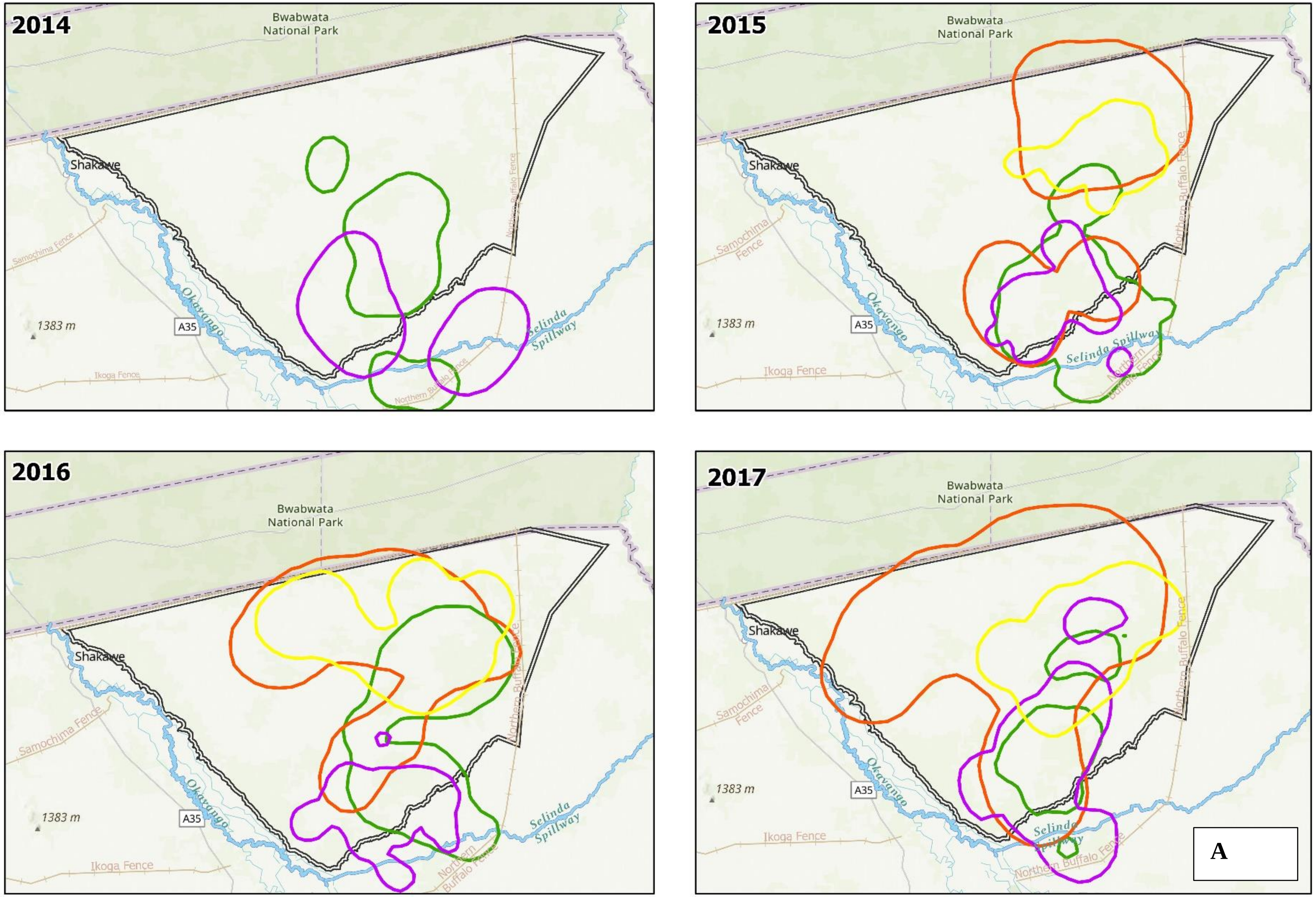
Chan



Appendix 2. Examples of male seasonal home ranges for (A - G; B – Howard; C- The Bachelor; D – Whiskey and E Chan) in the early wet, late wet, early dry and late dry between 2014-2017, occurring at NG11 & NG13 in the eastern Okavango Panhandle.

Amantle



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Ikoga Fence
Northern Buffalo Fence
2017
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Okavango
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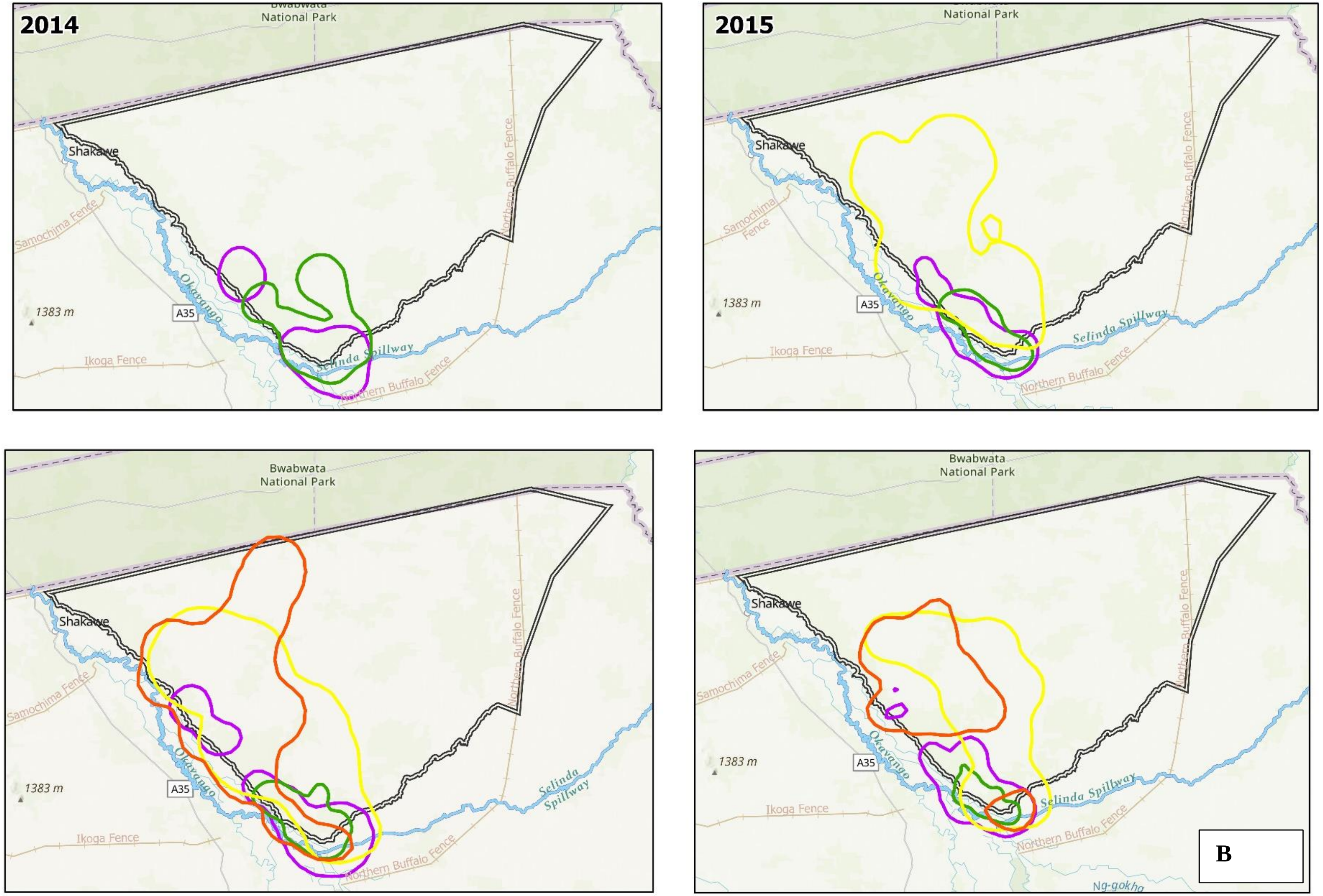
Ikoga Fence
Northern Buffalo Fence
A

Whisper



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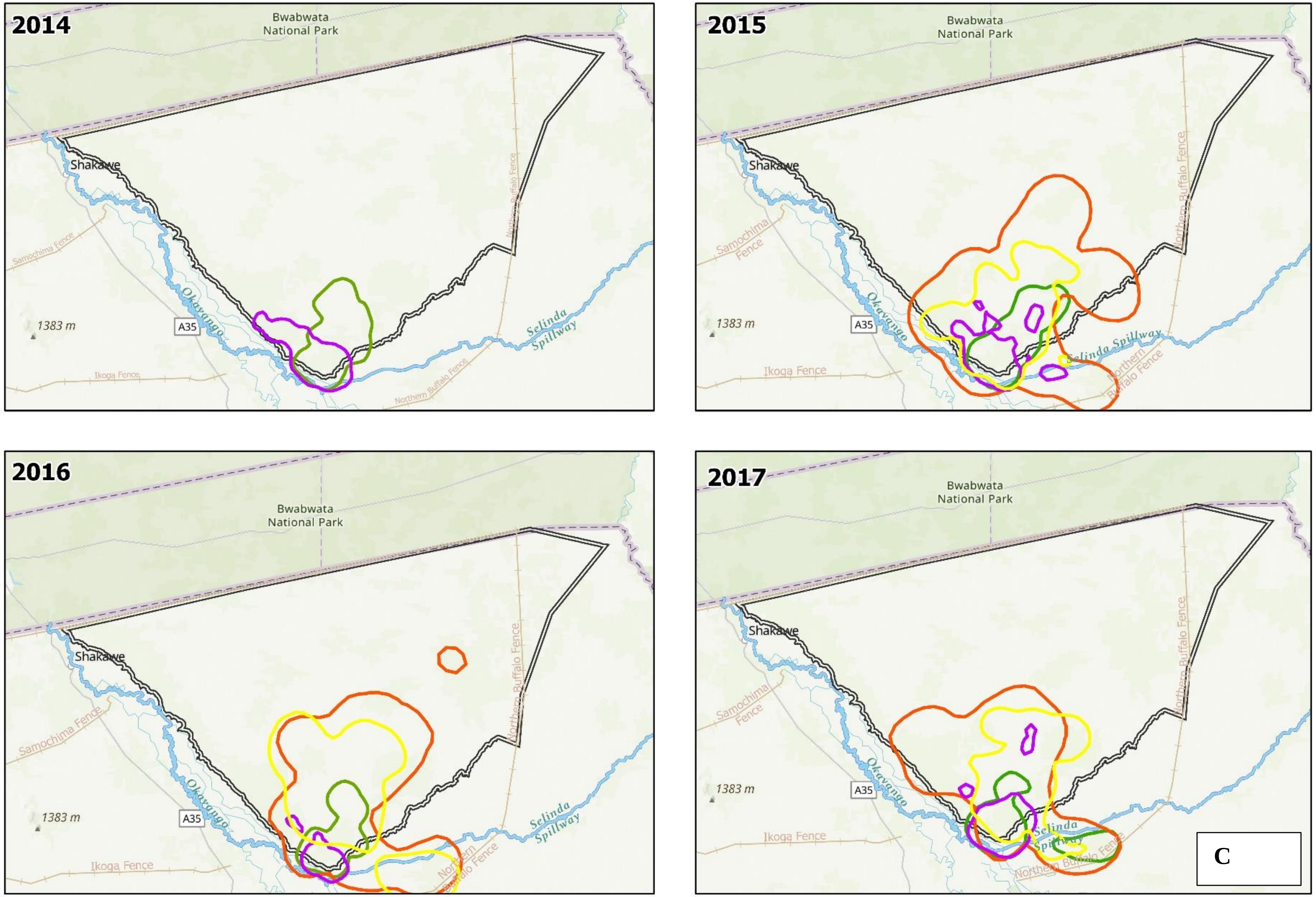
B

Ebby



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Selinda Spillway
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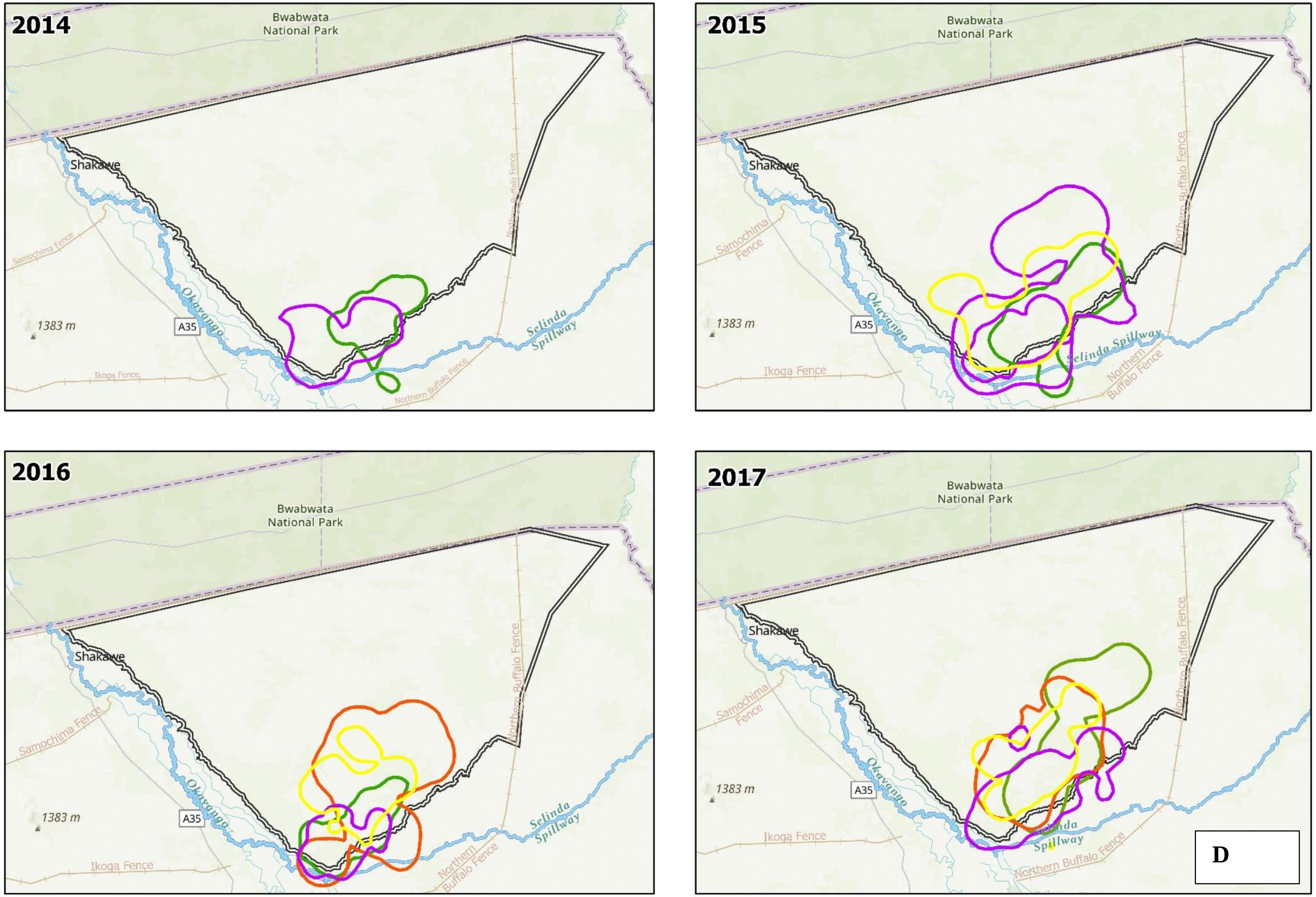
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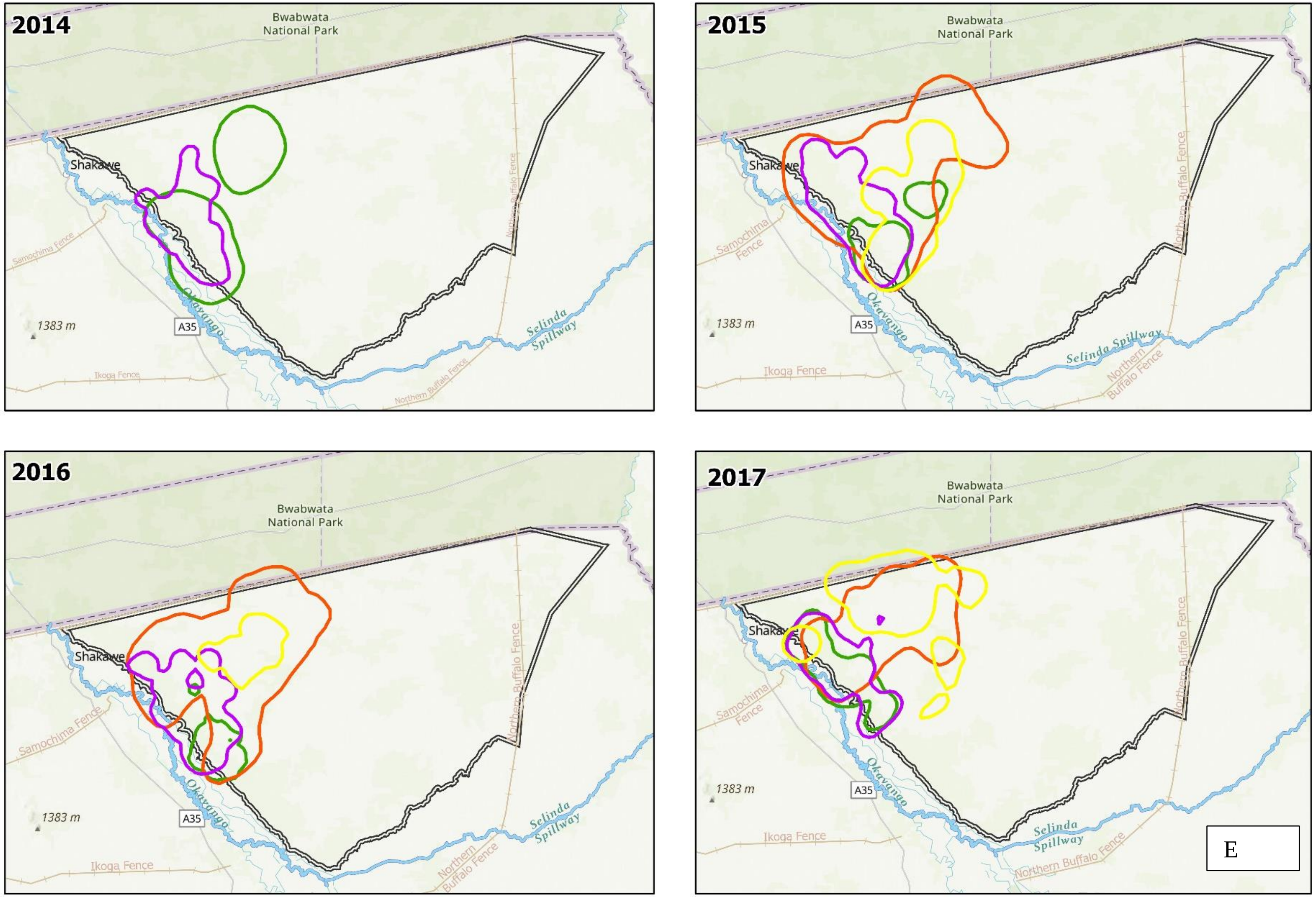
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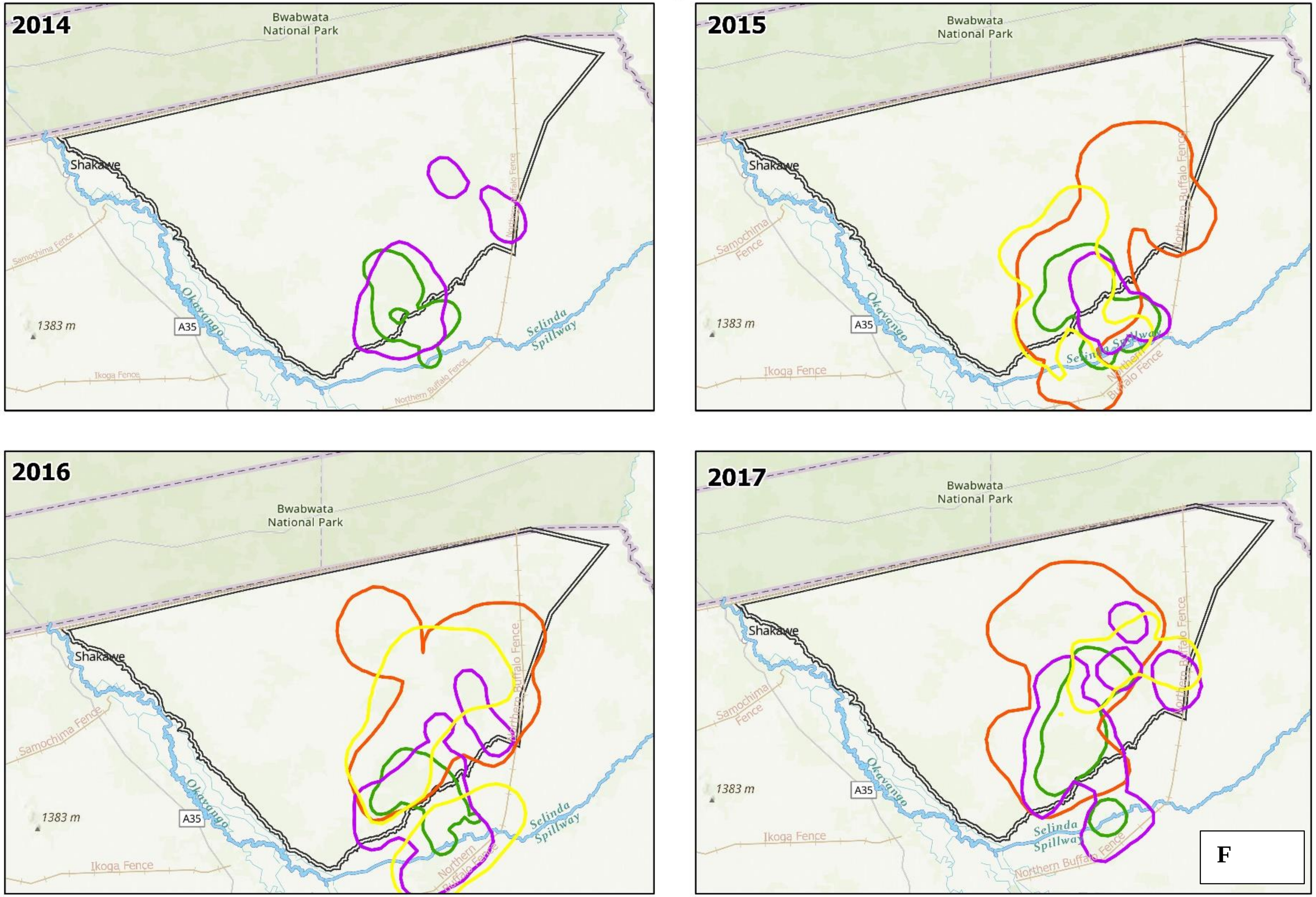
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Northern Buffalo Fence
F

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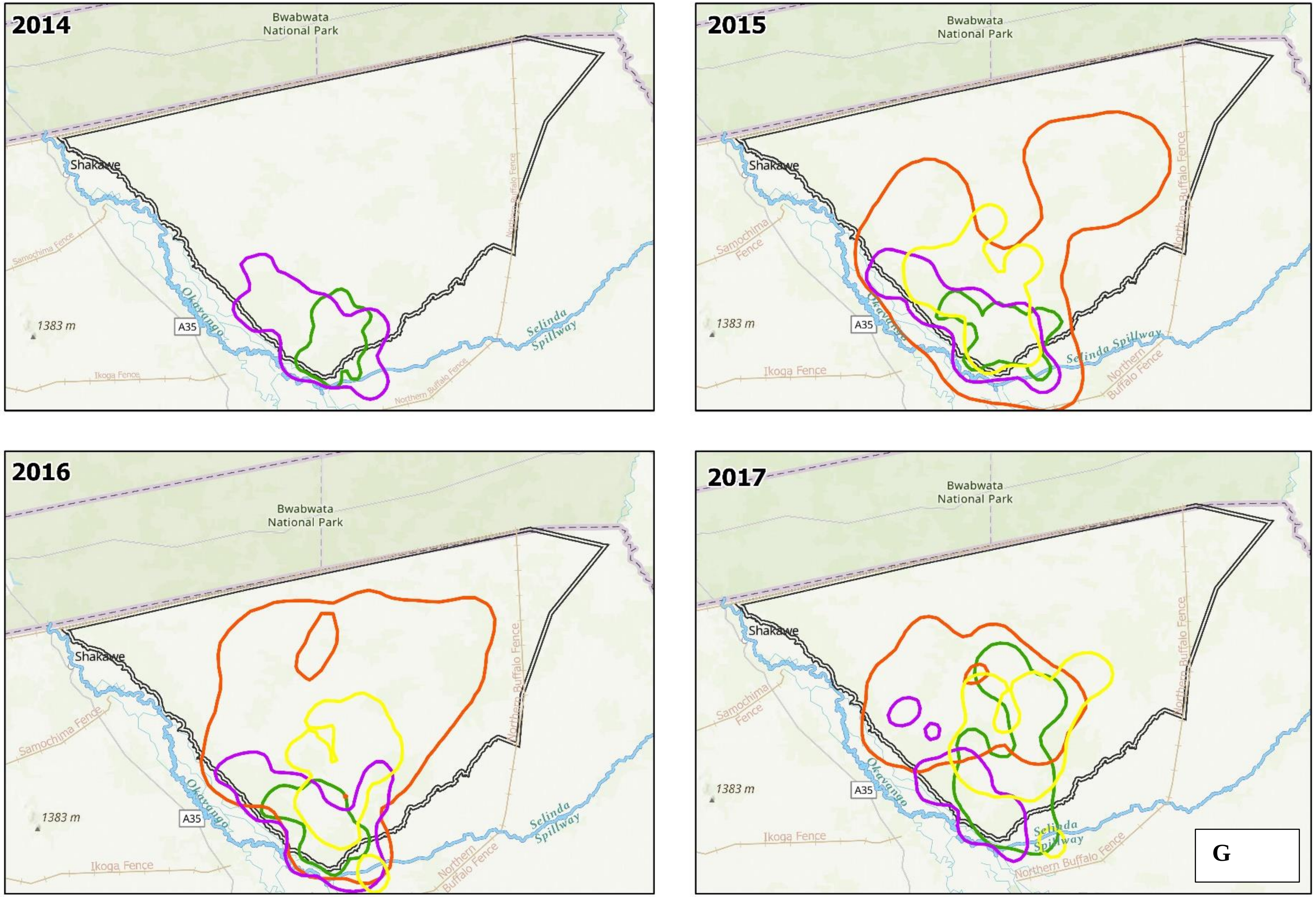

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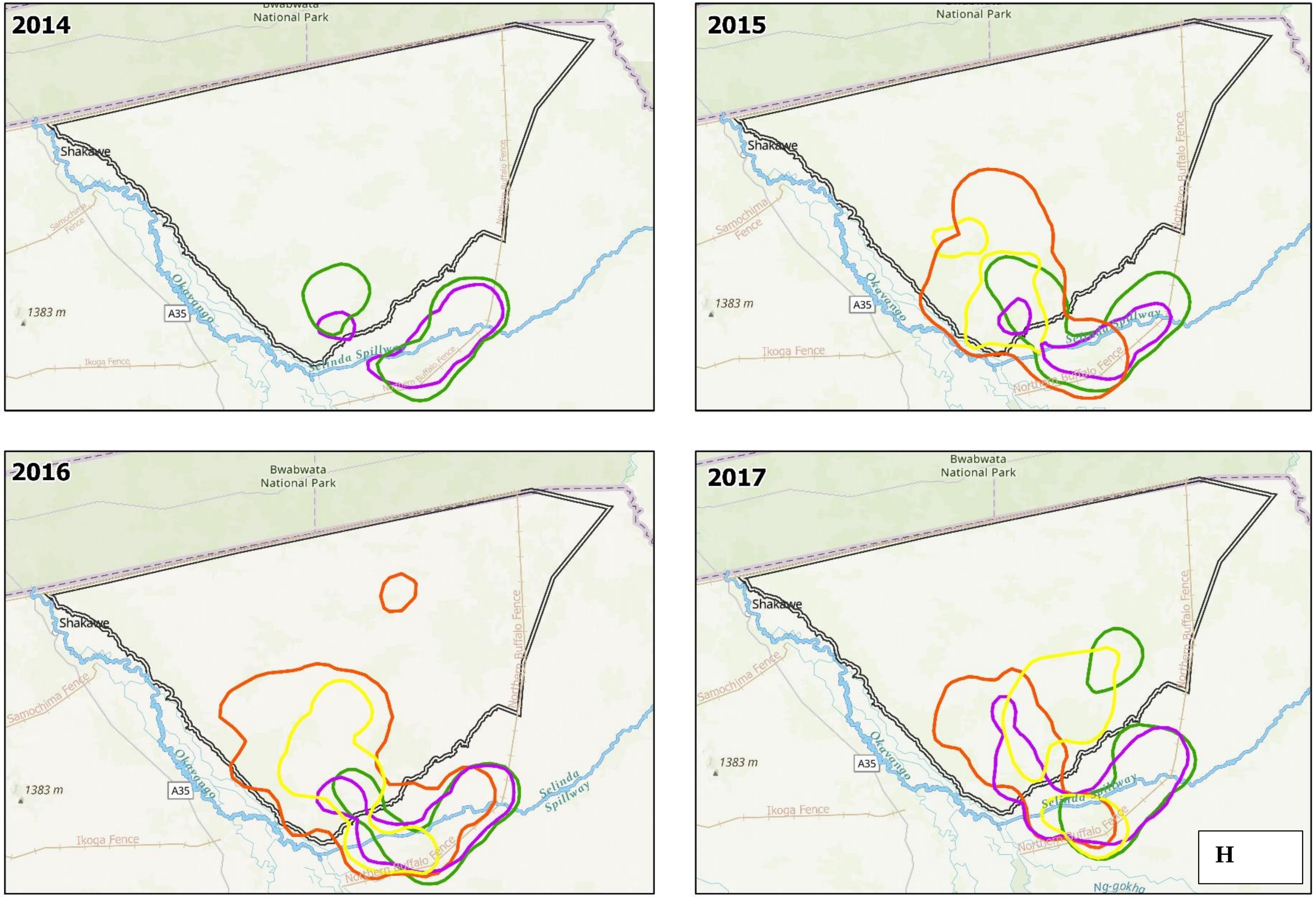
G

Pille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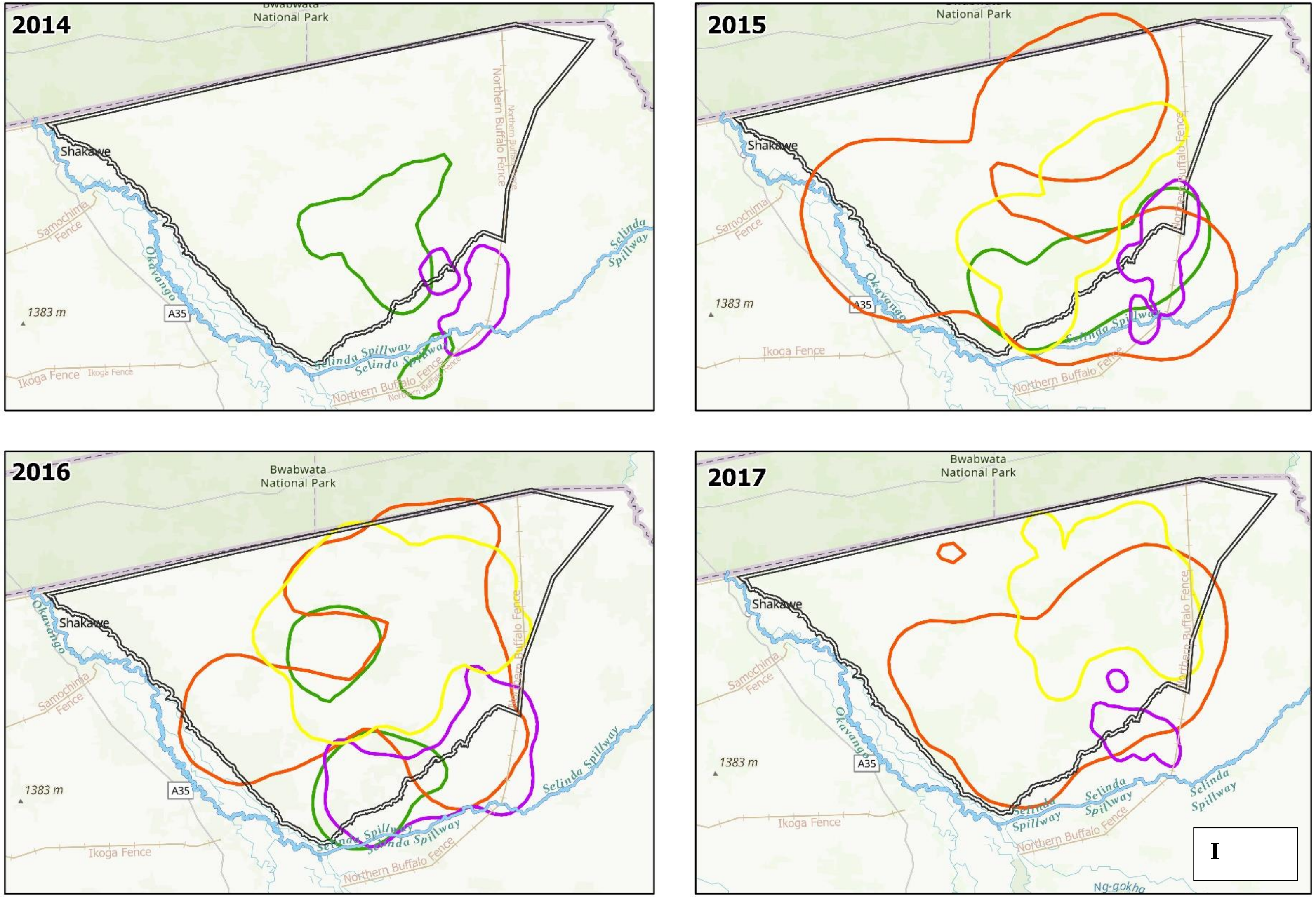
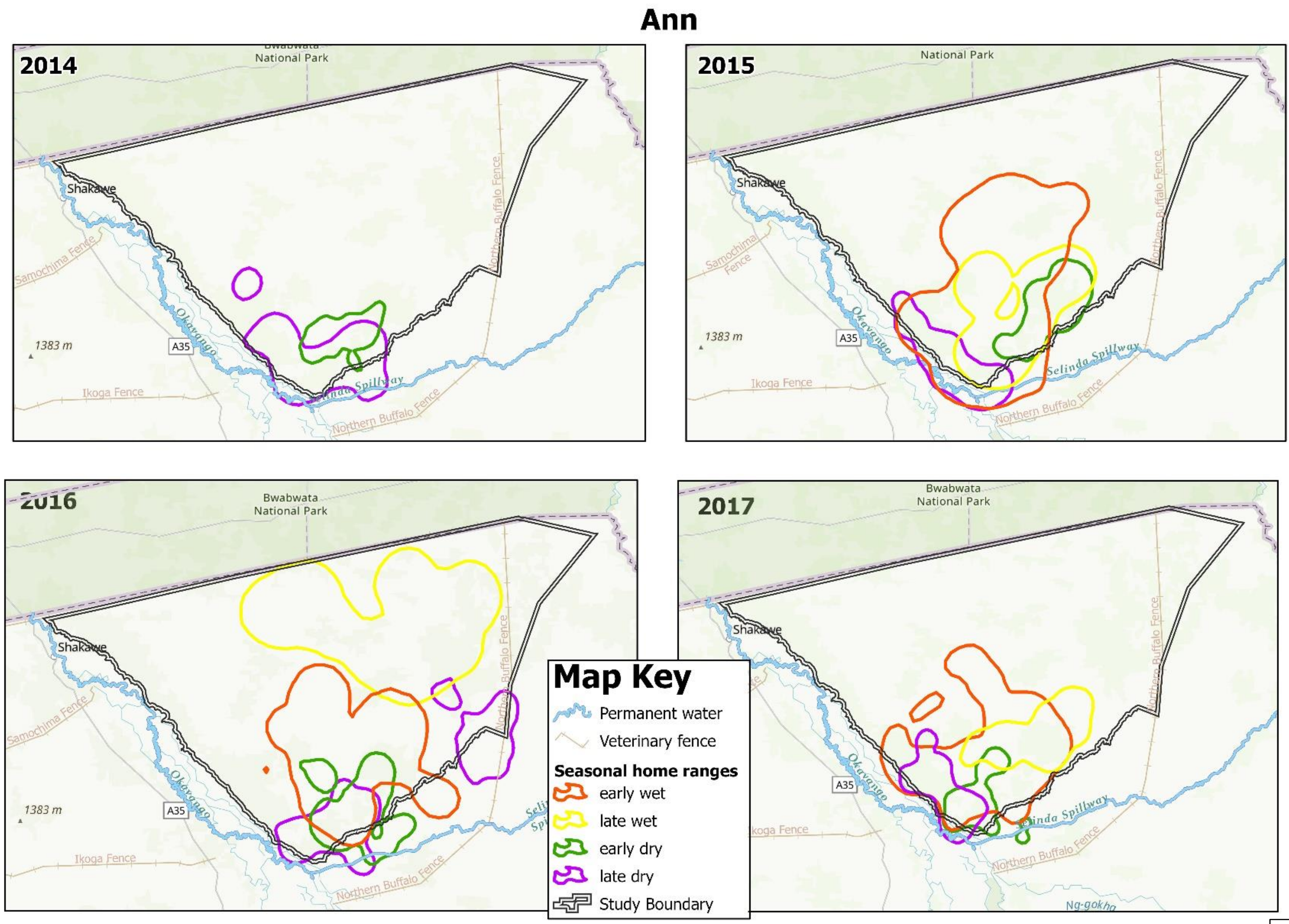
Samochima Fence
1383 m
A35
Okavango
Selinda Spillway
Ikoga Fence
Northern Buffalo Fence
2017
Bwabwata
National Park
Shakawe
Samochima Fence
1383 m
A35
Okavango
Selinda Spillway
Ikoga Fence
Northern Buffalo Fence
Ng-gokha
H

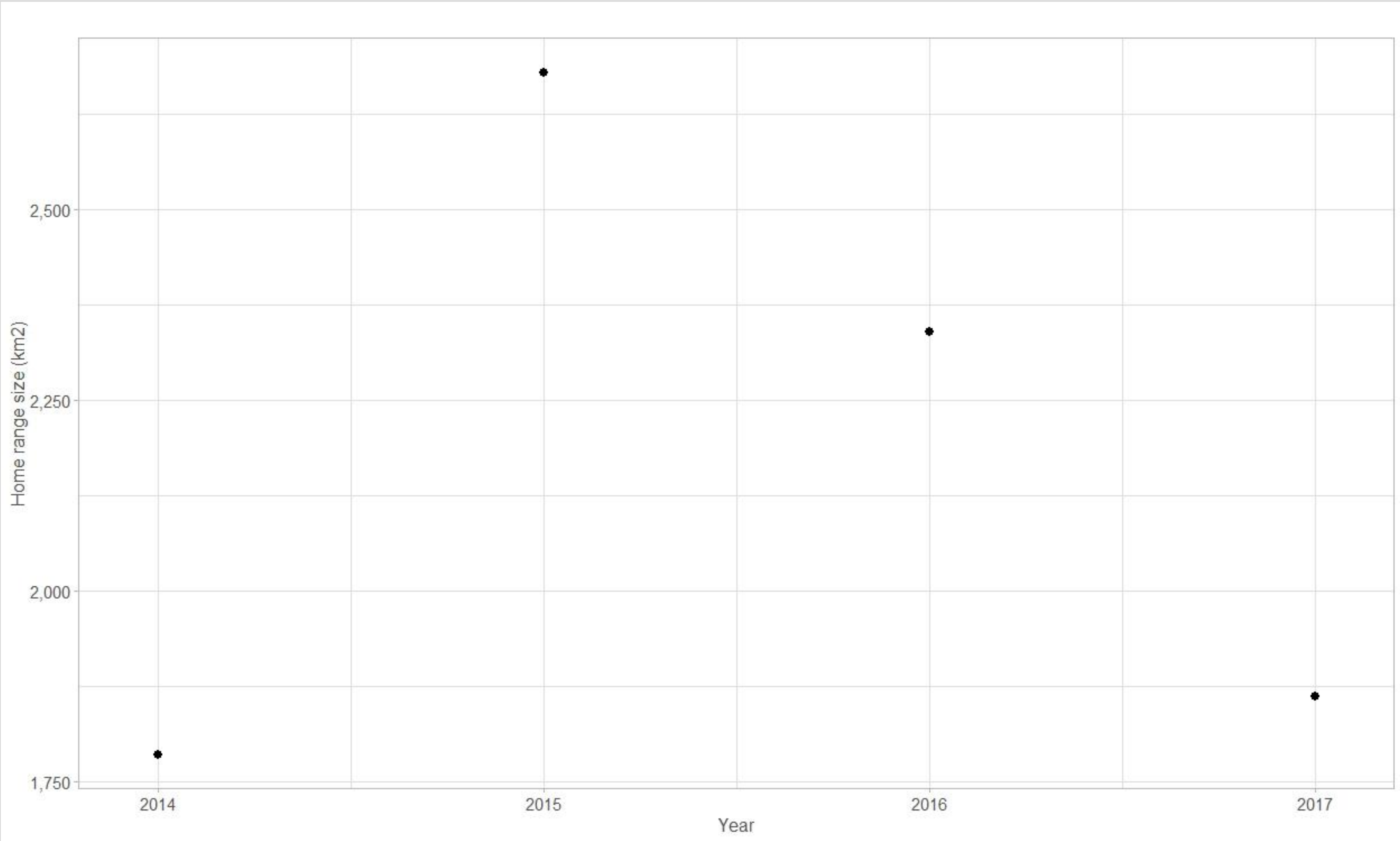
Rain


2014
2015
2016
2017
Bwabwata
National Park
Shakawe
Samochima
Fence
Okavango
1383 m
A35
Ikoga Fence
Selinda Spillway
Northern Buffalo Fence
Ng-gokha
I

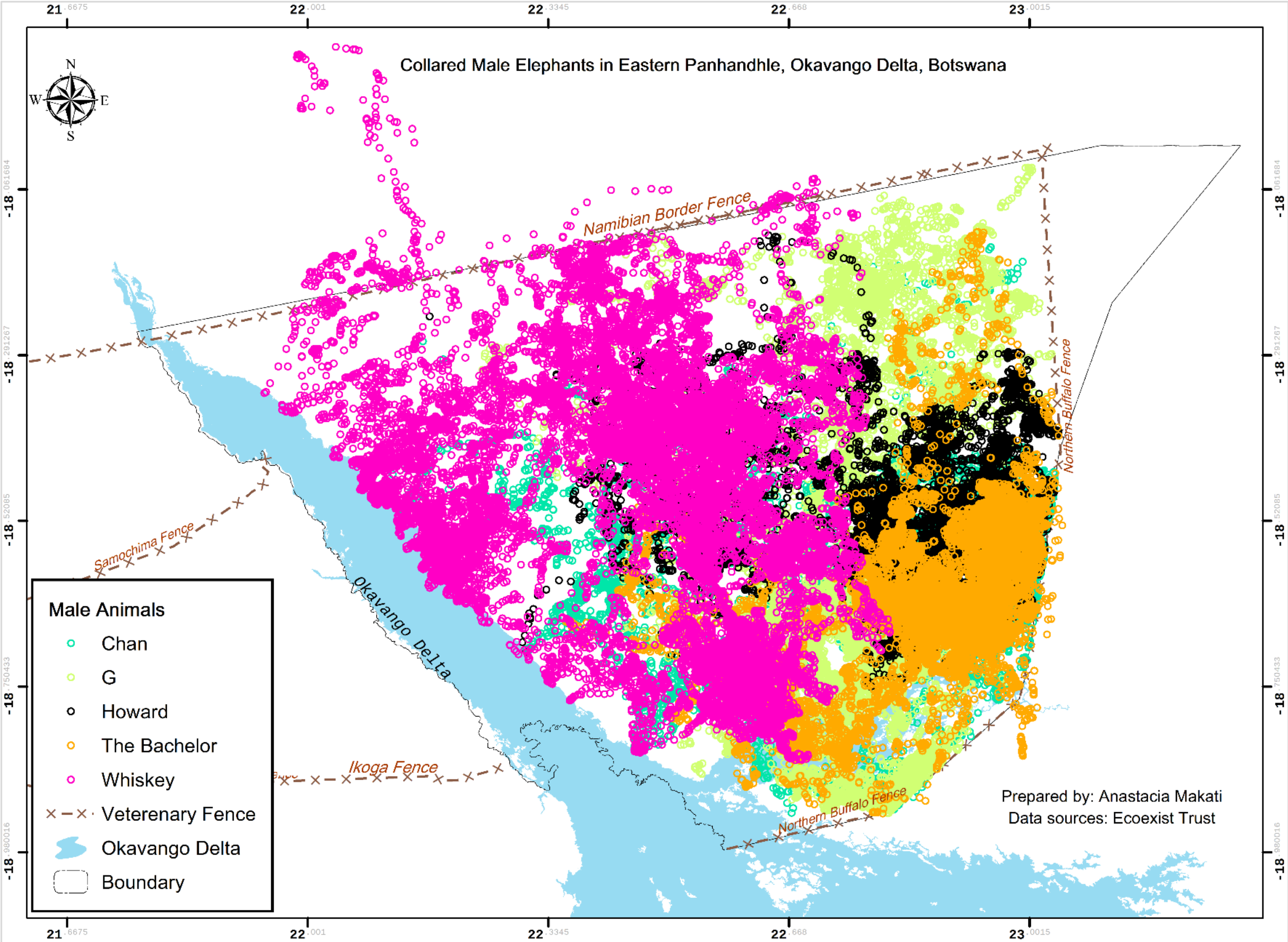


J

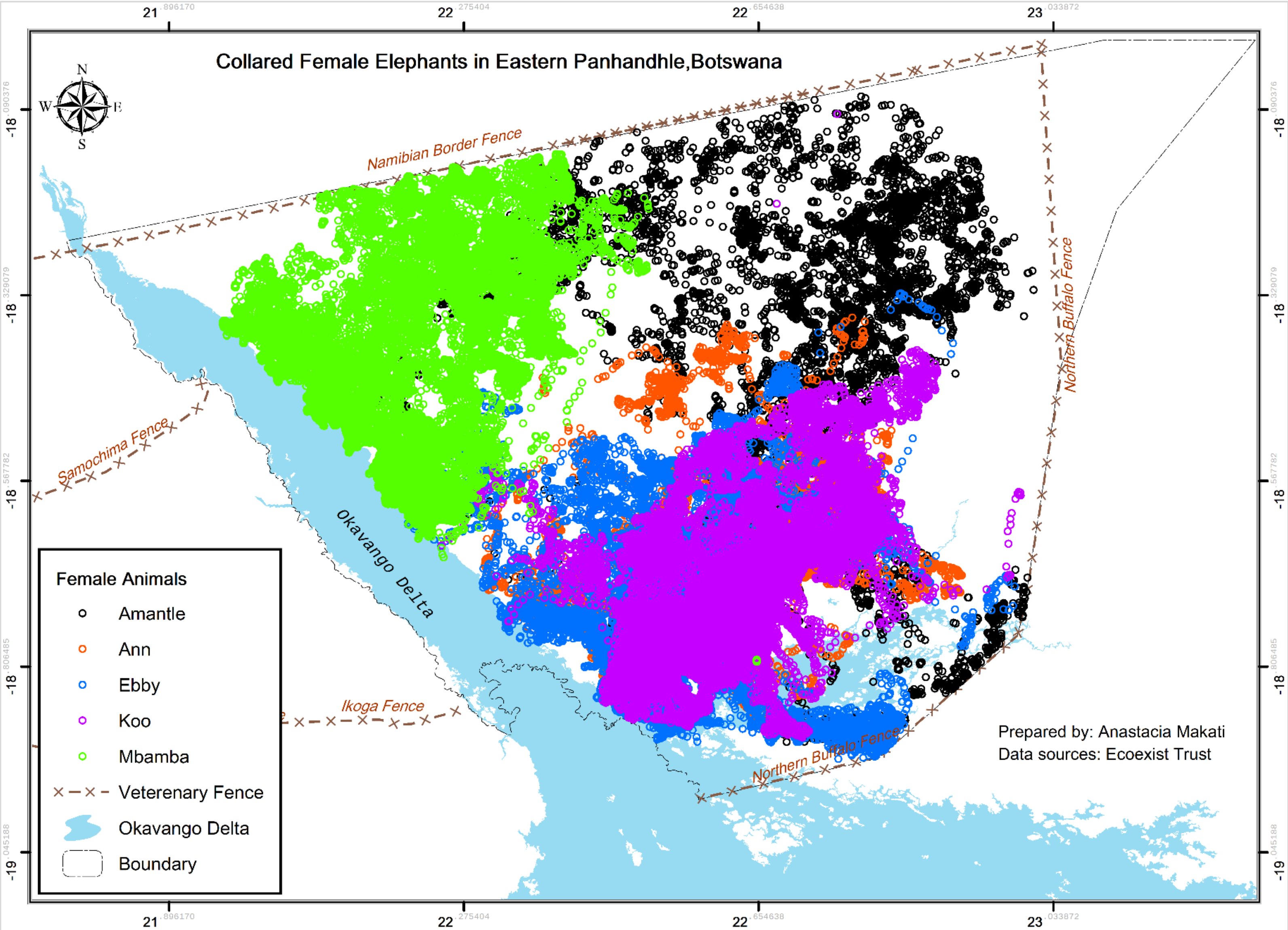
Appendix 3. Examples of female seasonal home ranges from (A - Amantle; B – Whisper; C- Ebby; D – Koo; E Mbamba; F Mpule; G Nare; H Pille; I Rain and J Ann) in the early wet, late wet, early dry and late dry between 2014-2017, occurring at NG11 & NG13 in the eastern Okavango Panhandle.



Appendix 4. Annual Home ranges in the eastern Okavango Panhandle between 2014-2017. Home ranges were calculated using kernel density estimation



Appendix 5. Male elephants, Whiskey moving to Namibia, Angola and back to the study area.


Collared Female Elephants in Eastern Panhandhle,Botswana
N
W
E
S
Namibian Border Fence
Samochima Fence
Okavango Delta
Ikoga Fence
Northern Buffalo Fence
Northern Buffalo Fence
Female Animals
Amantle
Ann
Ebby
Koo
Mbamba
Veterenary Fence
Okavango Delta
Boundary
Prepared by: Anastacia Makati
Data sources: Ecoexist Trust
21
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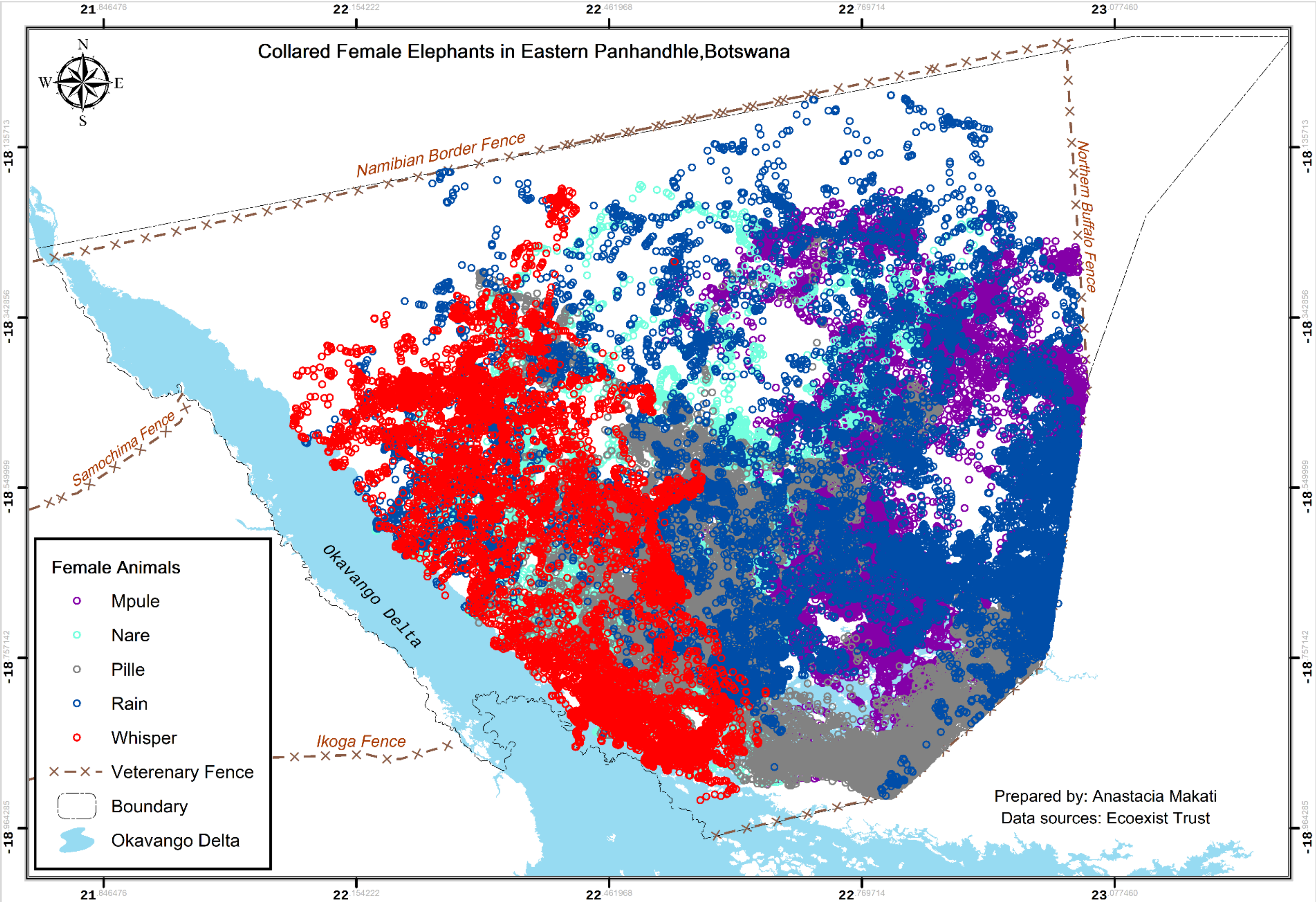
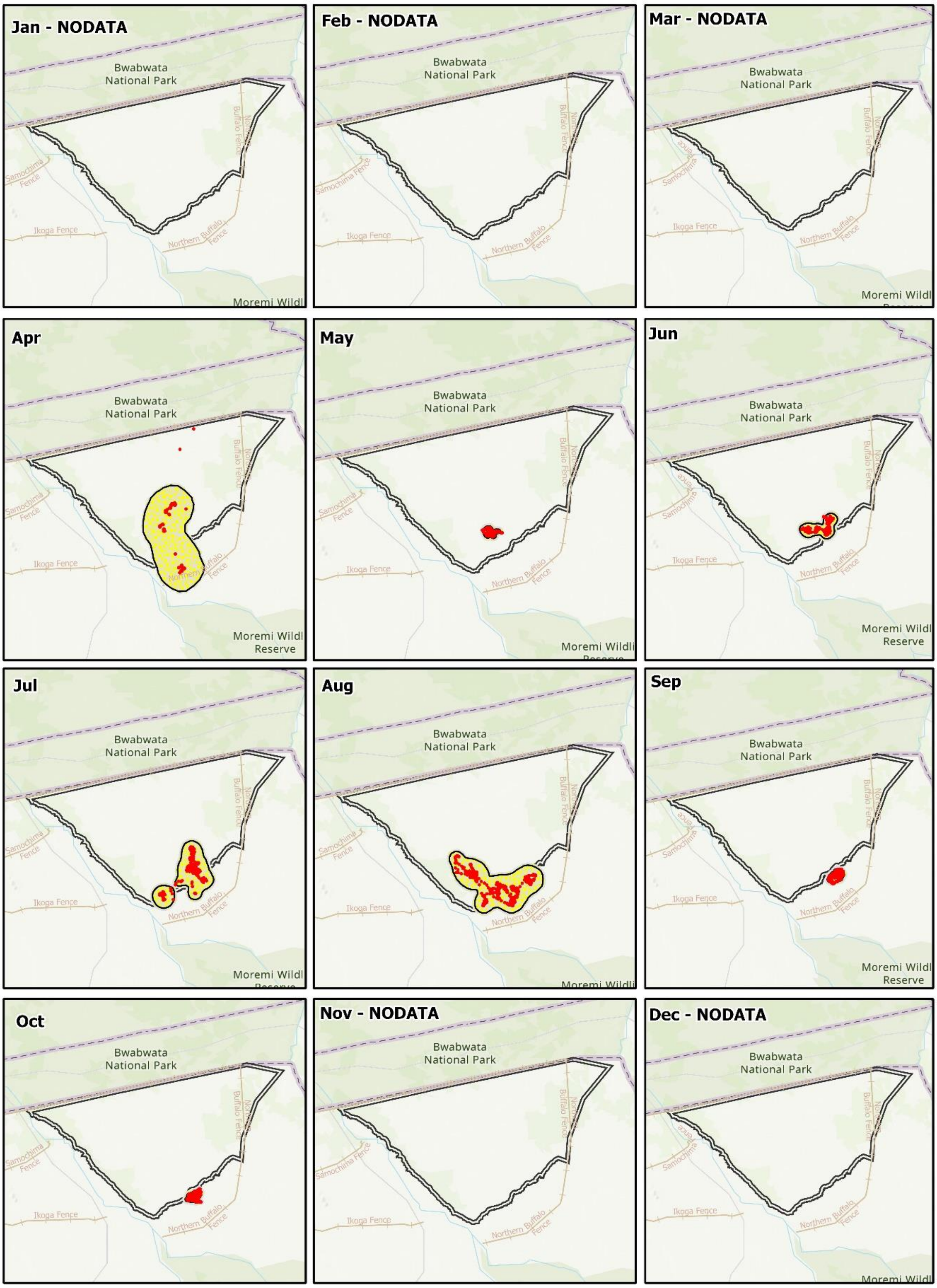
23
-18
-18
-18
-18
-19



Appendix 6a-b. Female elephants collared in the eastern Okavango Panhandle between 2014-2017

G in 2014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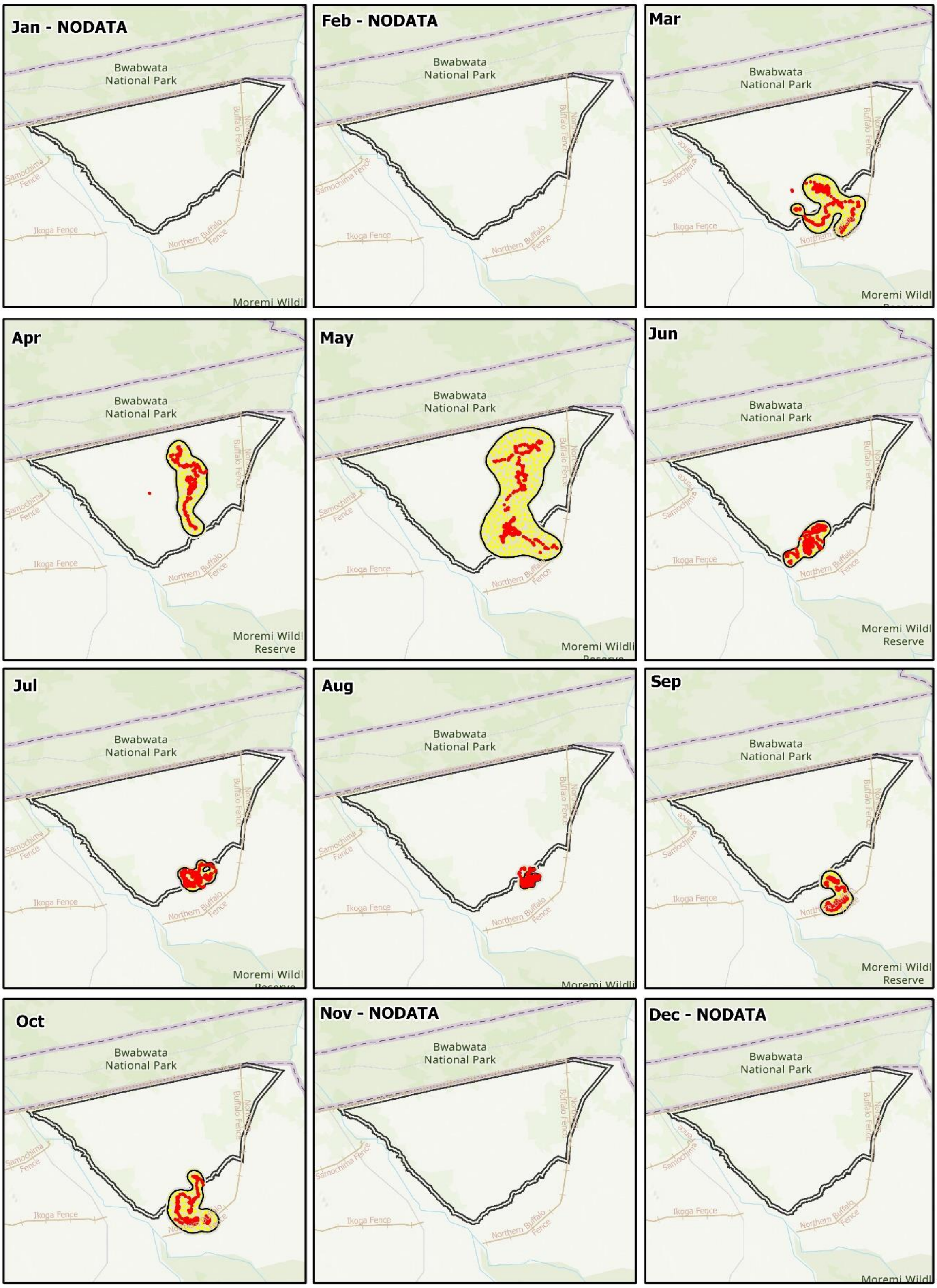
Nov - NODATA
Dec - NODATA
Bwabwata
National Park
Buffalo Fence
Samochima Fence
Ikoga Fence
Northern Buffalo Fence
Moremi Wildl
Reserve

G in 2015



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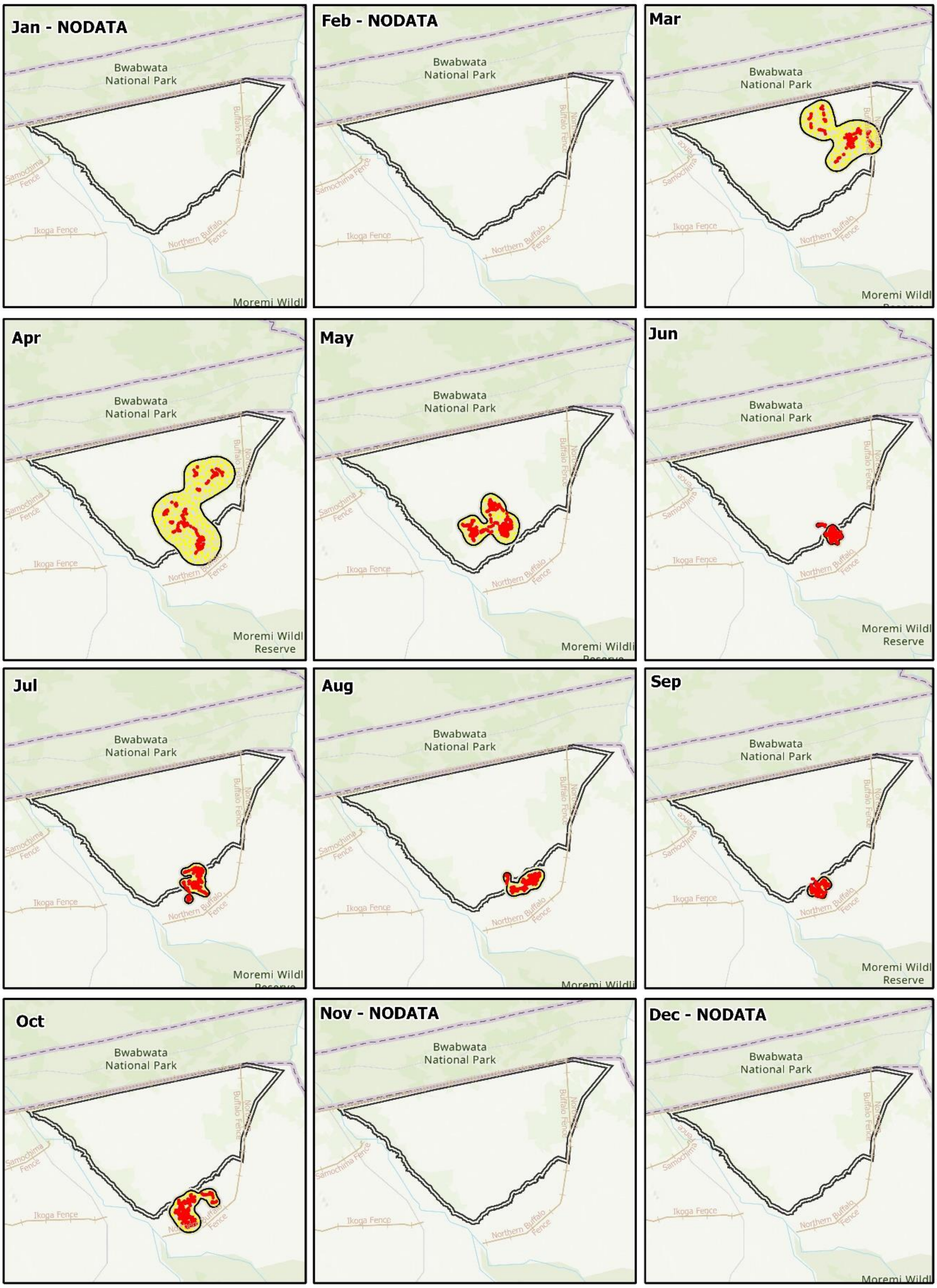
Bwabwata National Park
Buffalo Fence
Samochima Fence
Ikoga Fence
Northern Buffalo Fence
Moremi Wildl
Reserve

G in 2016



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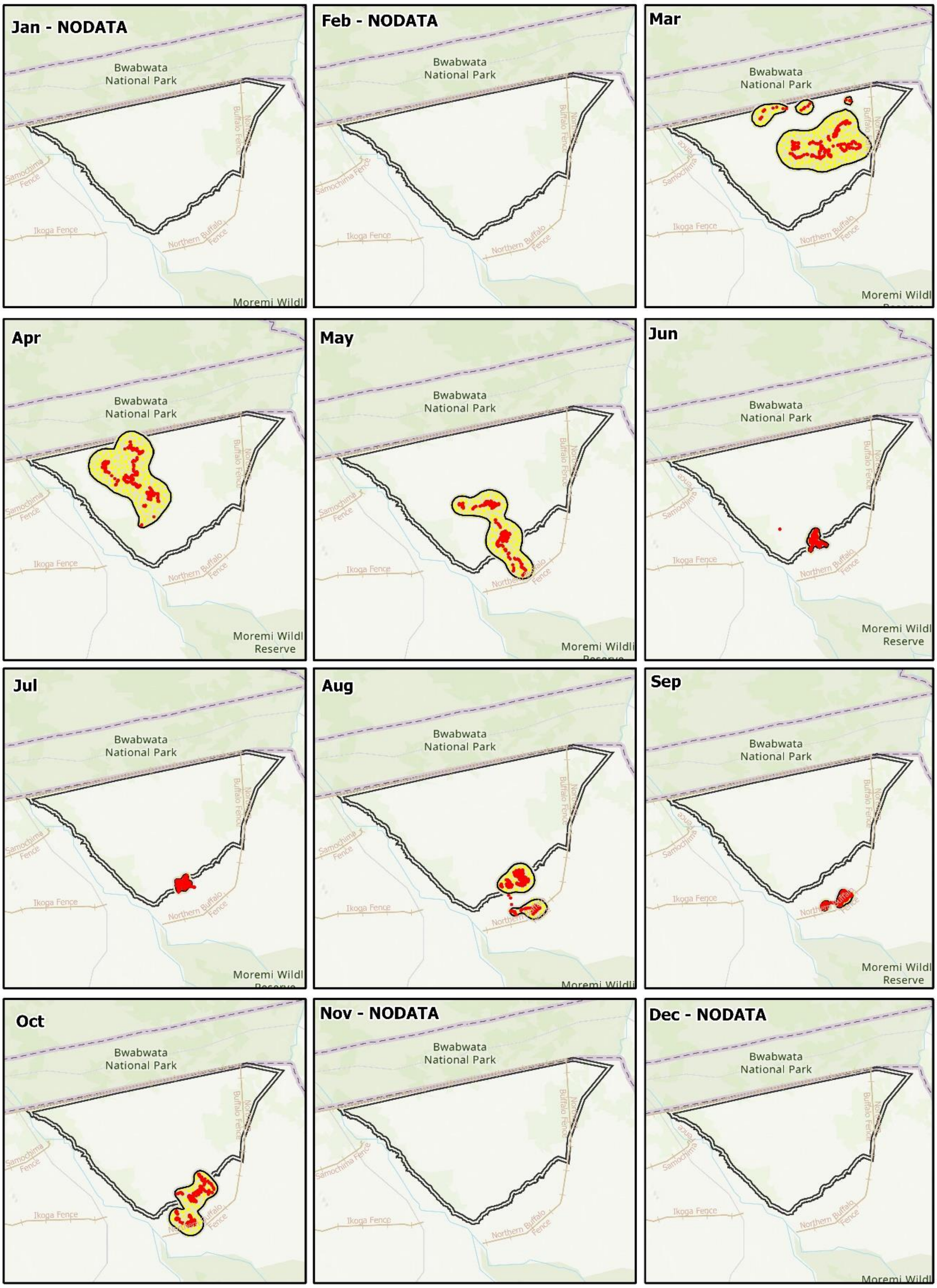
Bwabwata National Park
Buffalo Fence
Samochima Fence
Ikoga Fence
Northern Buffalo Fence
Reserve

G in 2017



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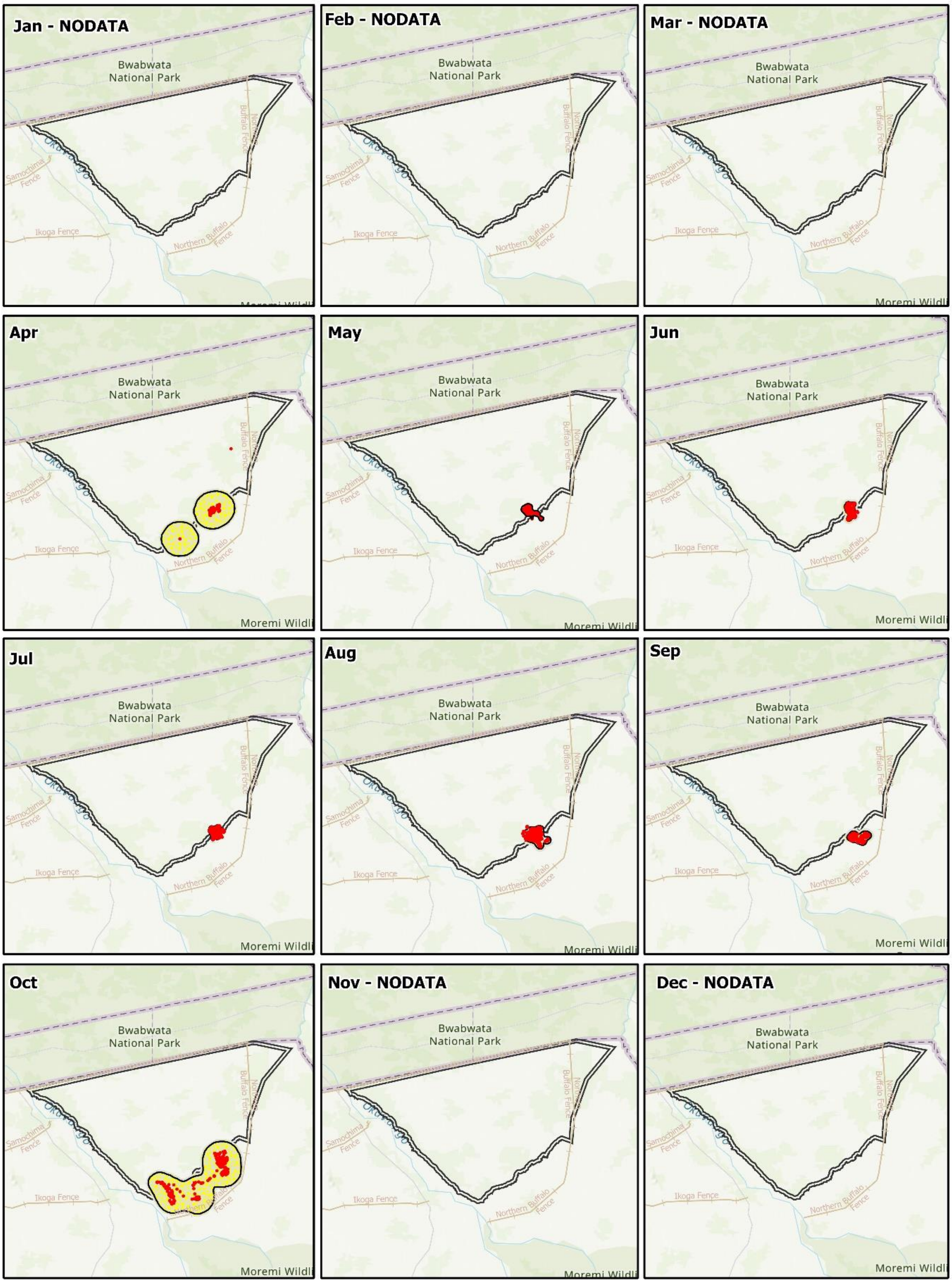
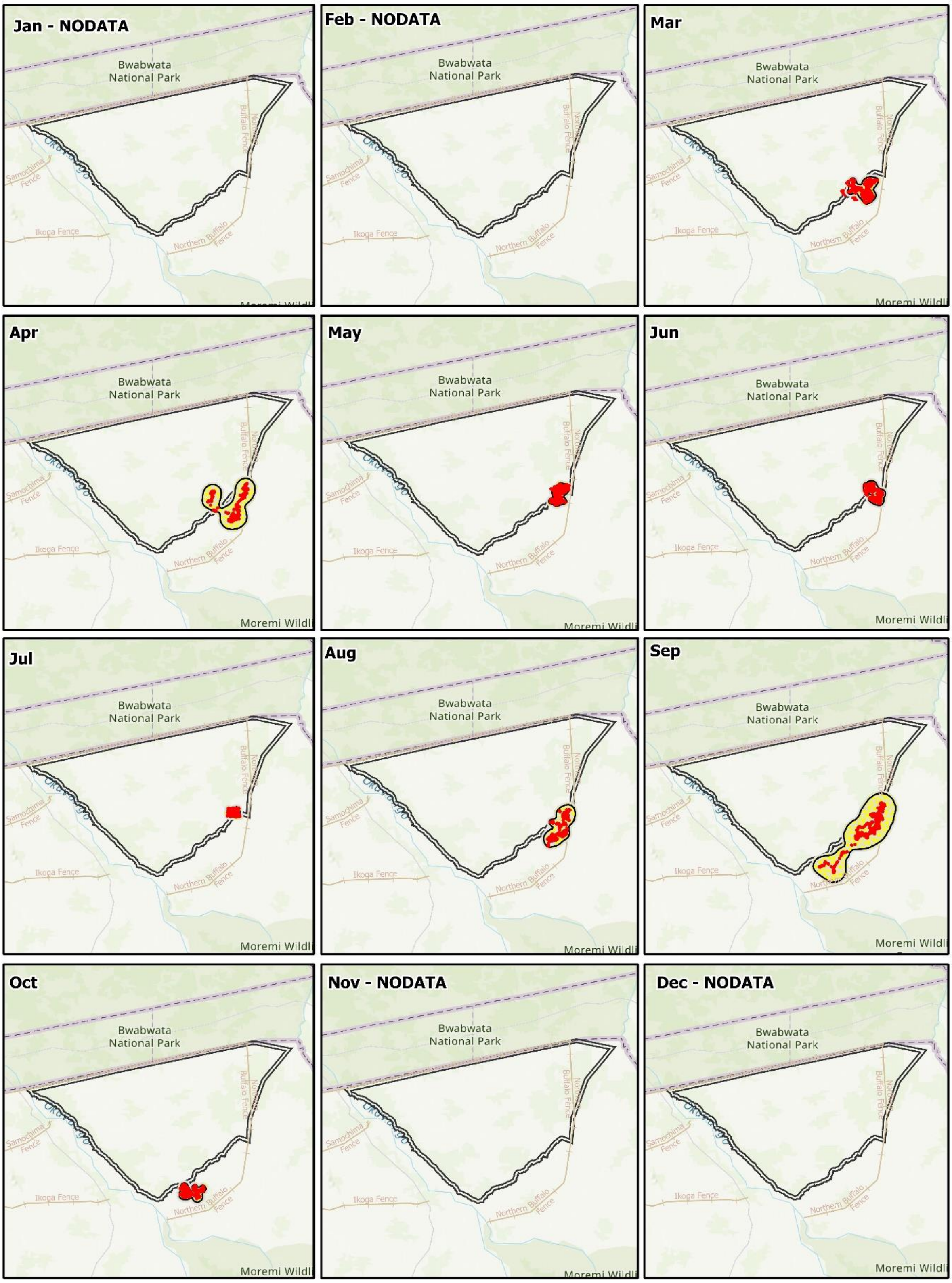
Bwabwata National Park
Northern Buffalo Fence
Samochima Fence
Ikoga Fence
Reserve

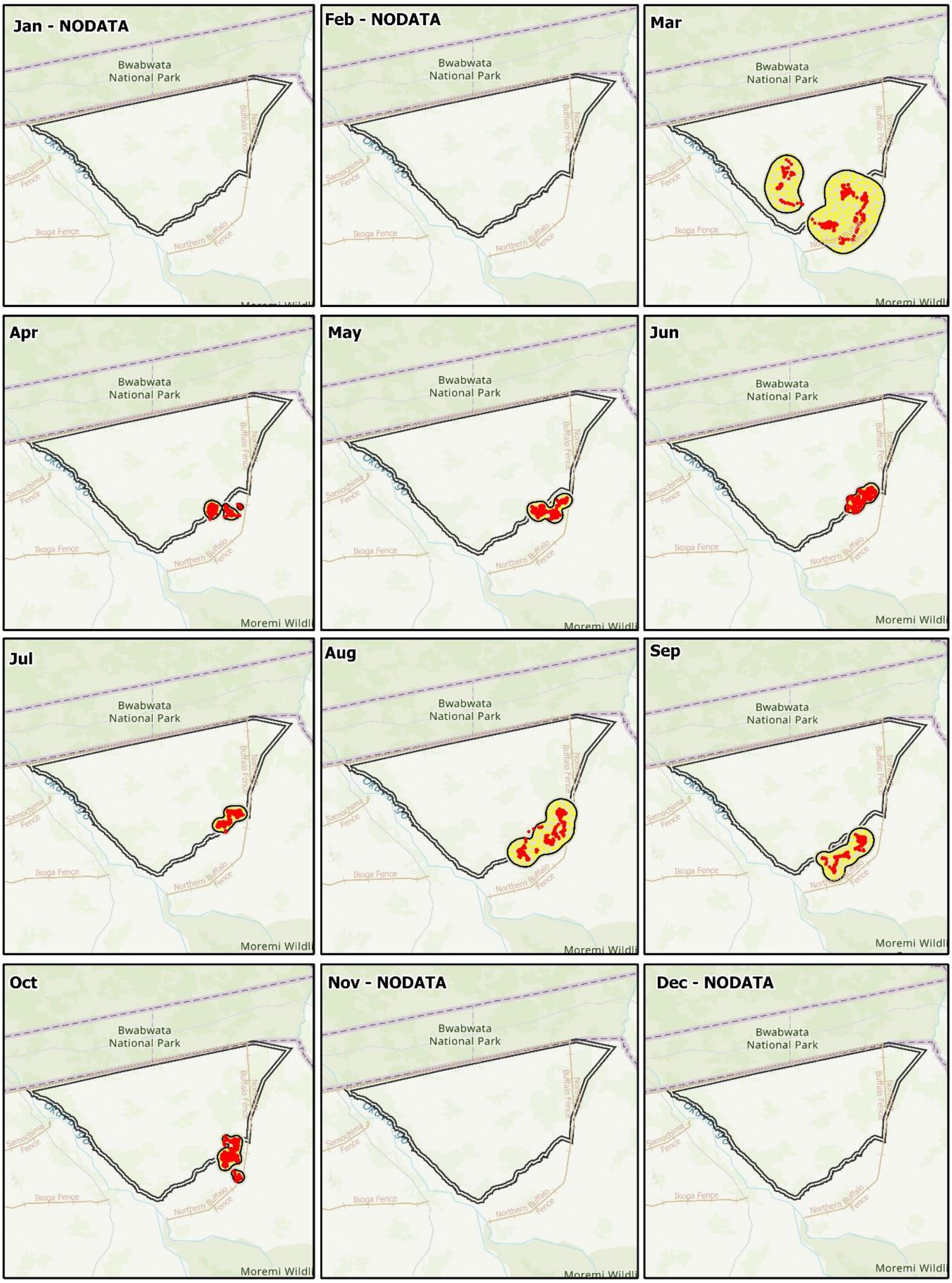
The Bachelor in 2014



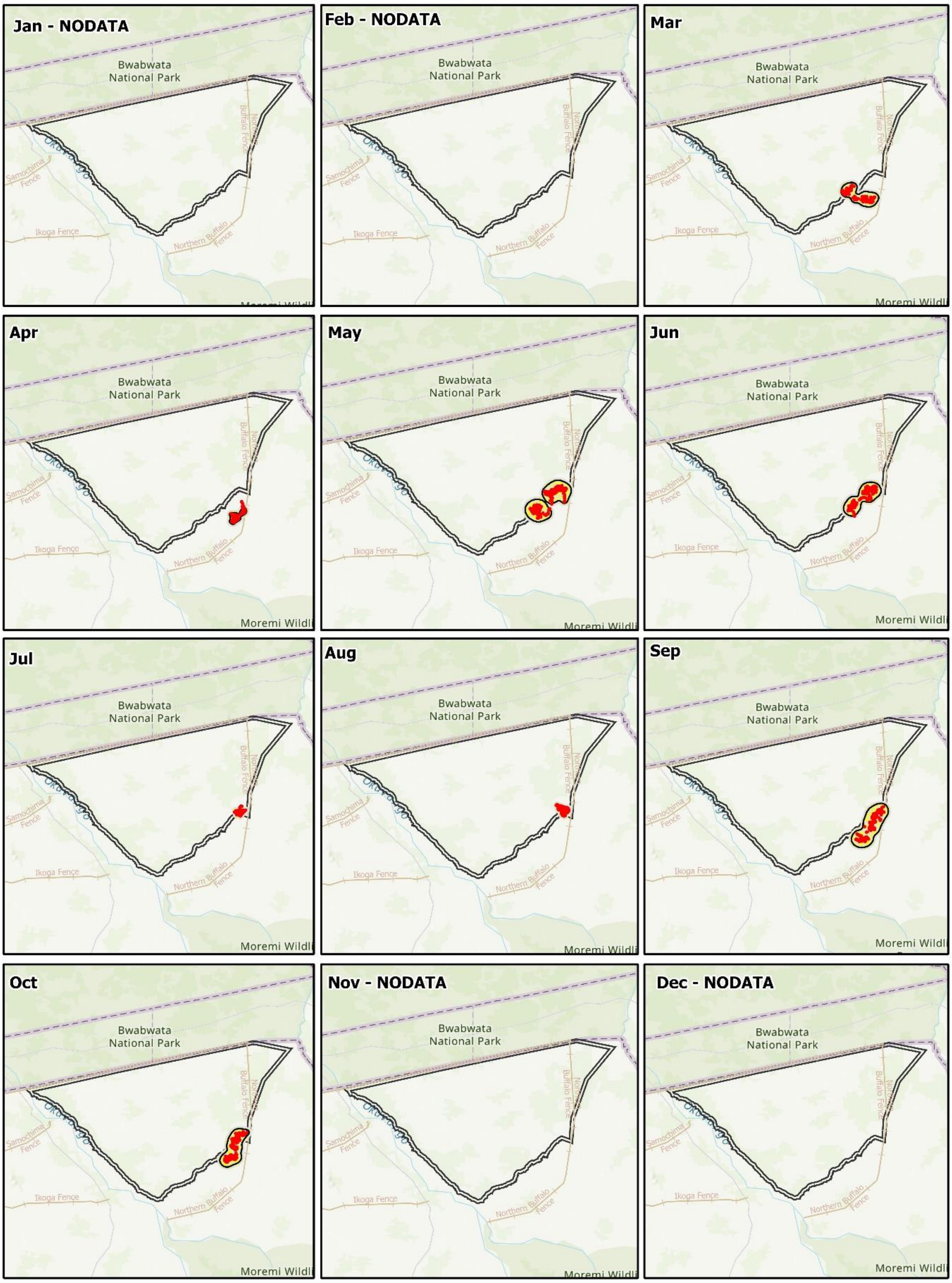
The Bachelor in 2015



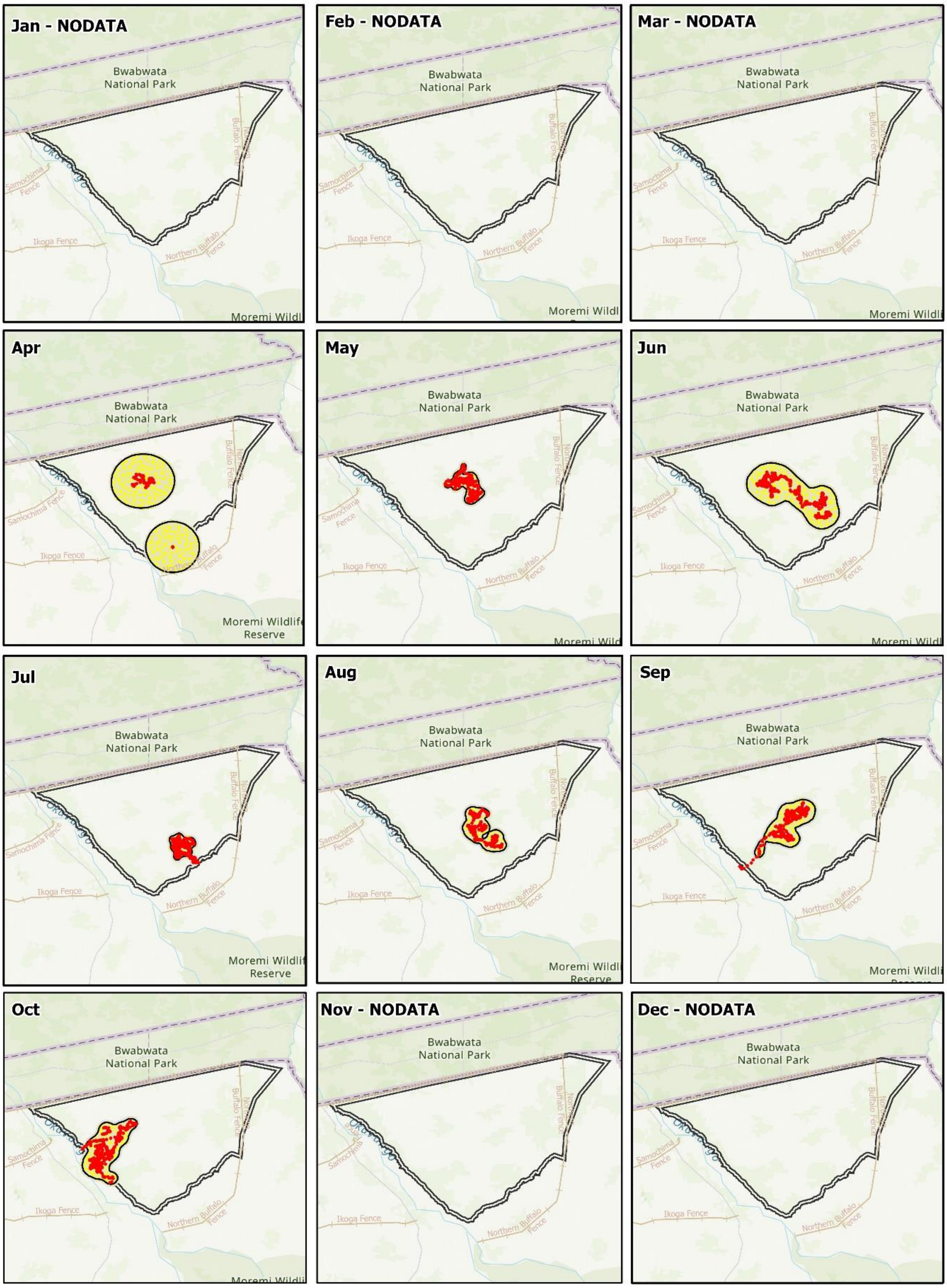
The Bachelor in 2016



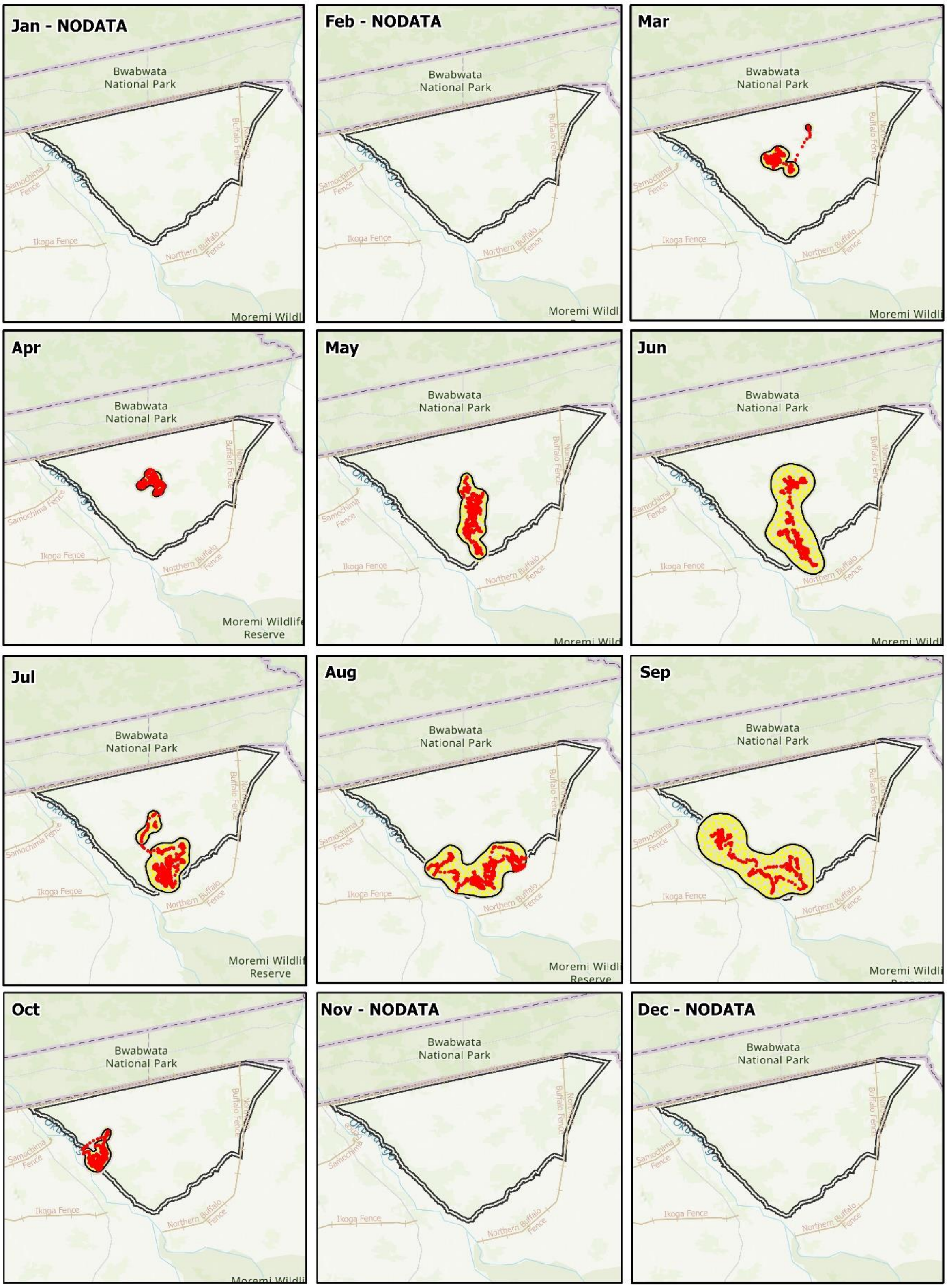
The Bachelor in 2017



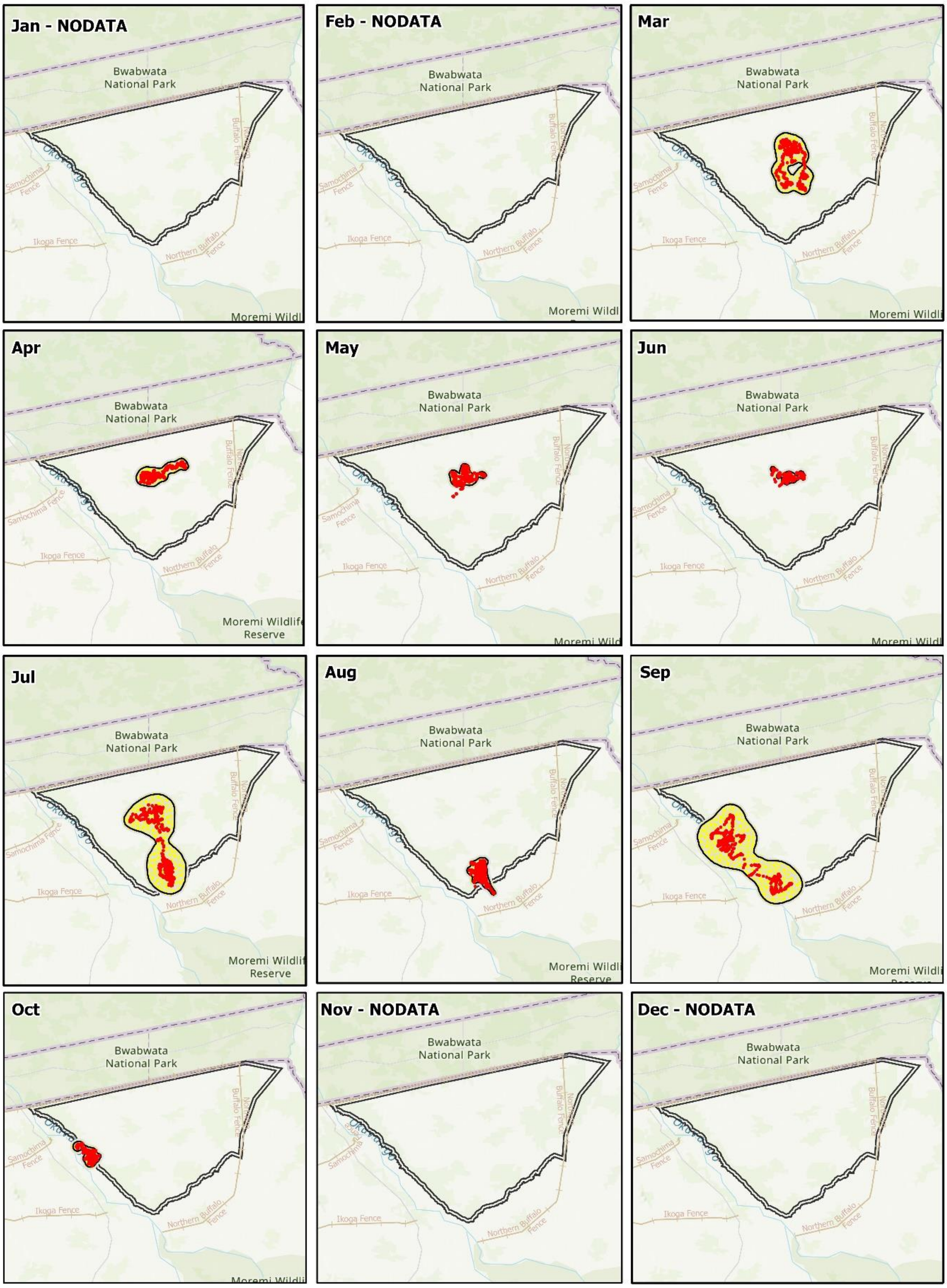
Whiskey in 2014



Whiskey in 2015

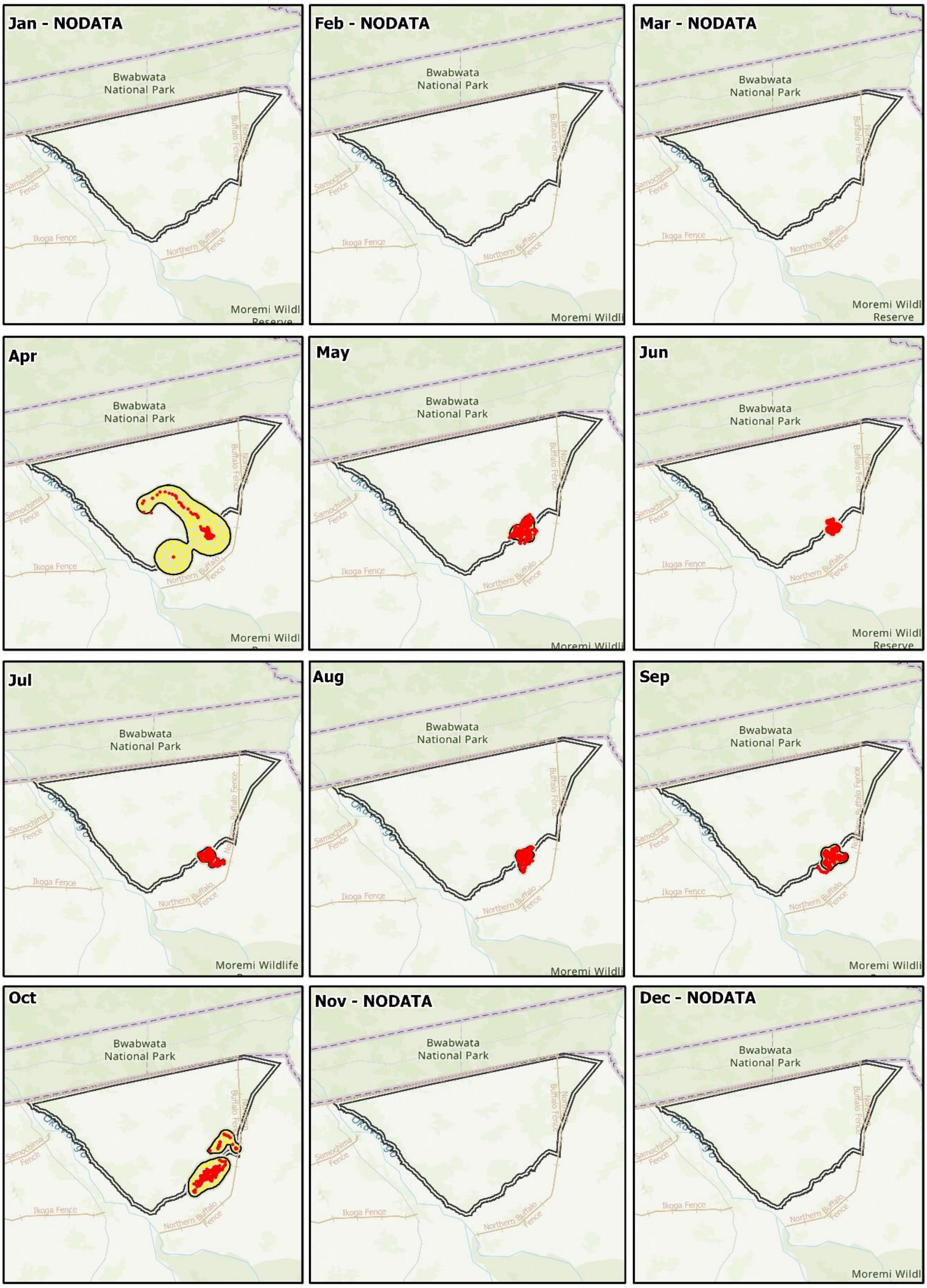


Whiskey in 2016

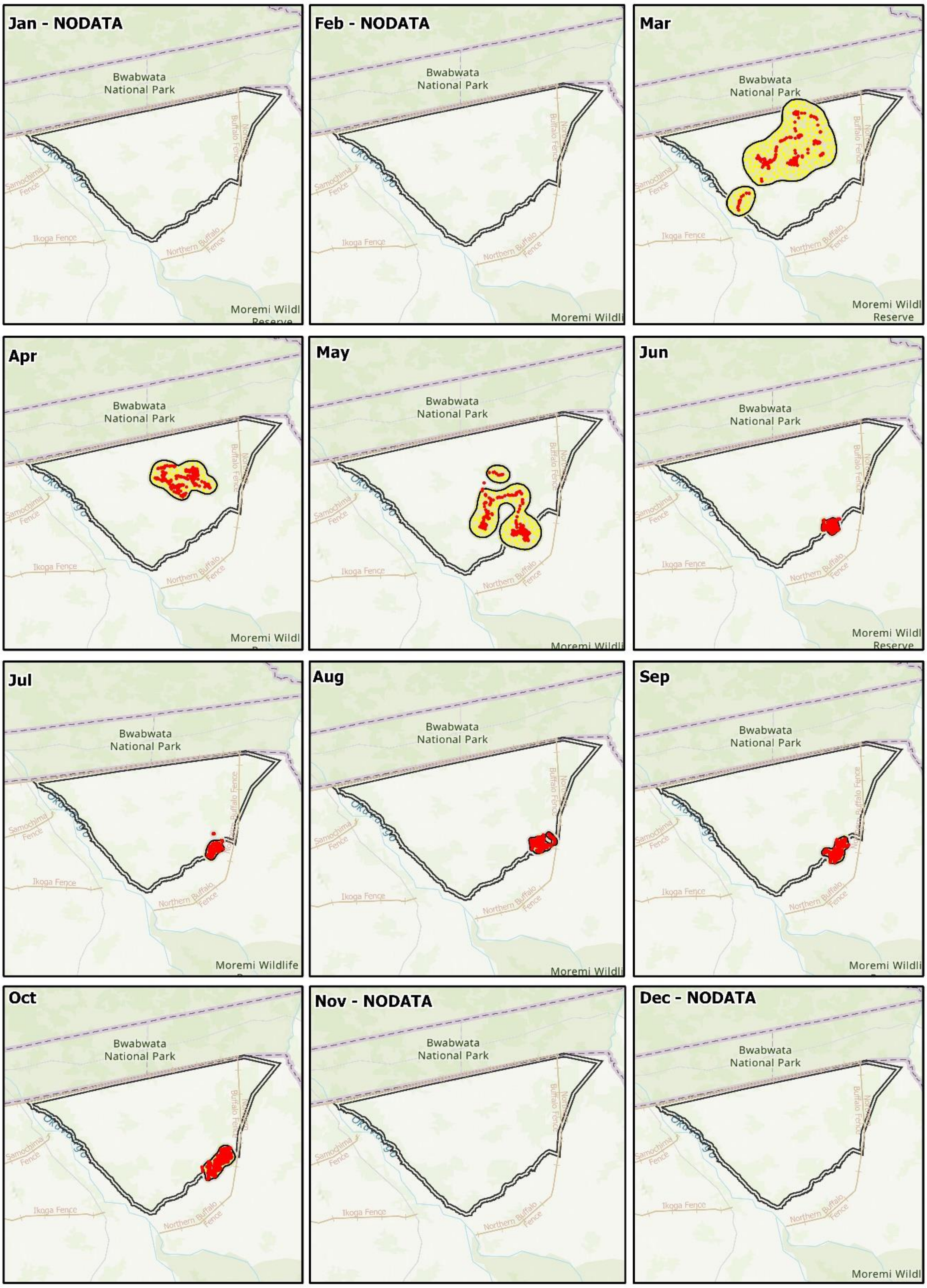


Whiskey in 2017

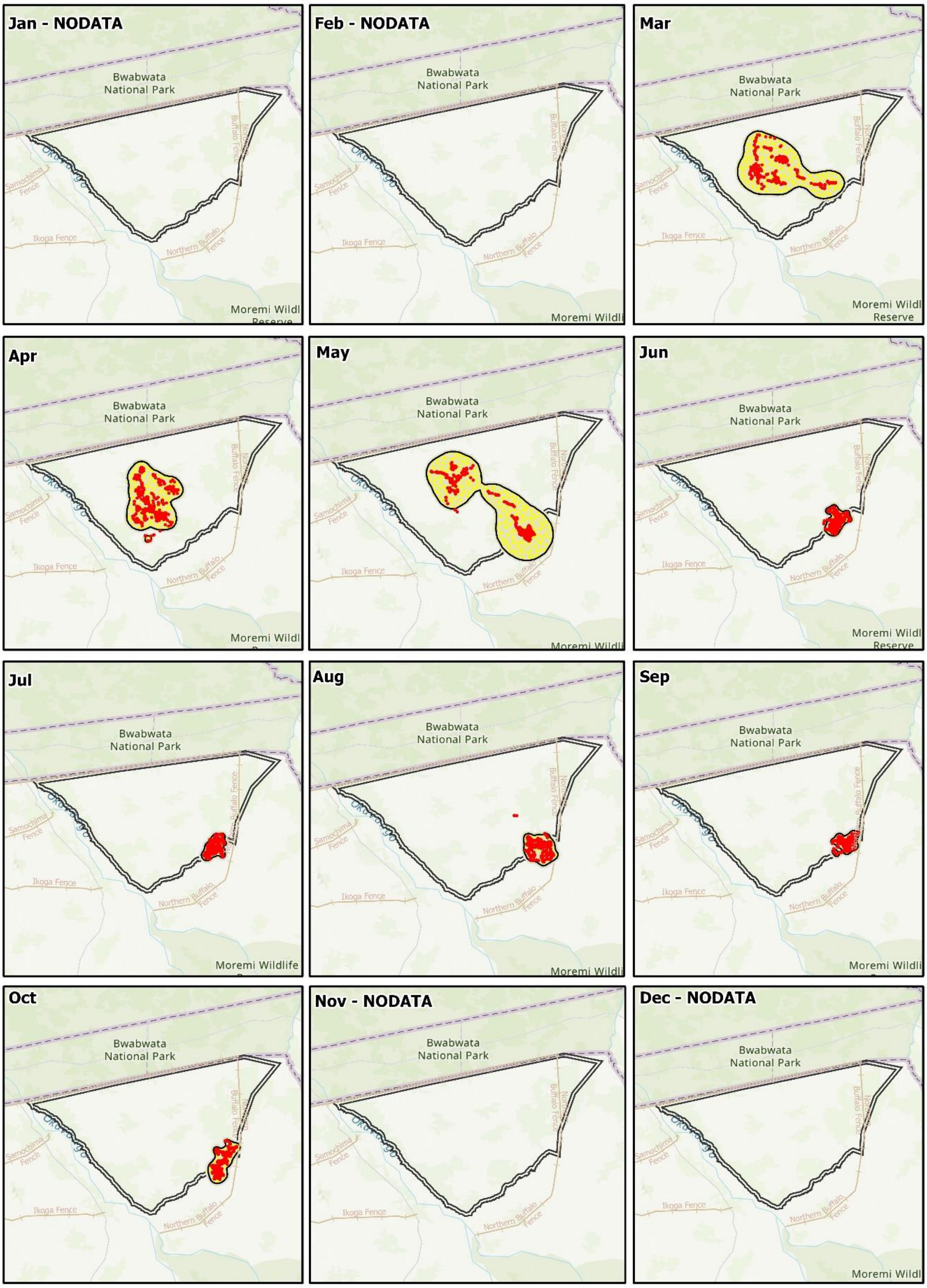
Howard in 2014



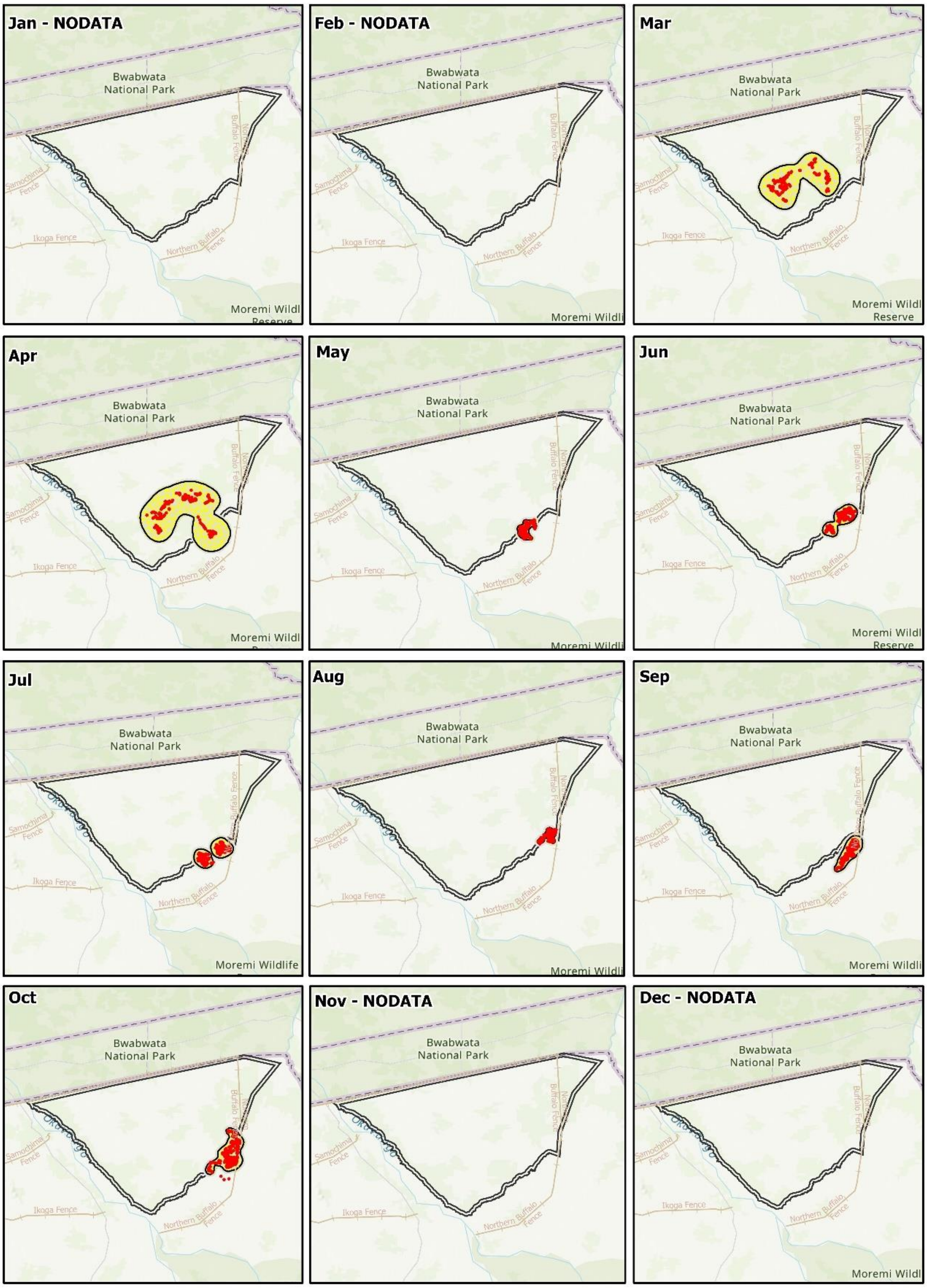
Howard in 2015



Howard in 2016

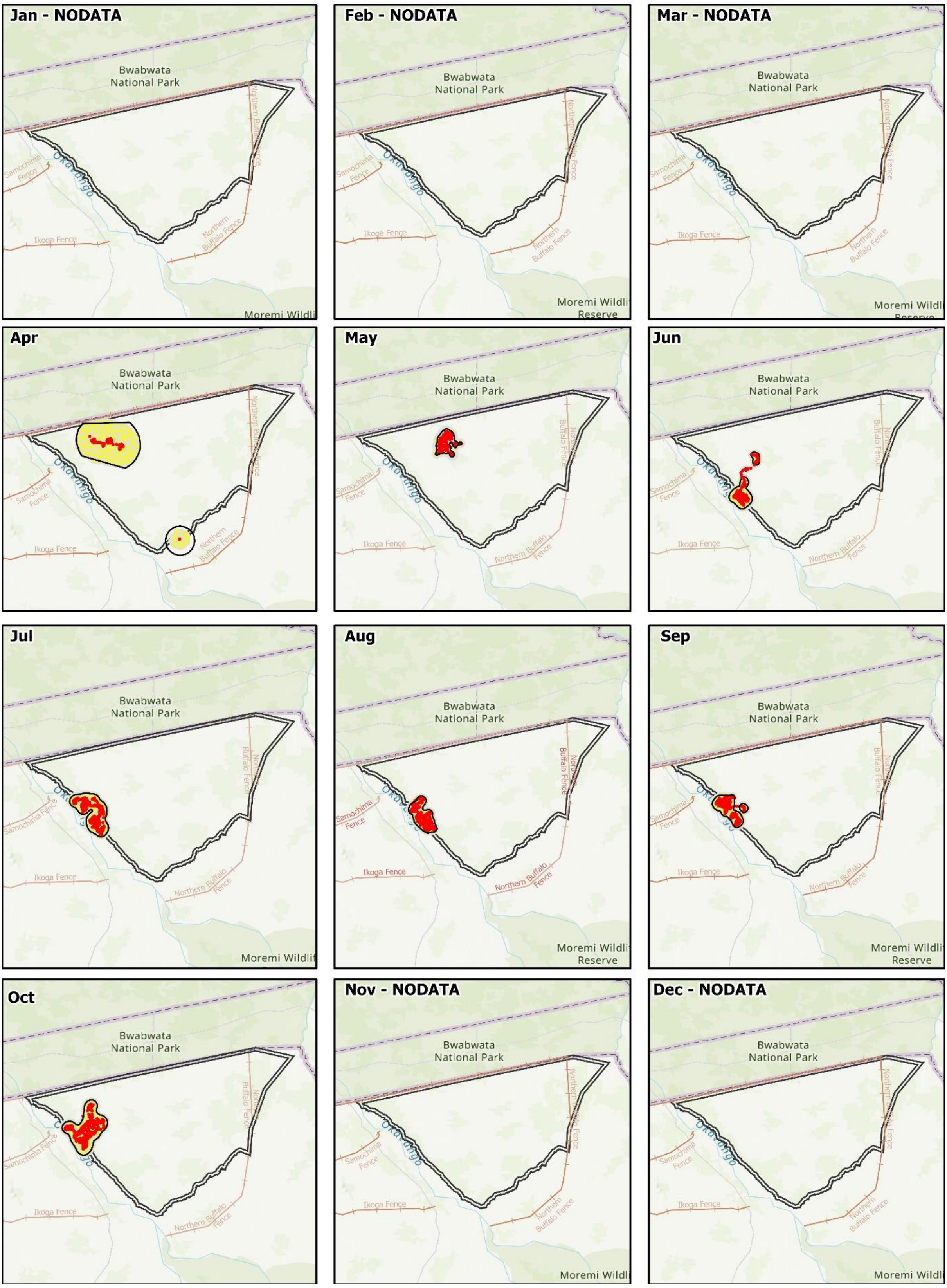


Howard in 2017

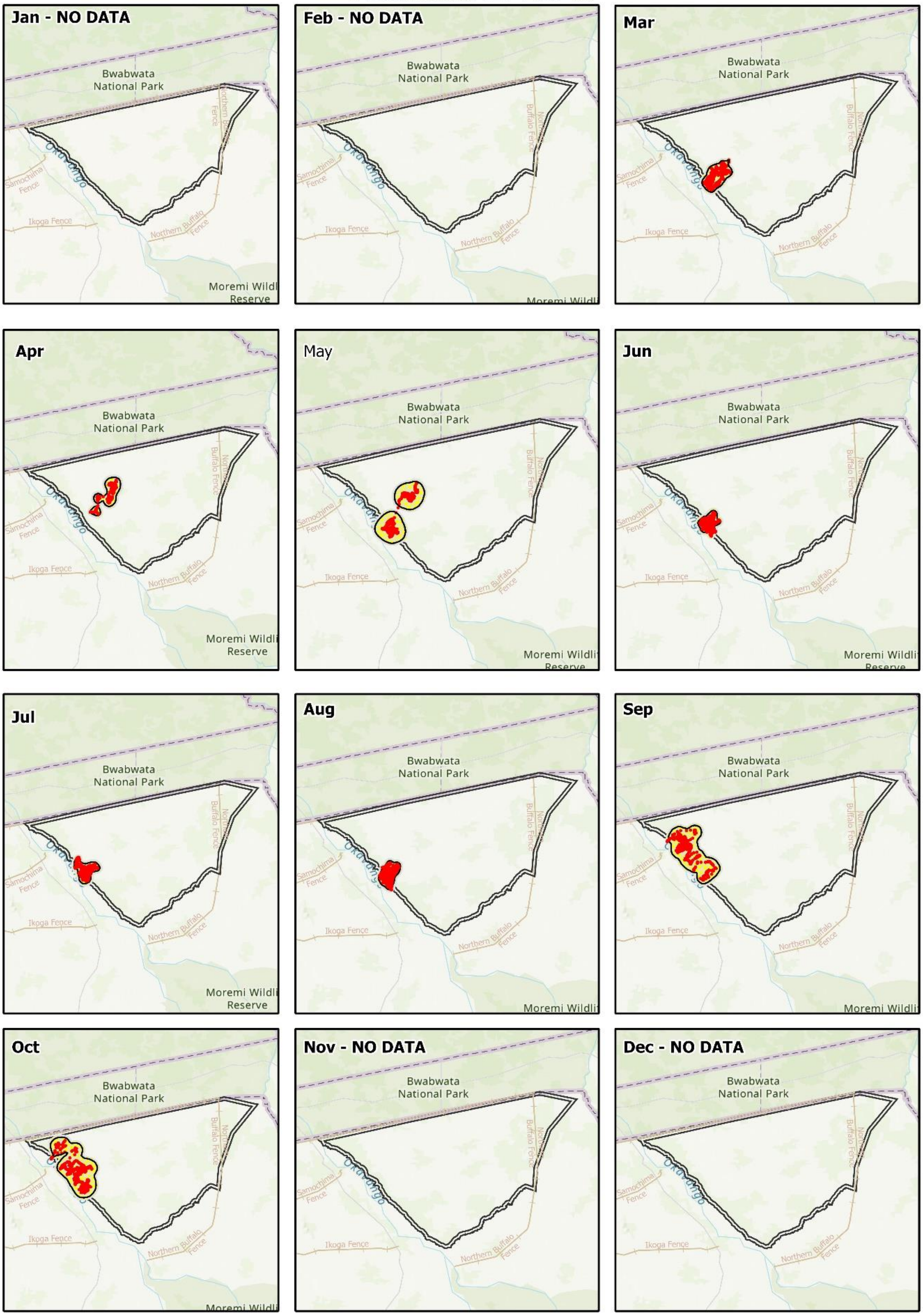


Appendix 7. An example of male elephants (G, The Bachelor, Whiskey and Howard) monthly home ranges. The data was derived in preparation for the Resource selection function analysis using R statistics between 2014.- Red dots denote to actual fixes whilst the yellow dots indicate random fixes over a month for example in 2014 (April-October) and from 2015 -2017 home ranges were generated from March -October. Months with no data are also shown

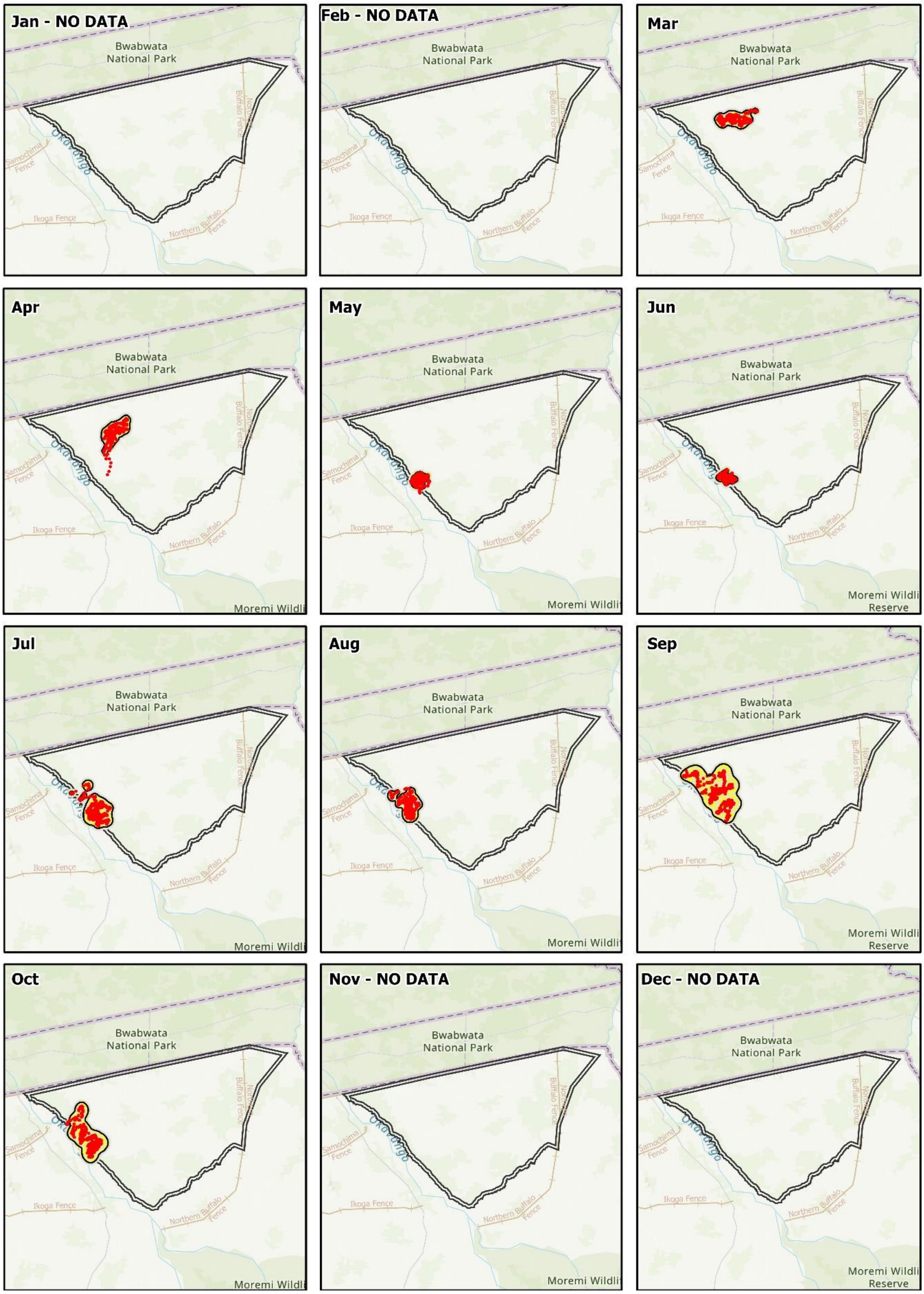
Mbamba in 2014



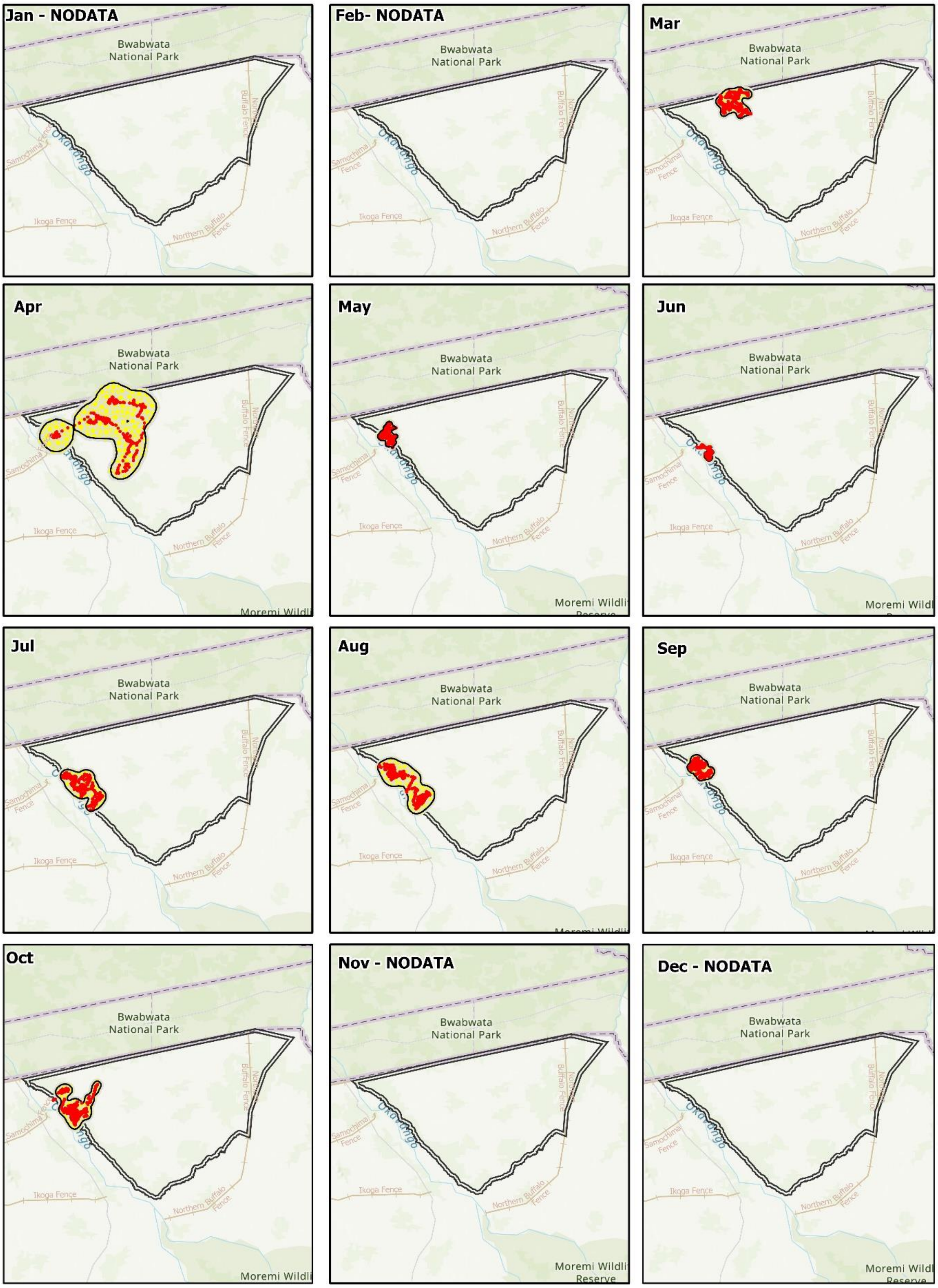
Mbamba in 2015



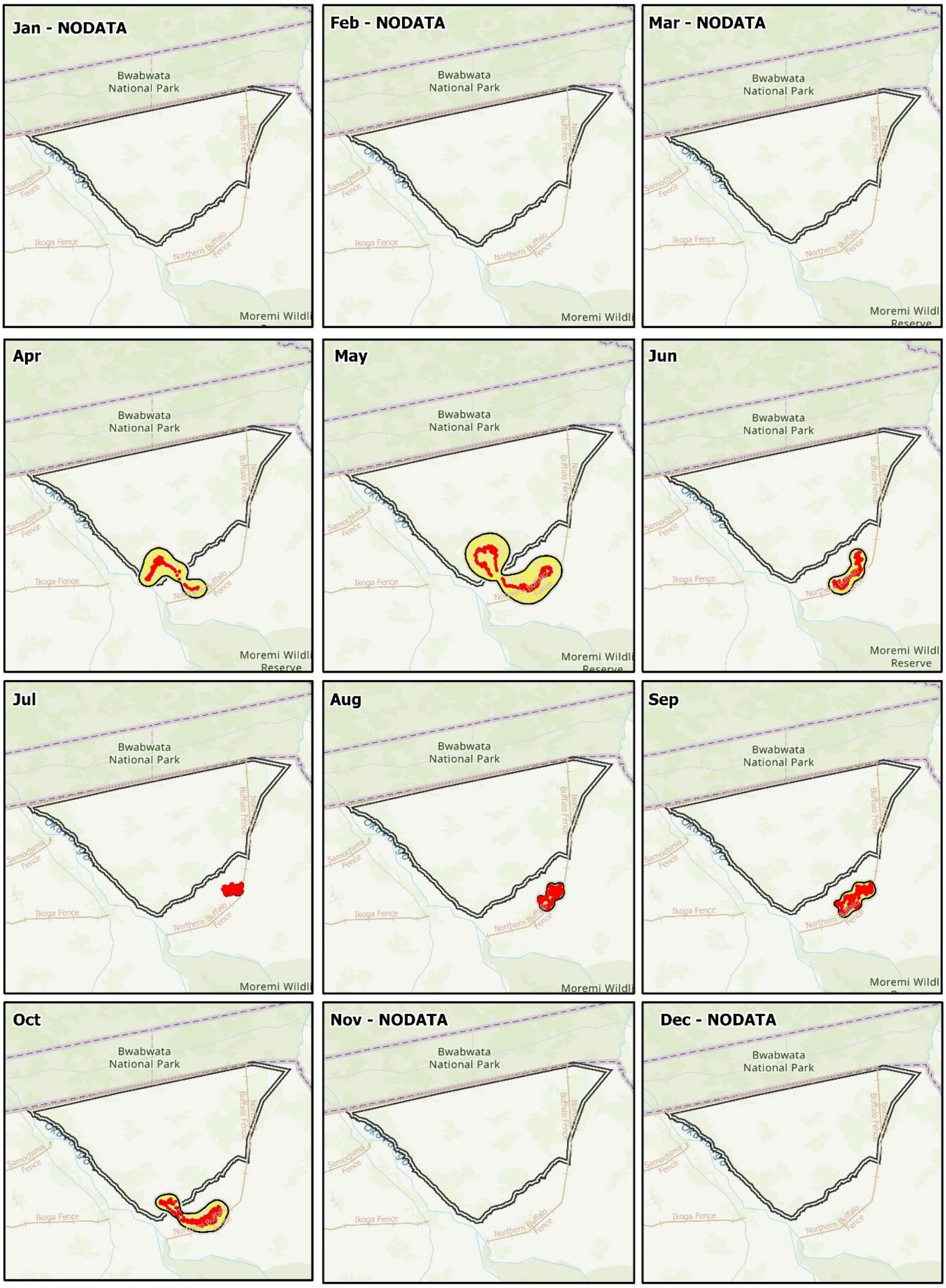
Mbamba in 2016



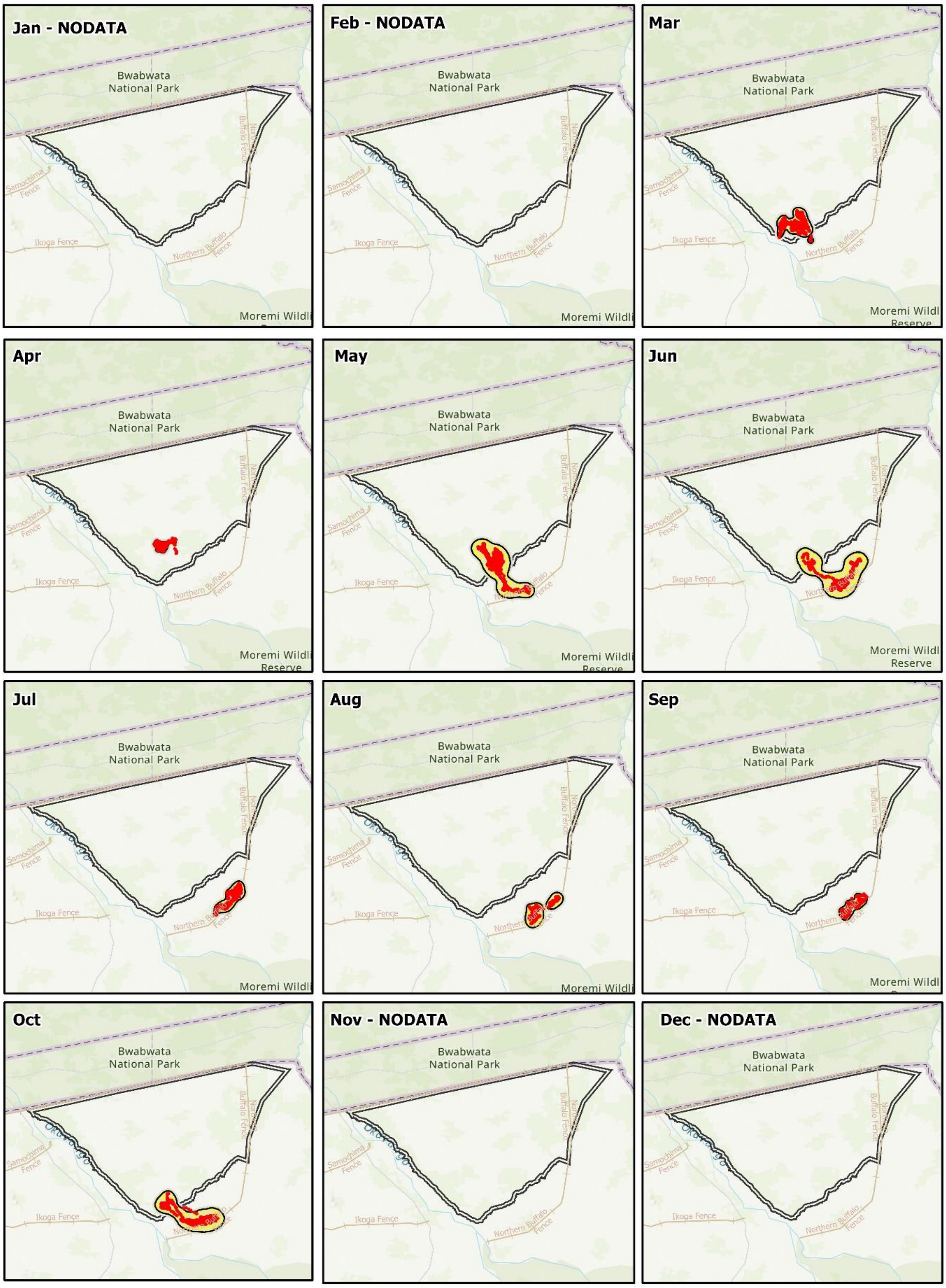
Mbamba in 2017



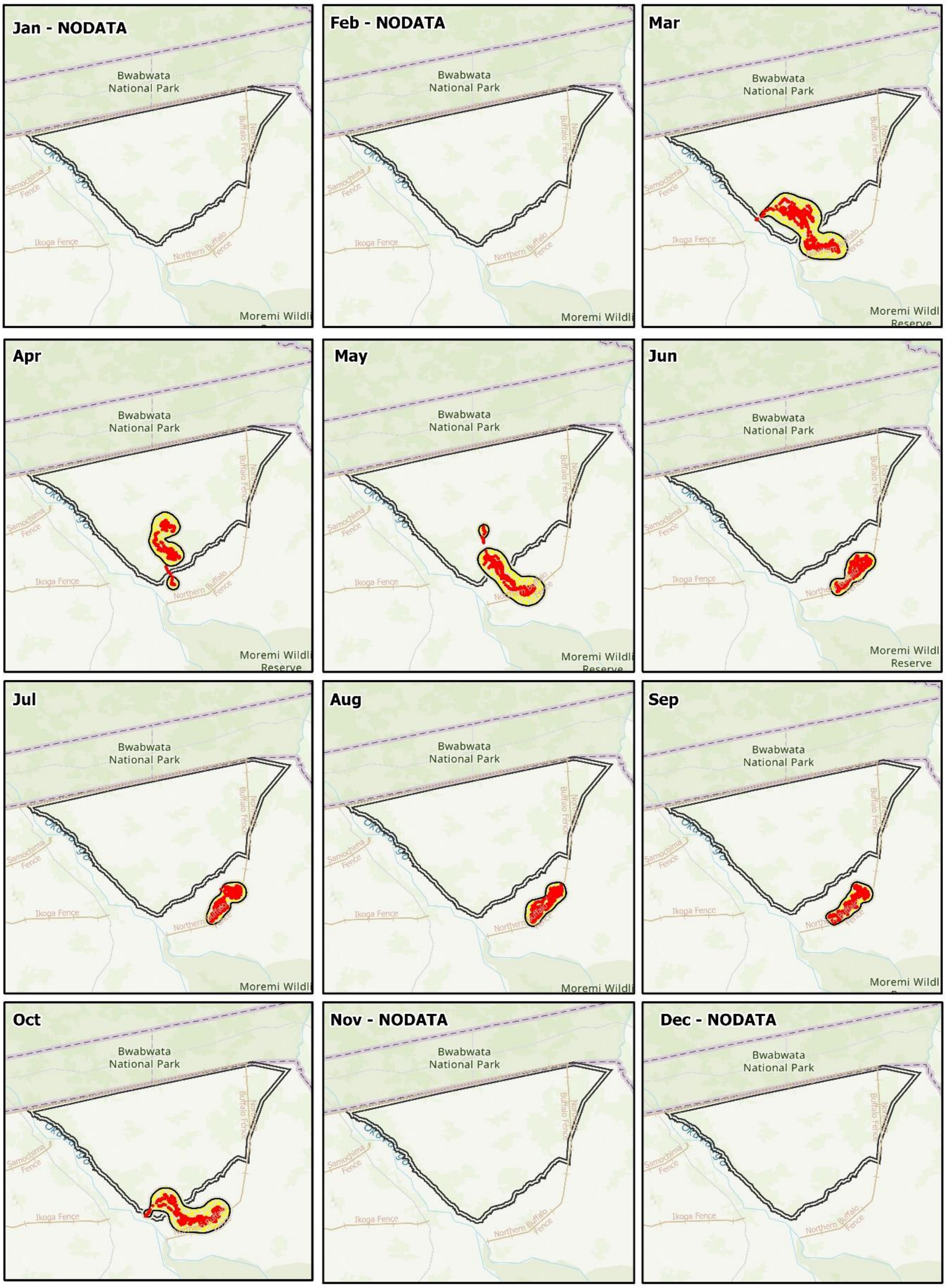
Pille in 2014



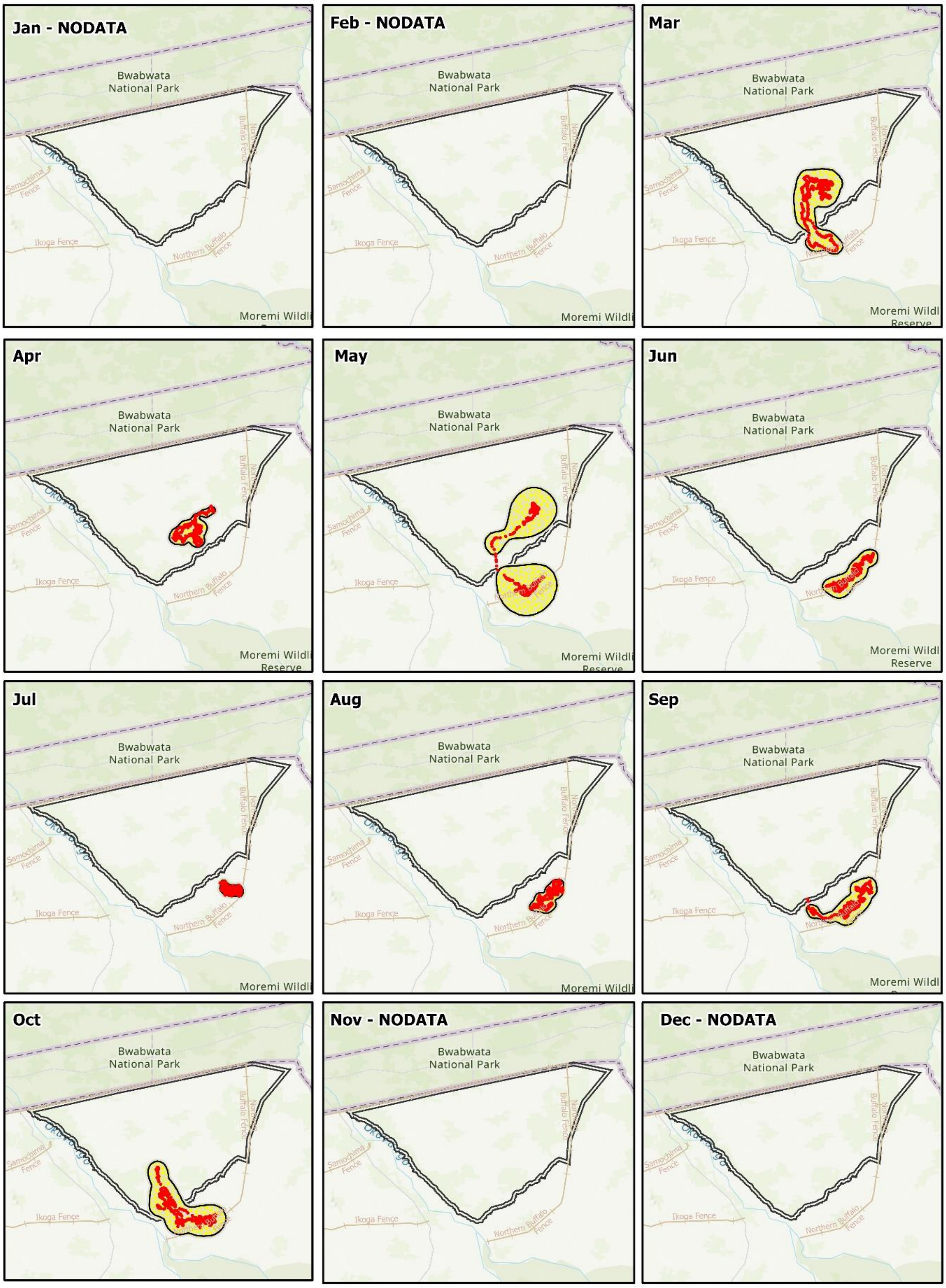
Pille in 2015



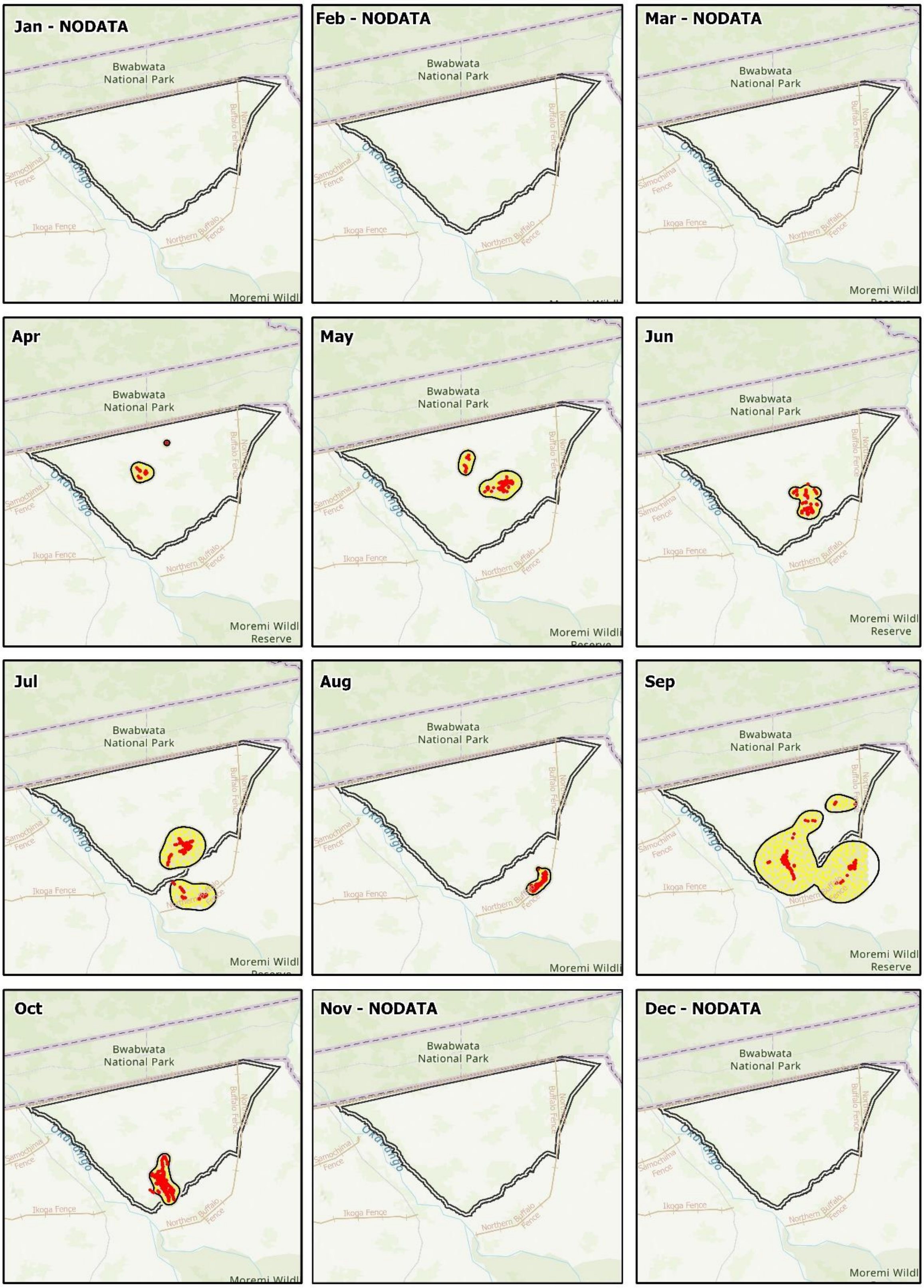
Pille in 2016



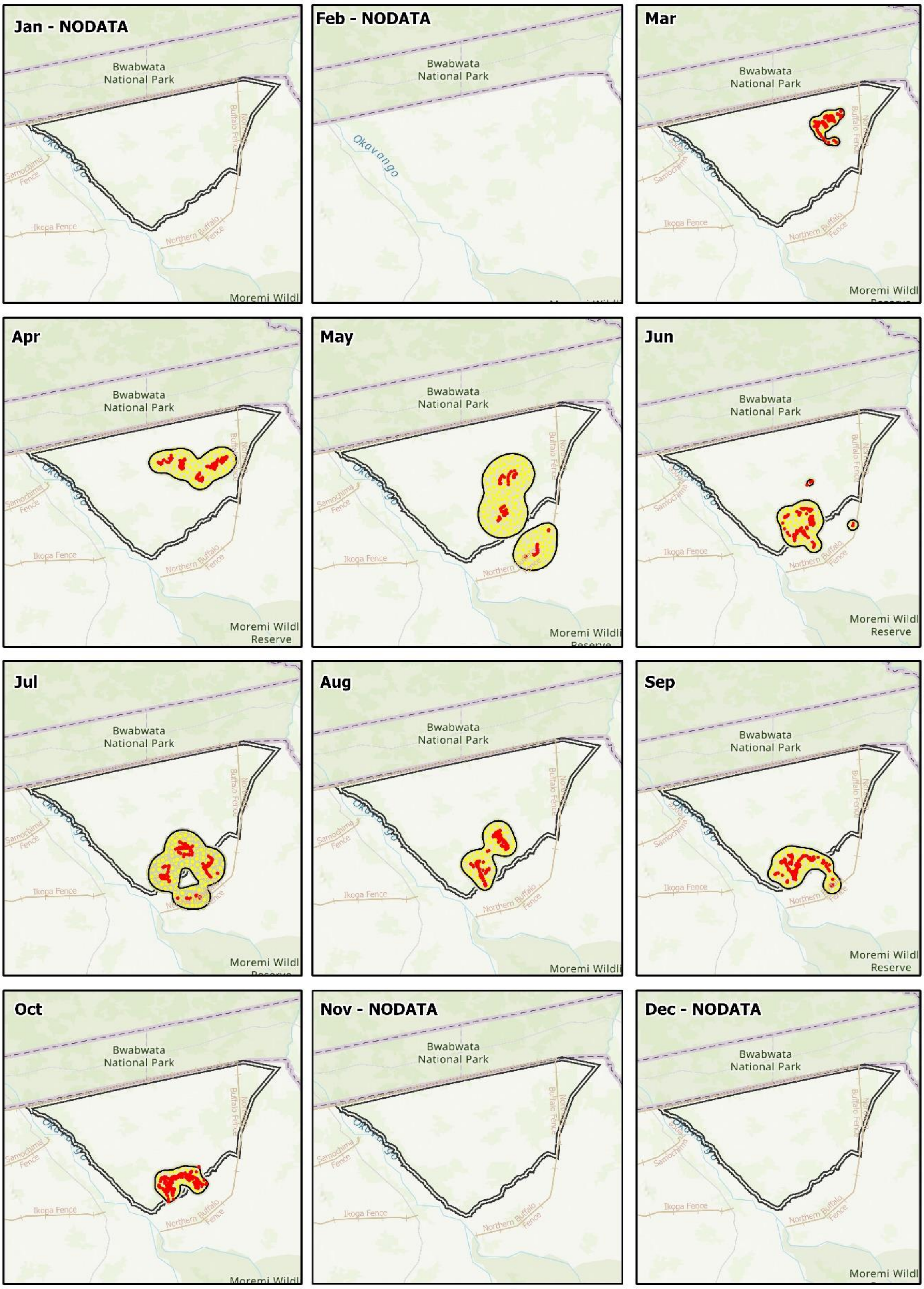
Pille in 2017



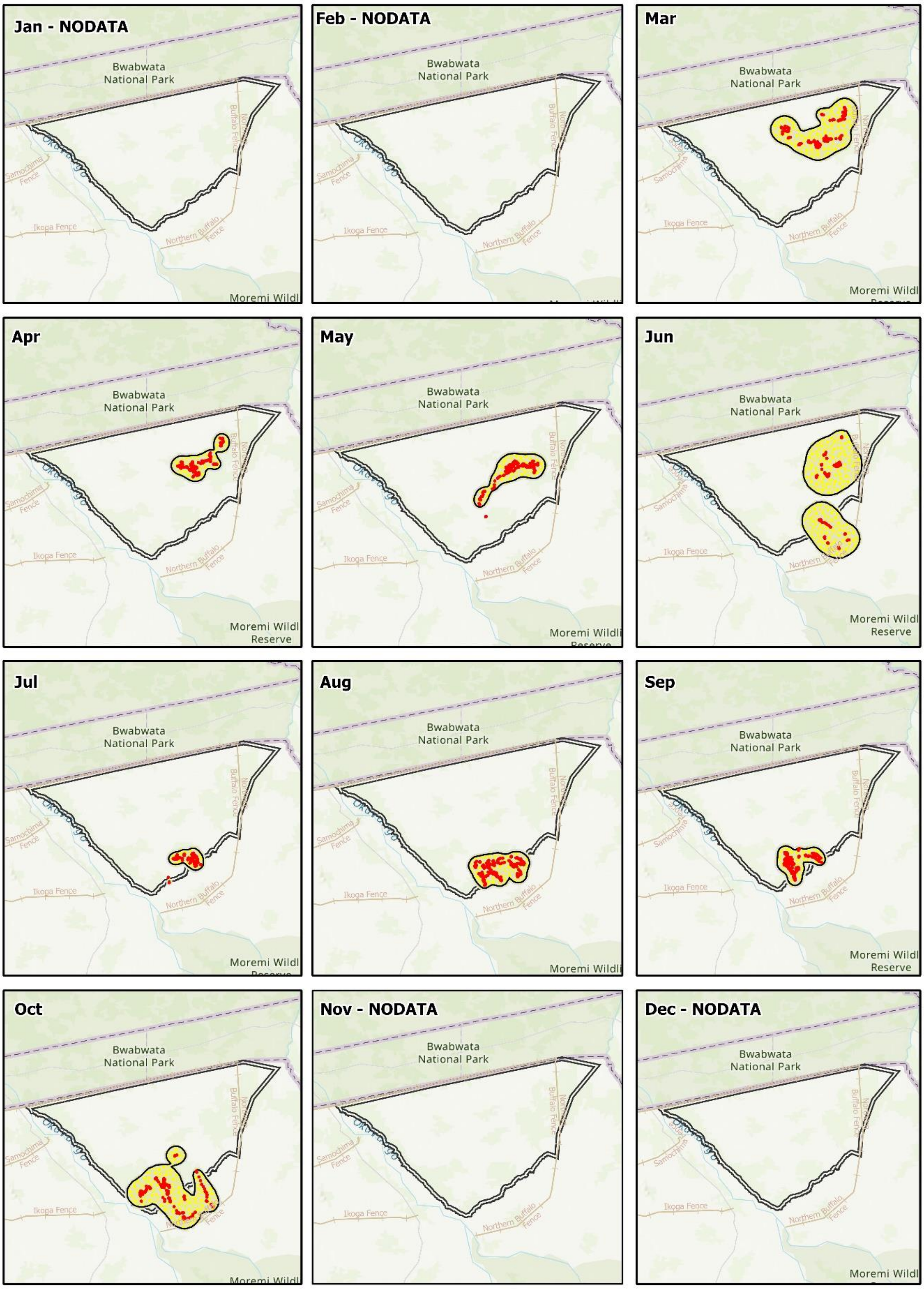
Amantle in 2014



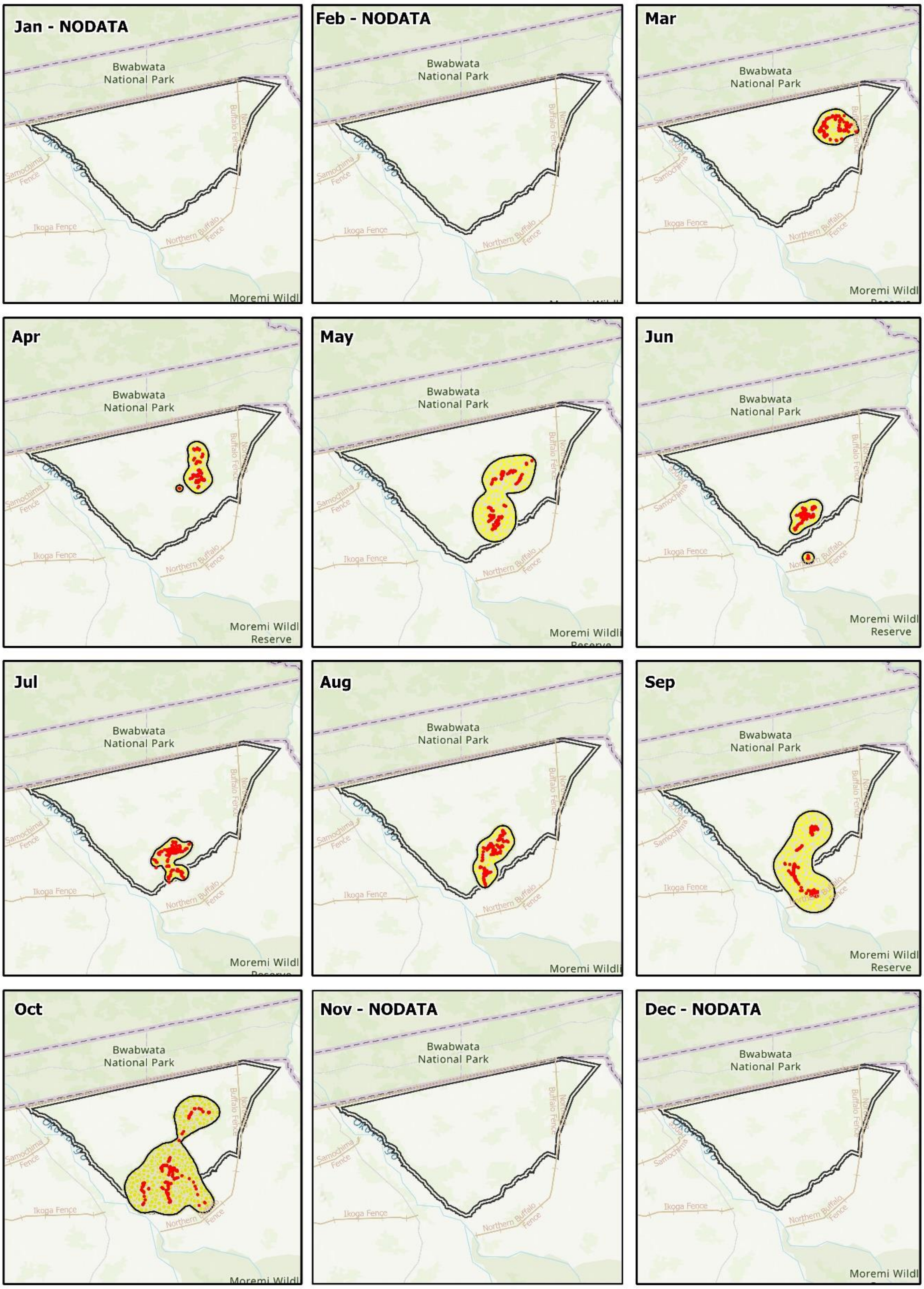
Amantle in 2015



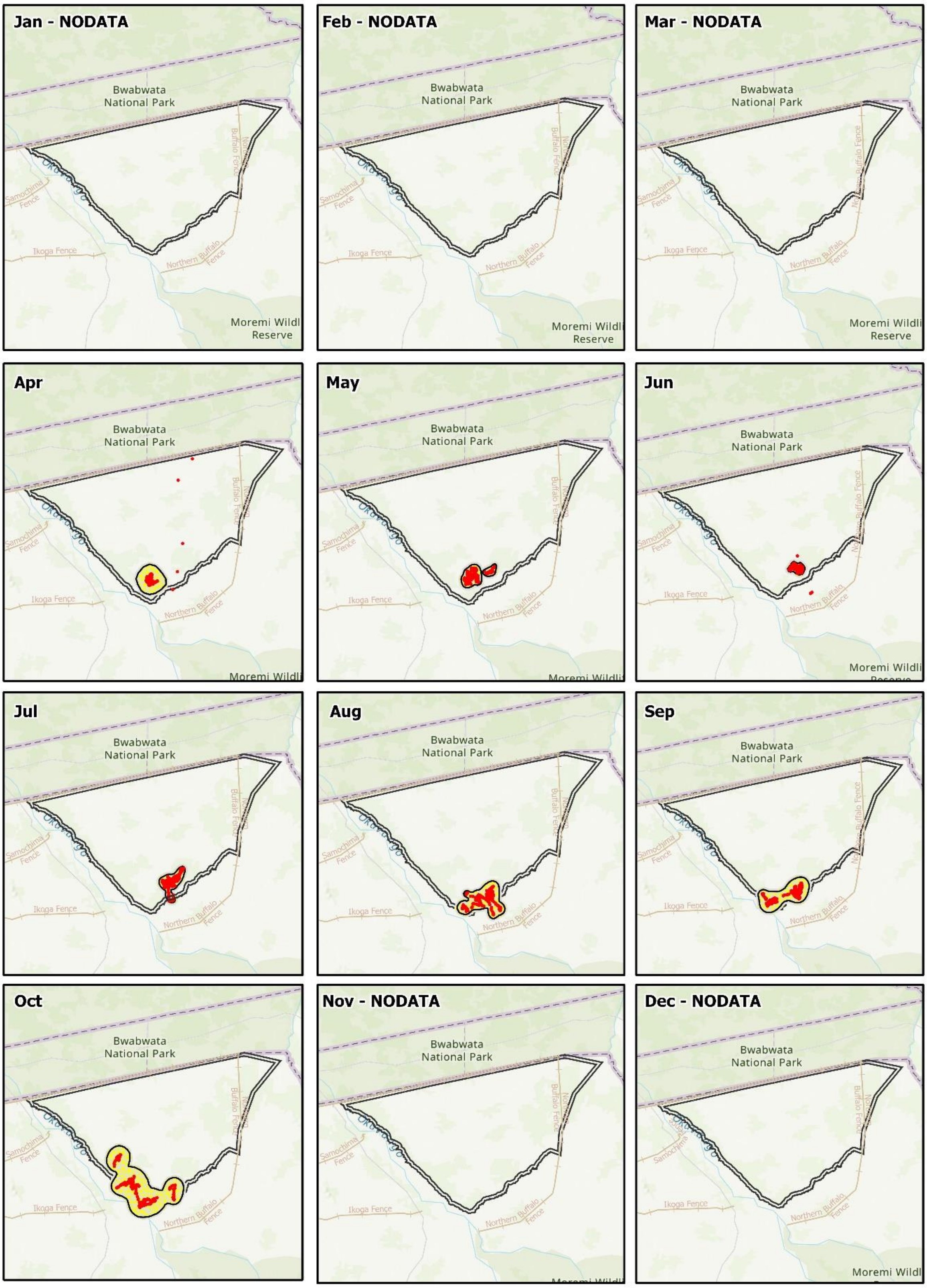
Amantle in 2016



Amantle in 2017



Ann in 2014



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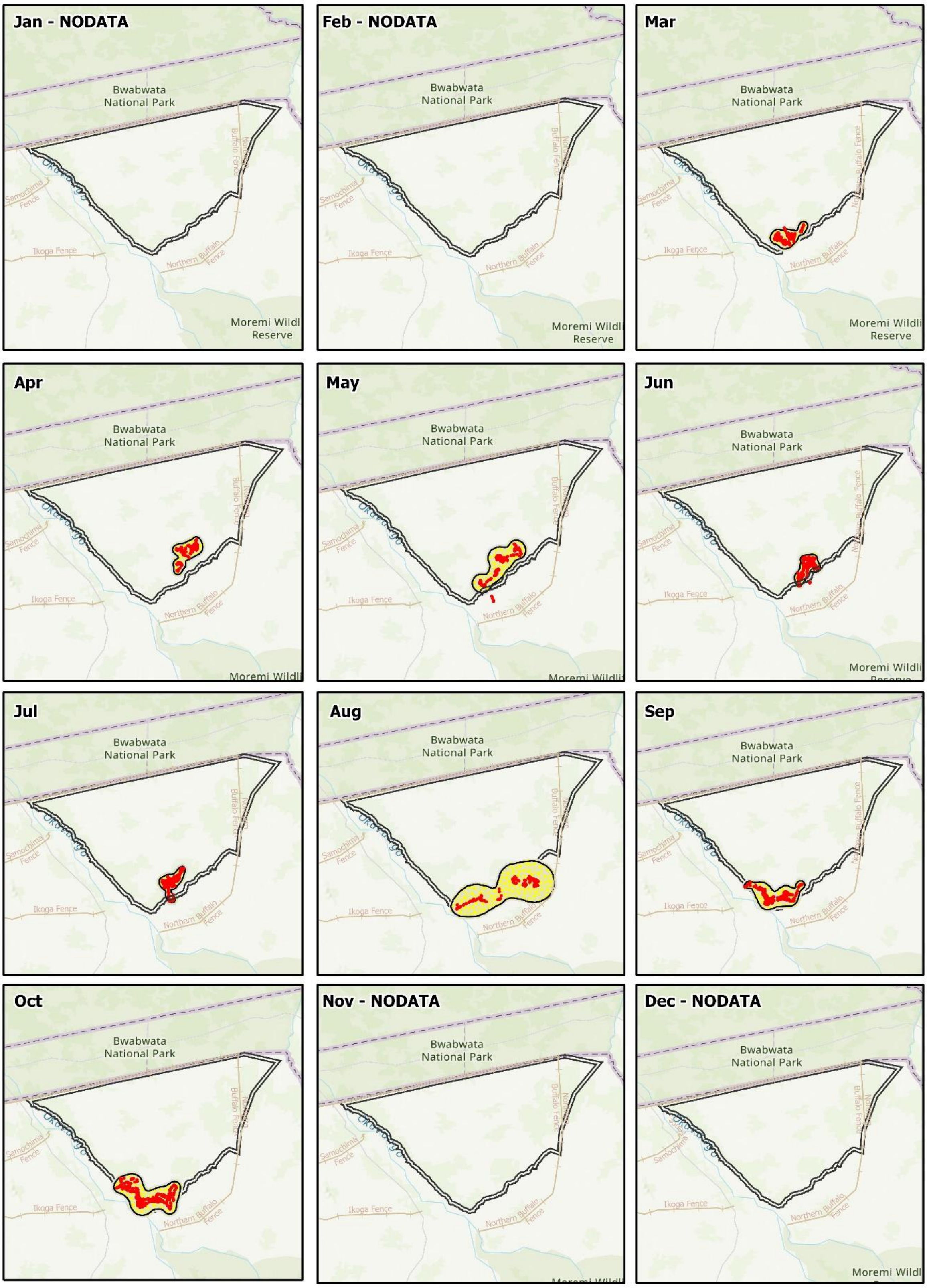
Samochima Fence
Ikoga Fence
Northern Buffalo Fence
Buffalo Fence
Moremi Wildl Reserve

Ann in 2015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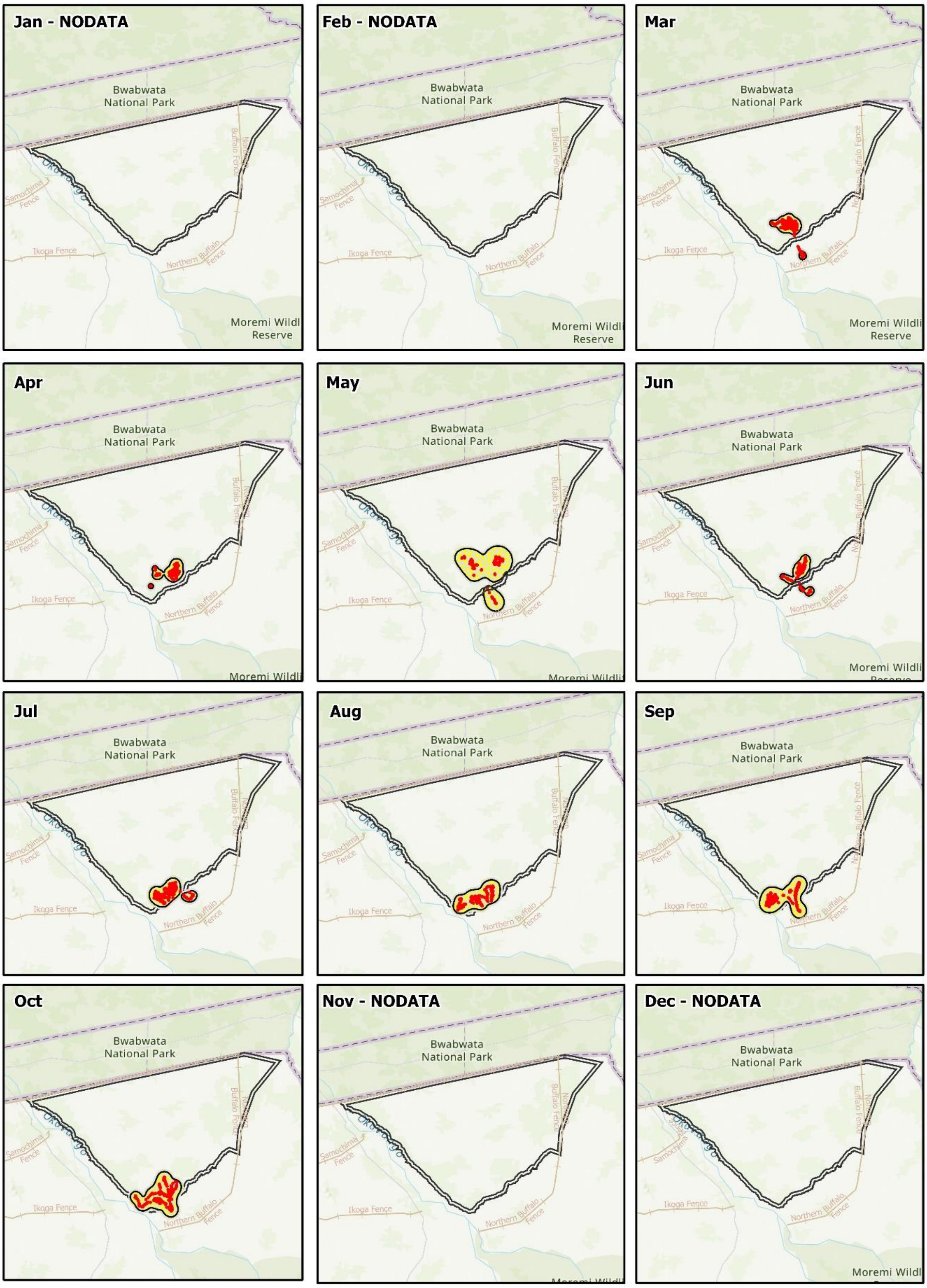
Northern Buffalo Fence
Buffalo Fence
Moremi Wildl Reserve

Ann in 2016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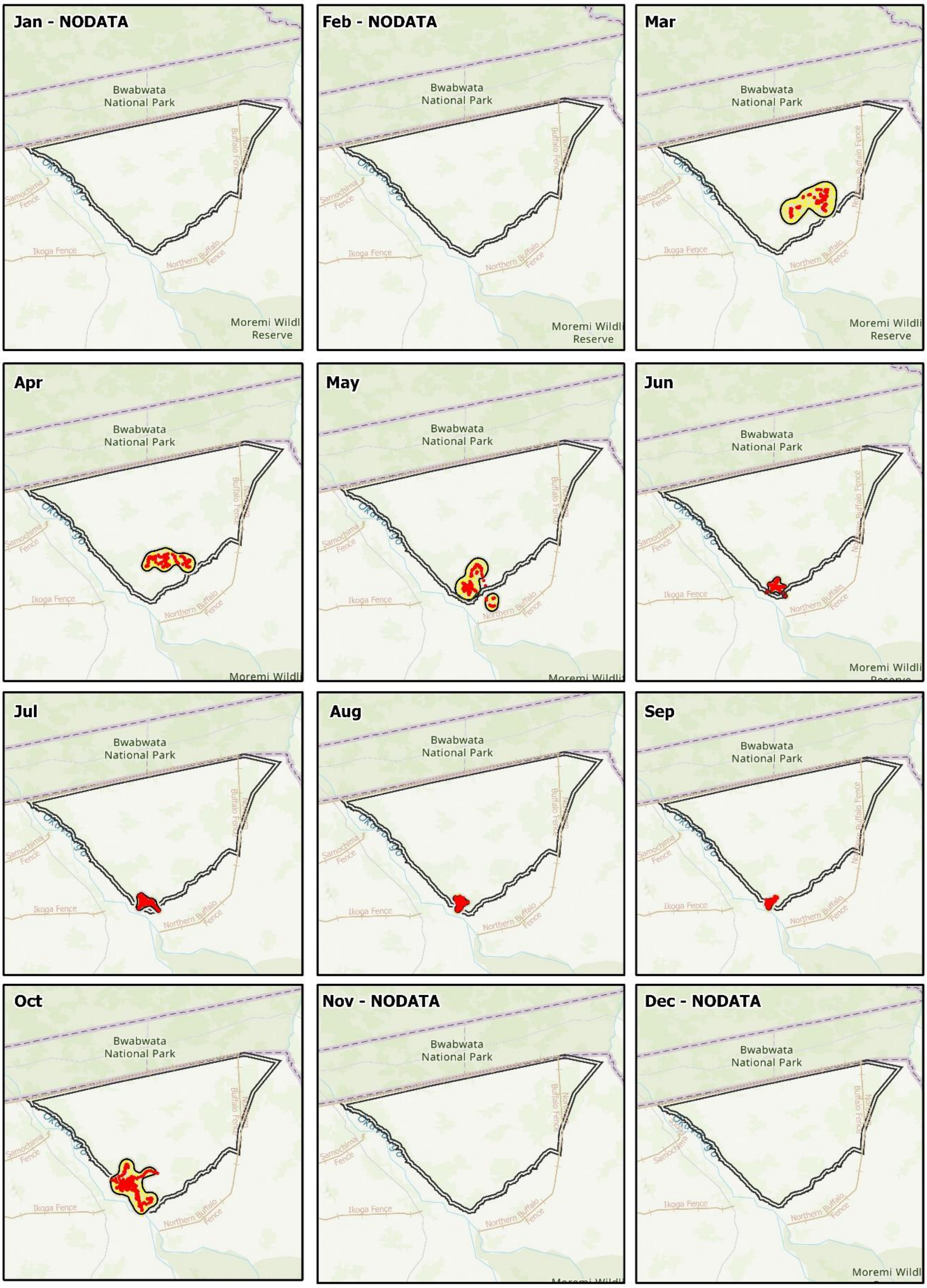
Samochima Fence
Ikoga Fence
Northern Buffalo Fence

Ann in 2017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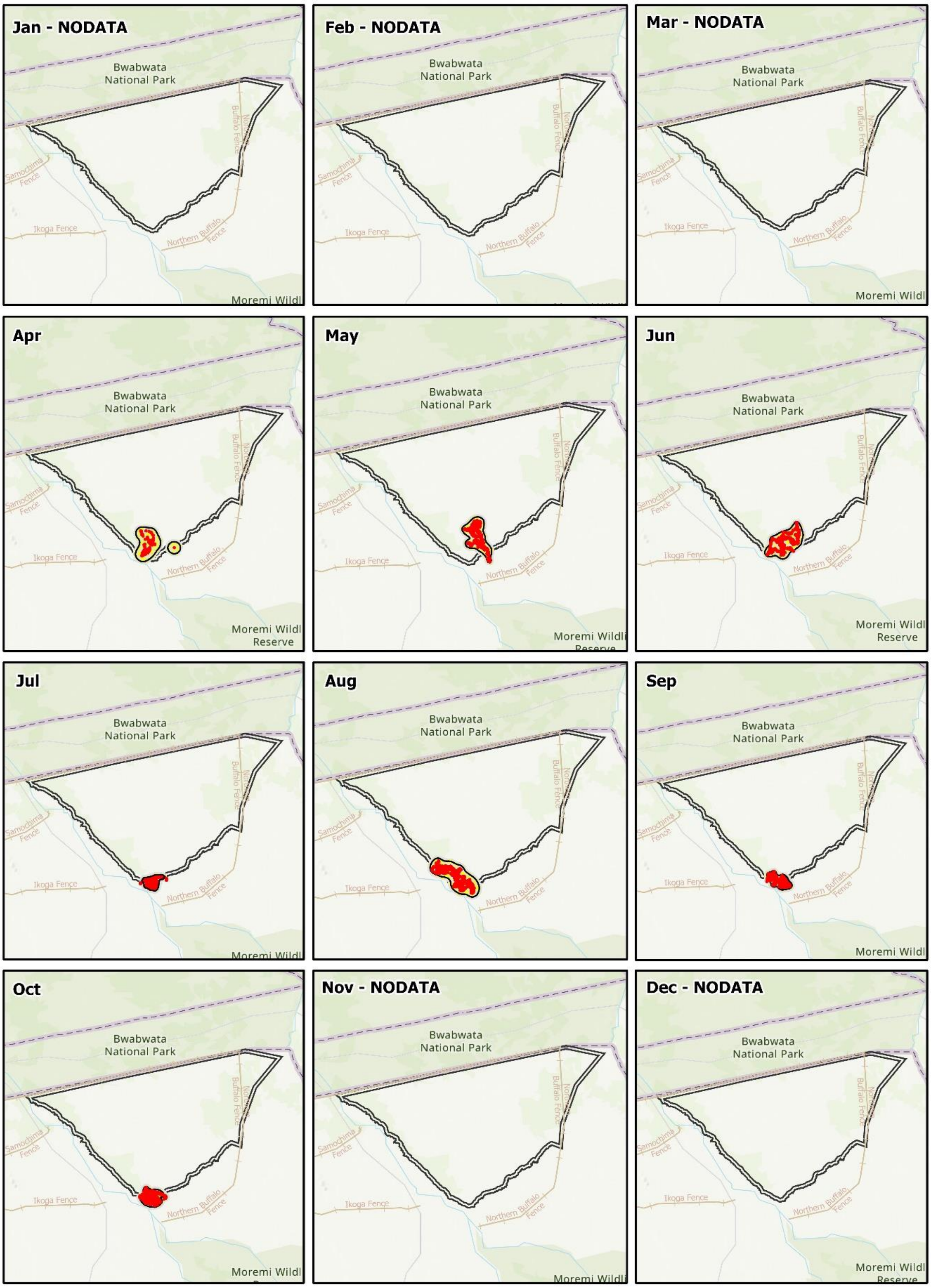
Okavango

Ebby in 2014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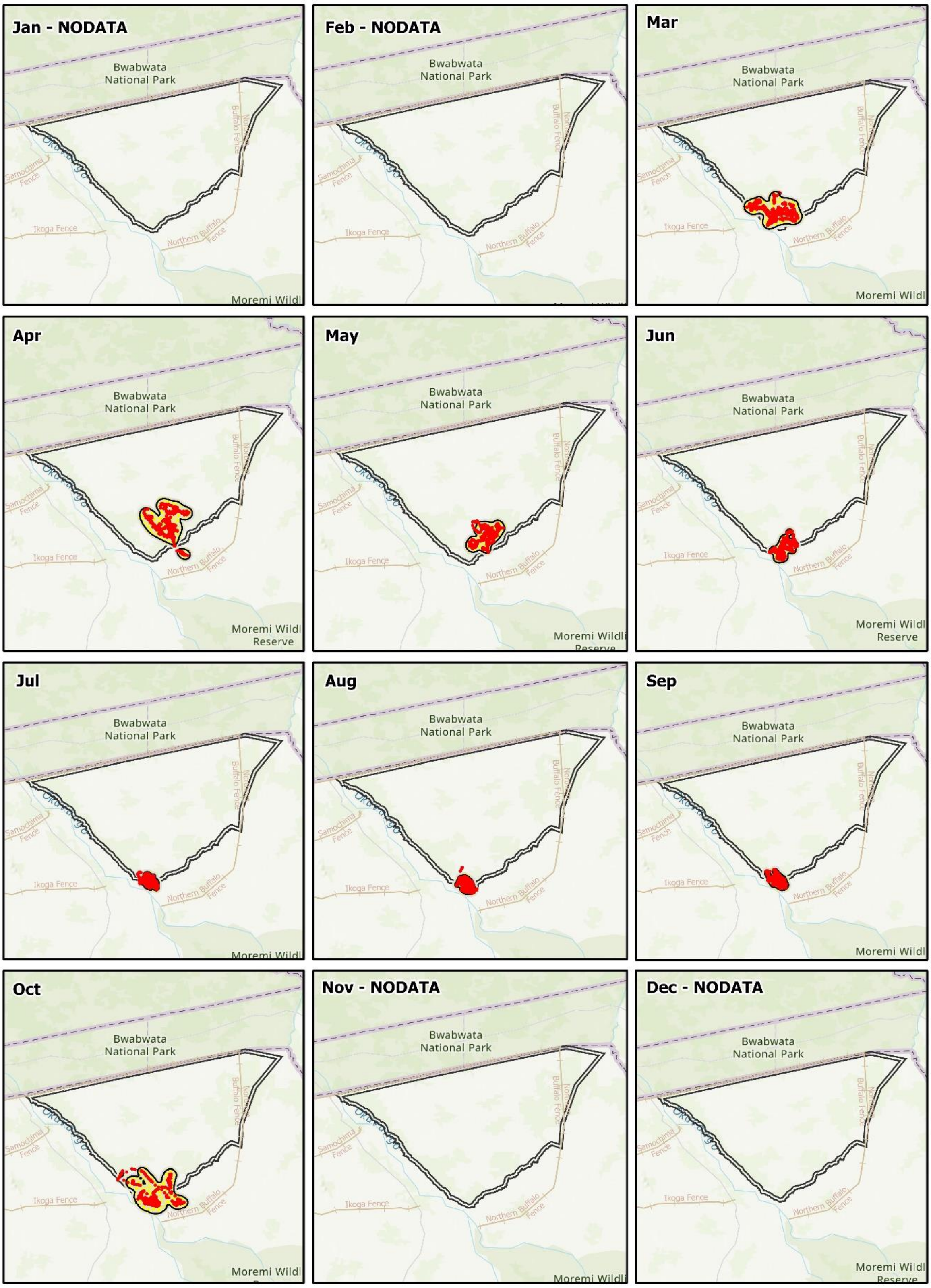
Ebby in 2015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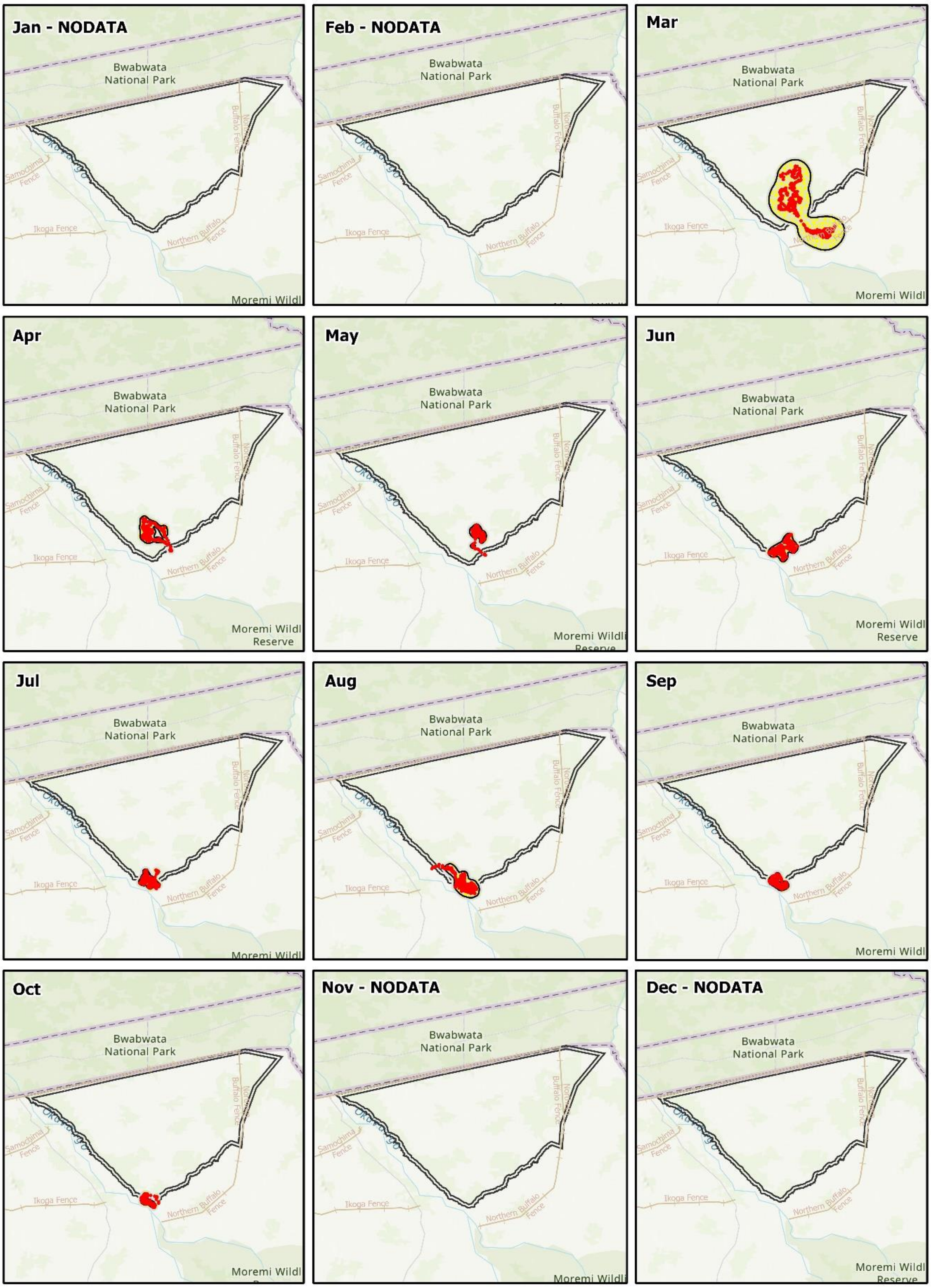
Ikoga Fence
Northern Buffalo Fence
Moremi Wildlife Reserve

Ebby in 2016



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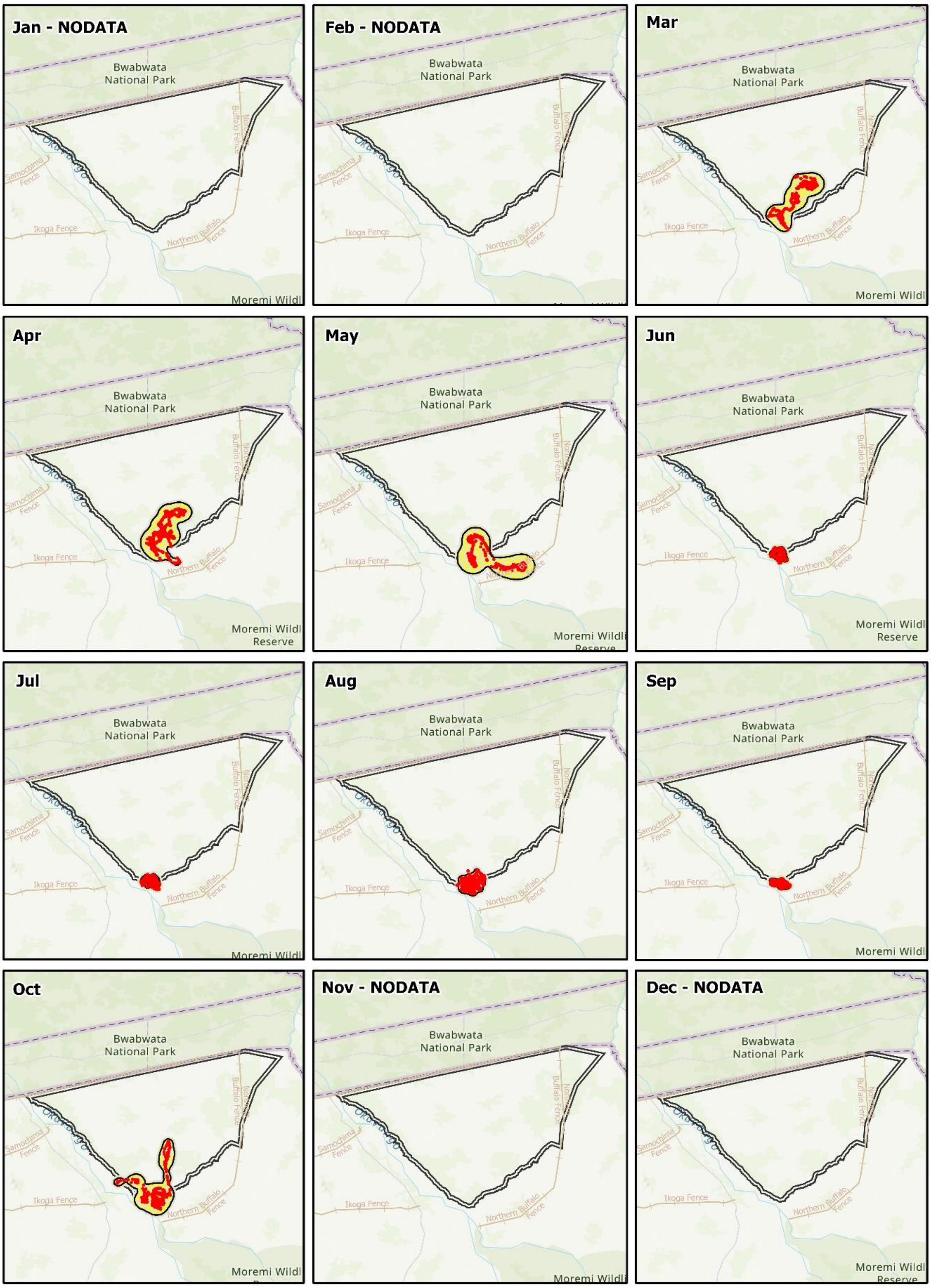
Northern Buffalo Fence
Buffalo Fence
Moremi Wildl Reserve

Ebby in 2017



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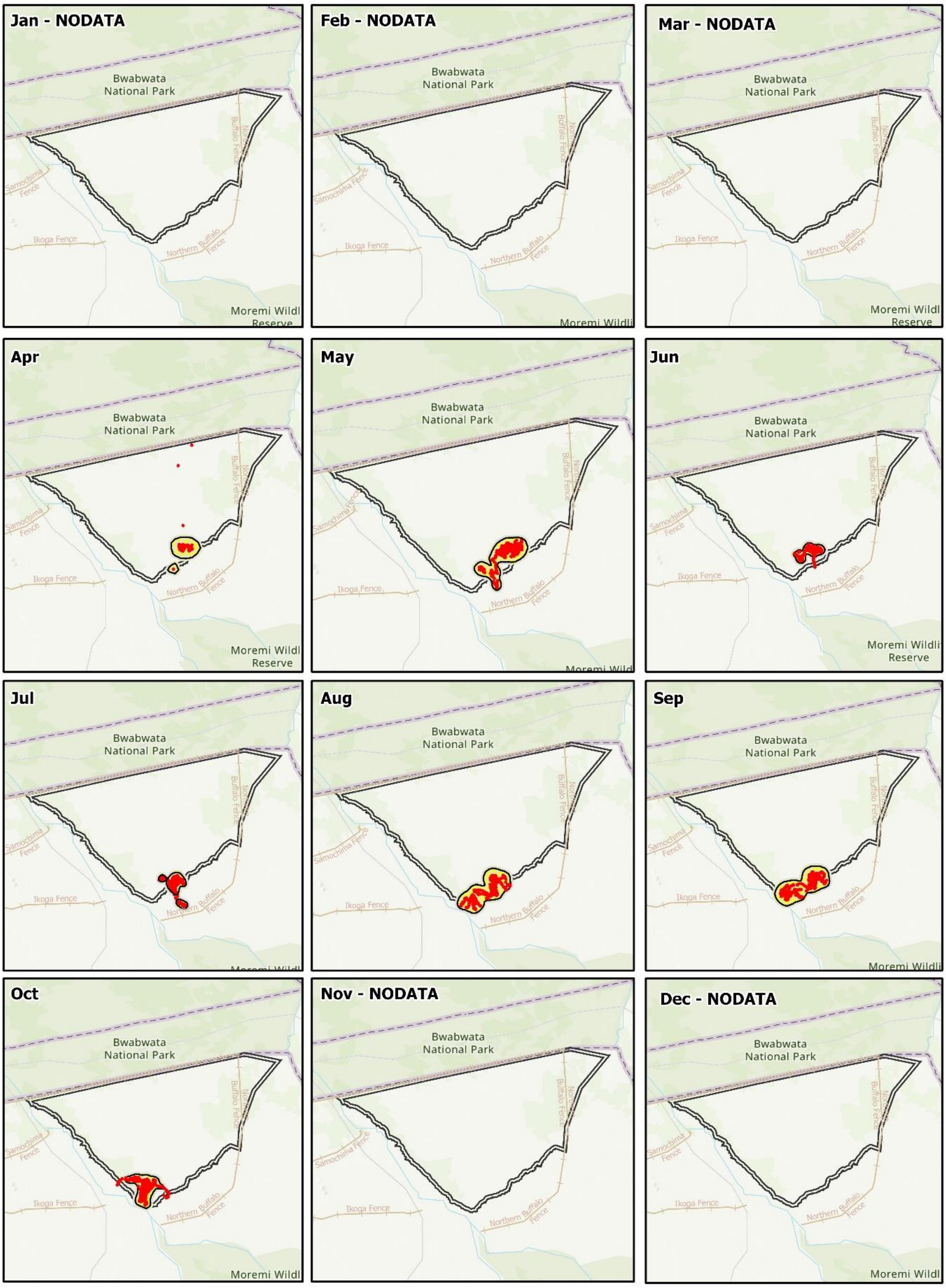
Samochima Fence
Ikoga Fence
Northern Buffalo Fence
Moremi Wildl Reserve

Koo in 2014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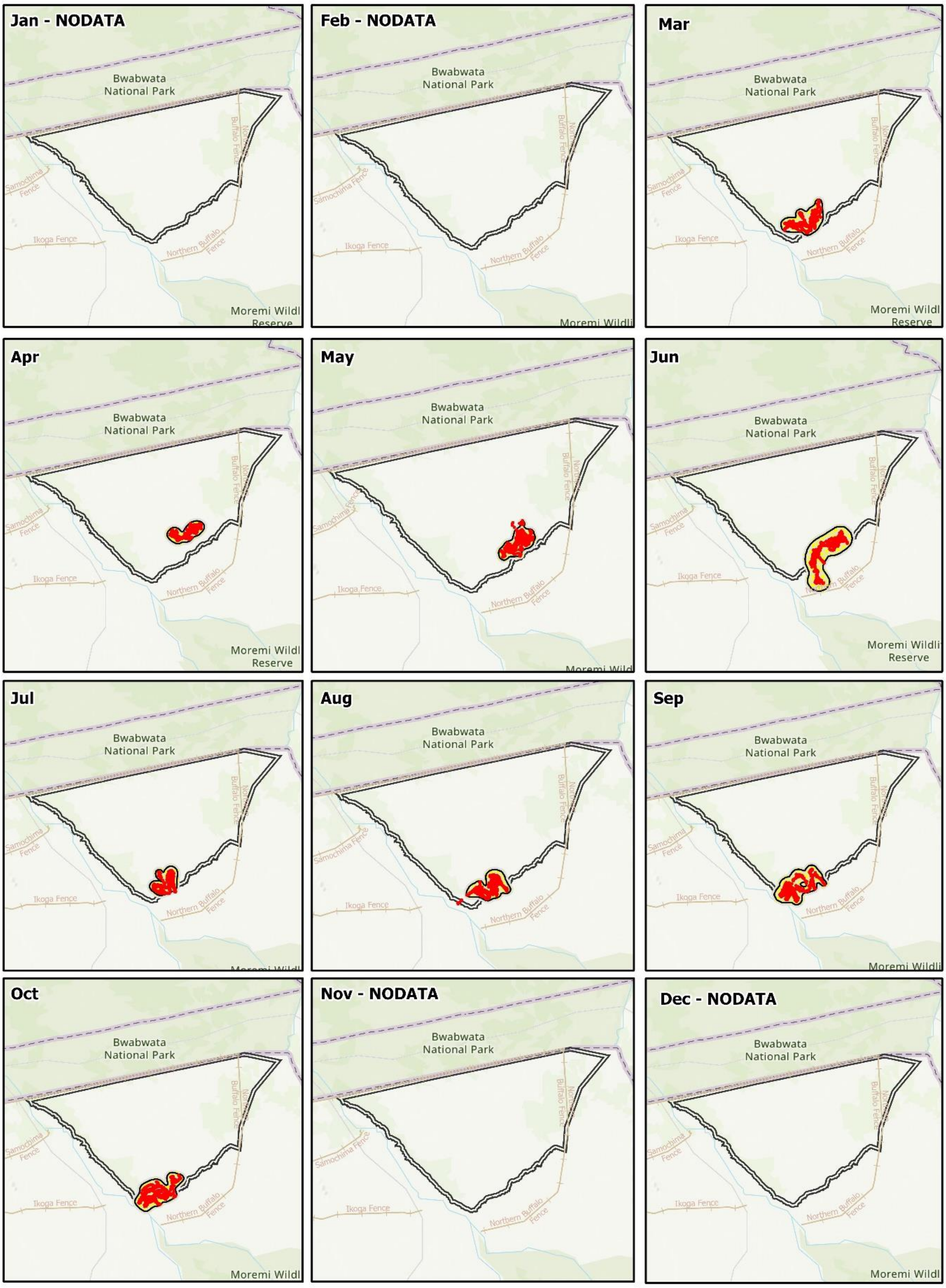
Northern Buffalo Fence
Moremi Wildl Reserve

Koo in 2015



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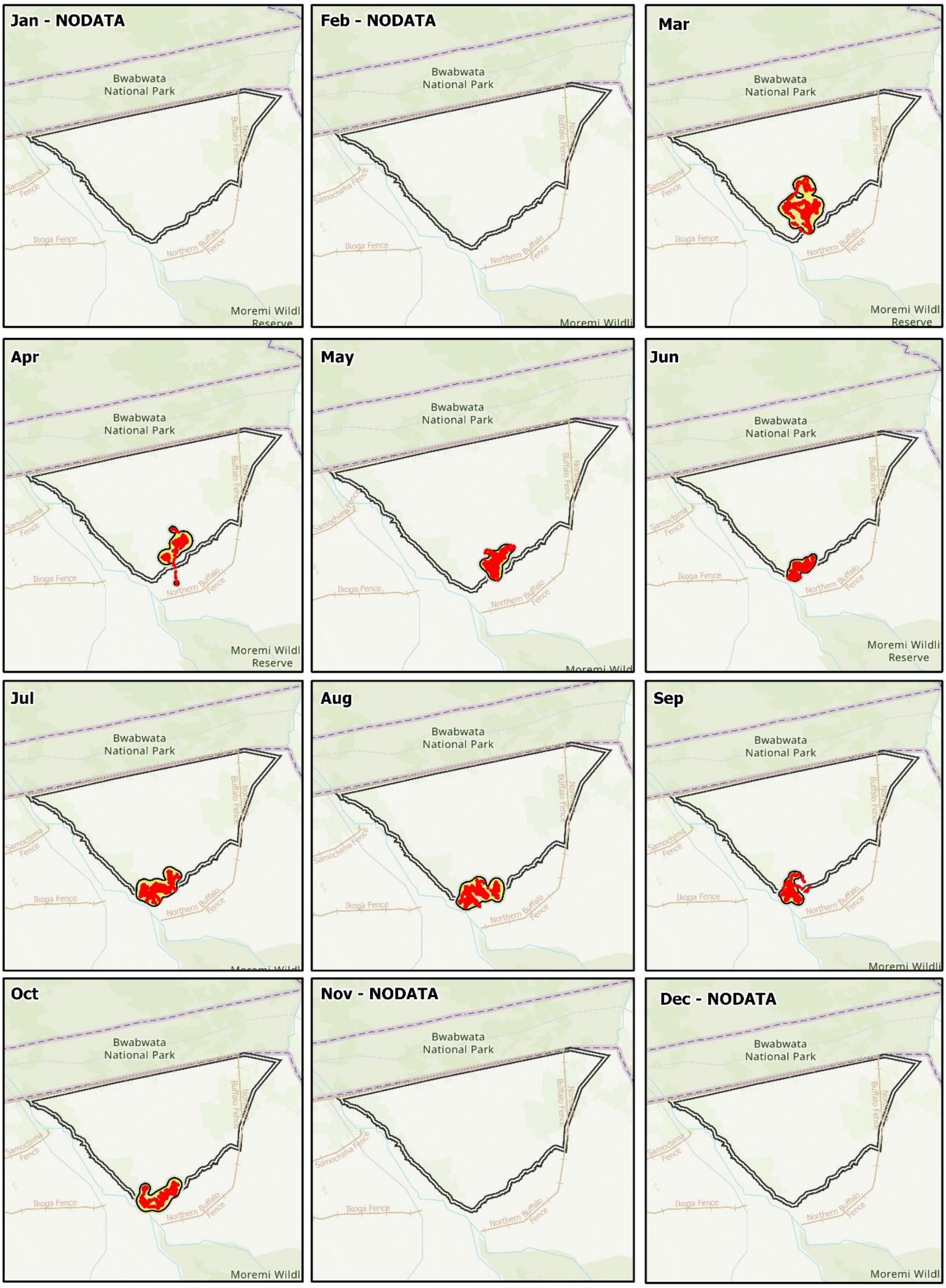
Ikoga Fence
Northern Buffalo Fence
Moremi Wildl Reserve

Koo in 2016



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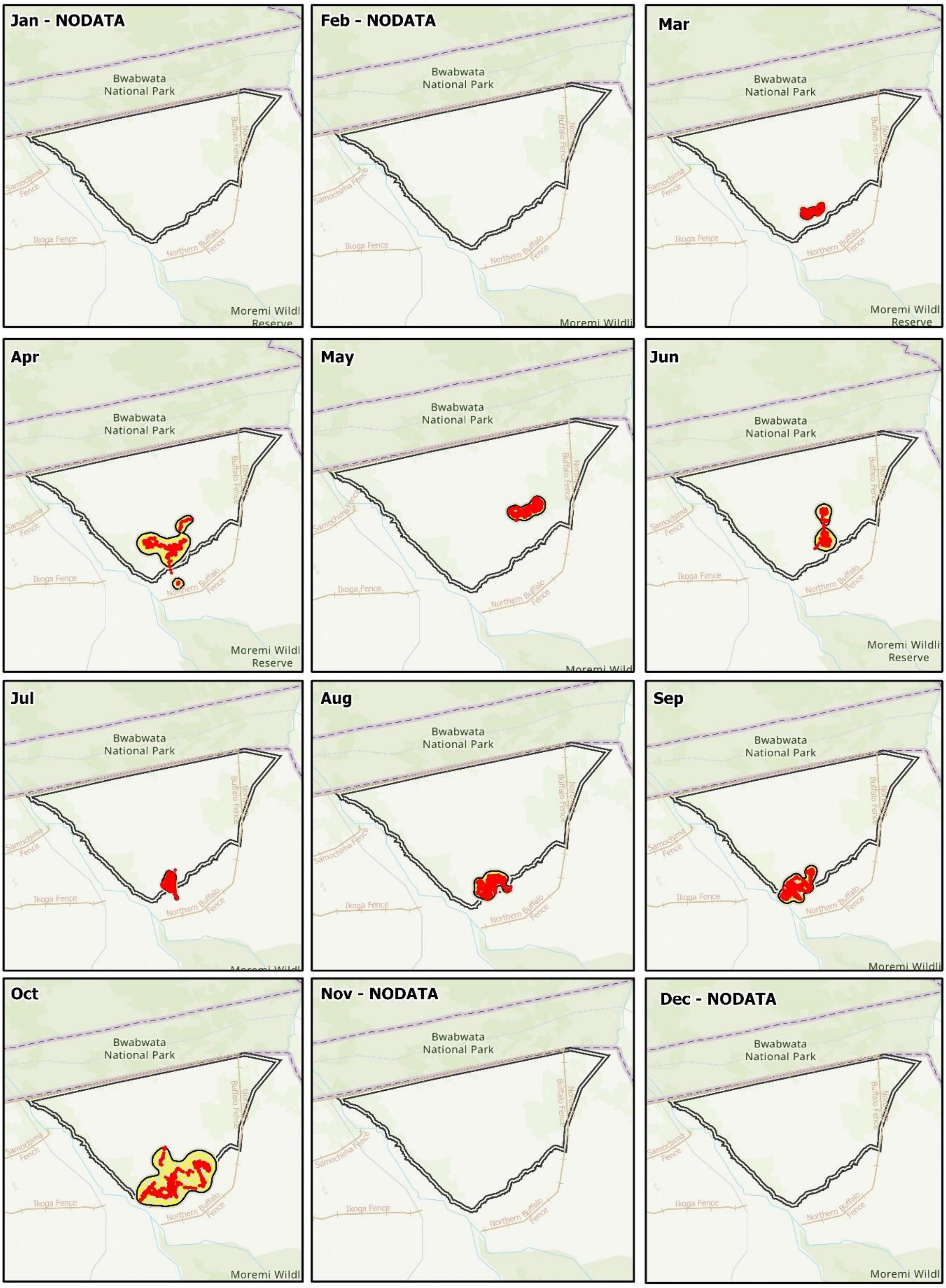
Ikoga Fence
Northern Buffalo Fence
Moremi Wildl Reserve

Koo in 2017



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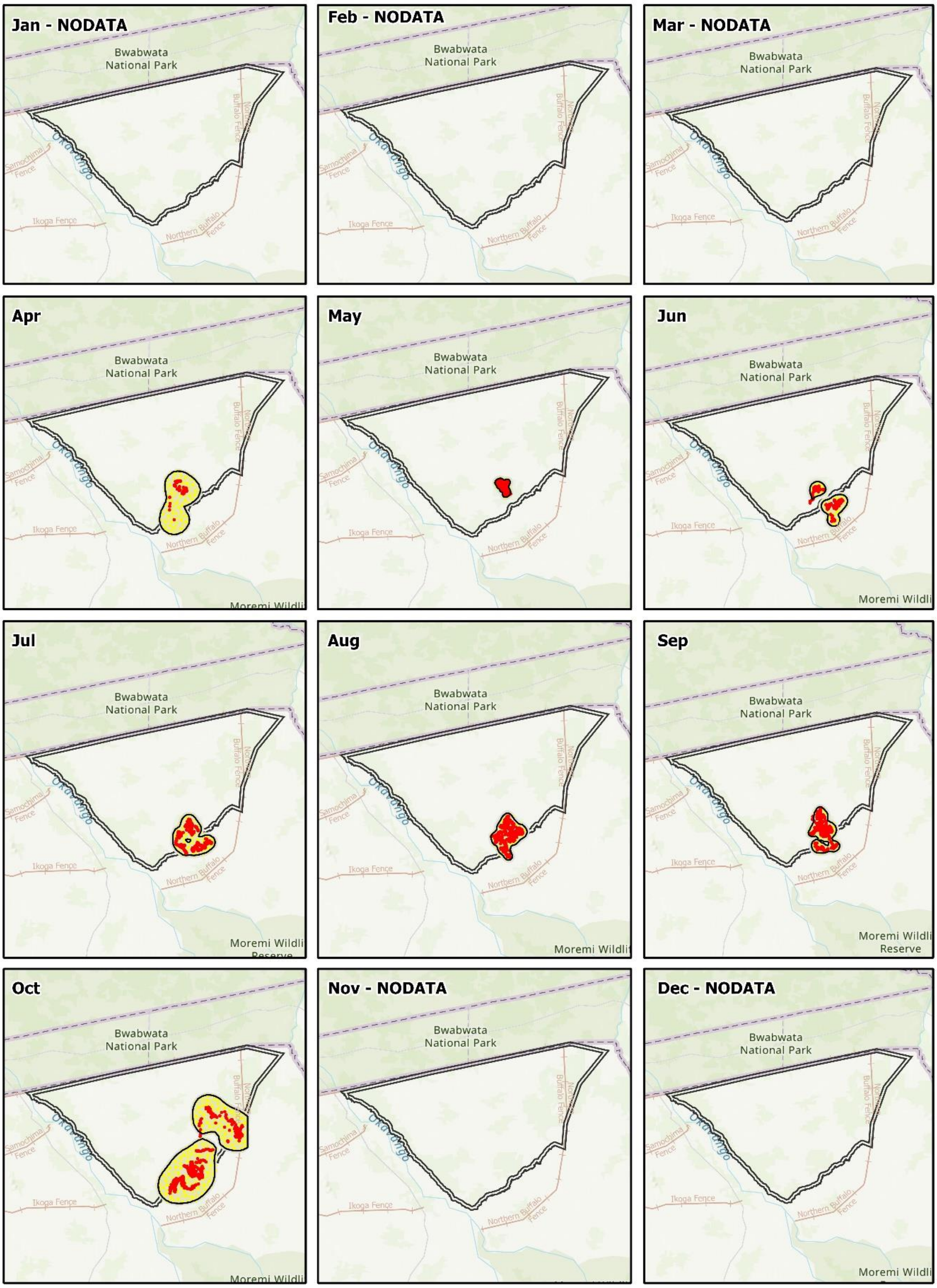
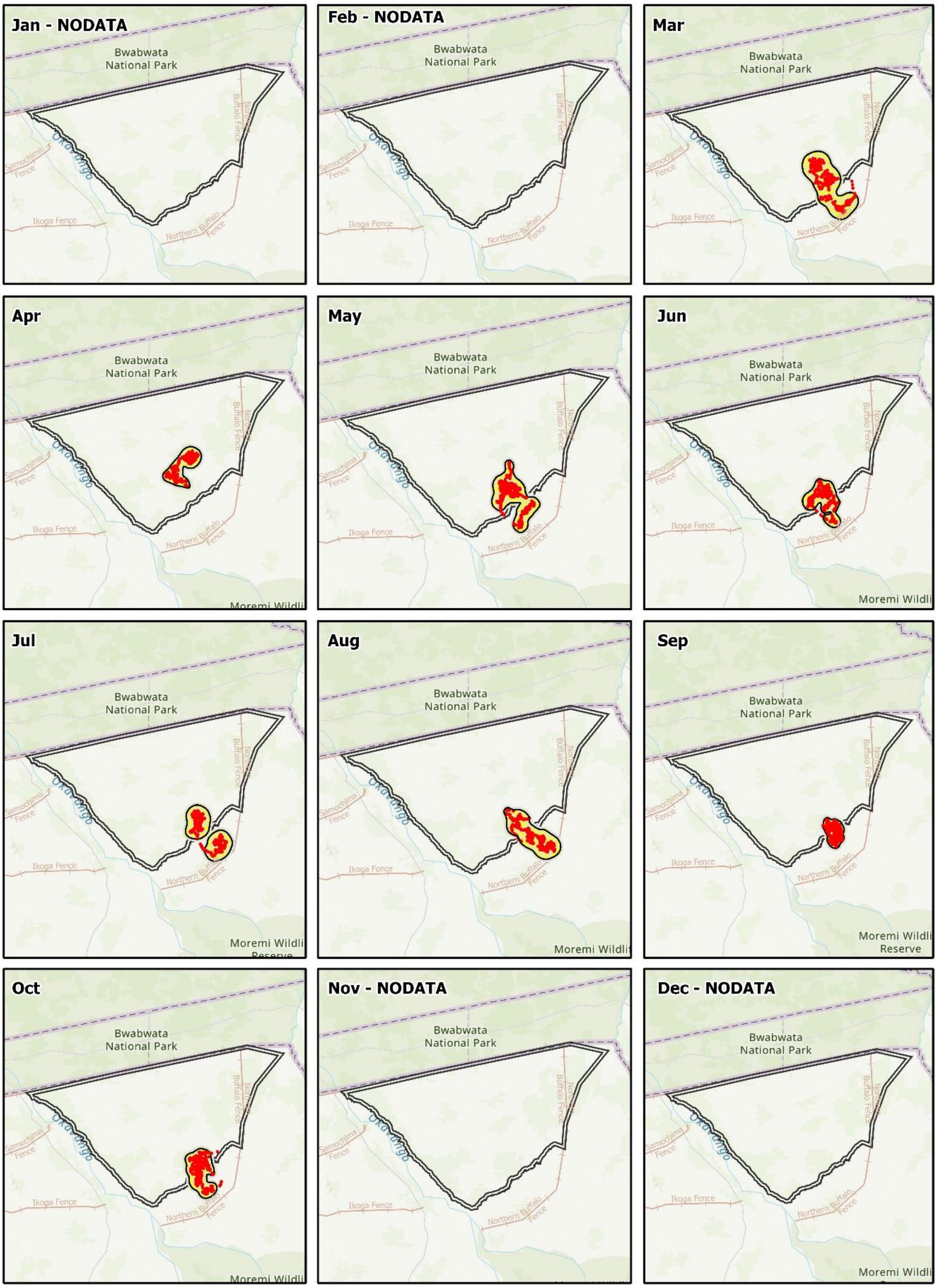
Ikoga Fence
Northern Buffalo Fence
Moremi Wildl Reserve

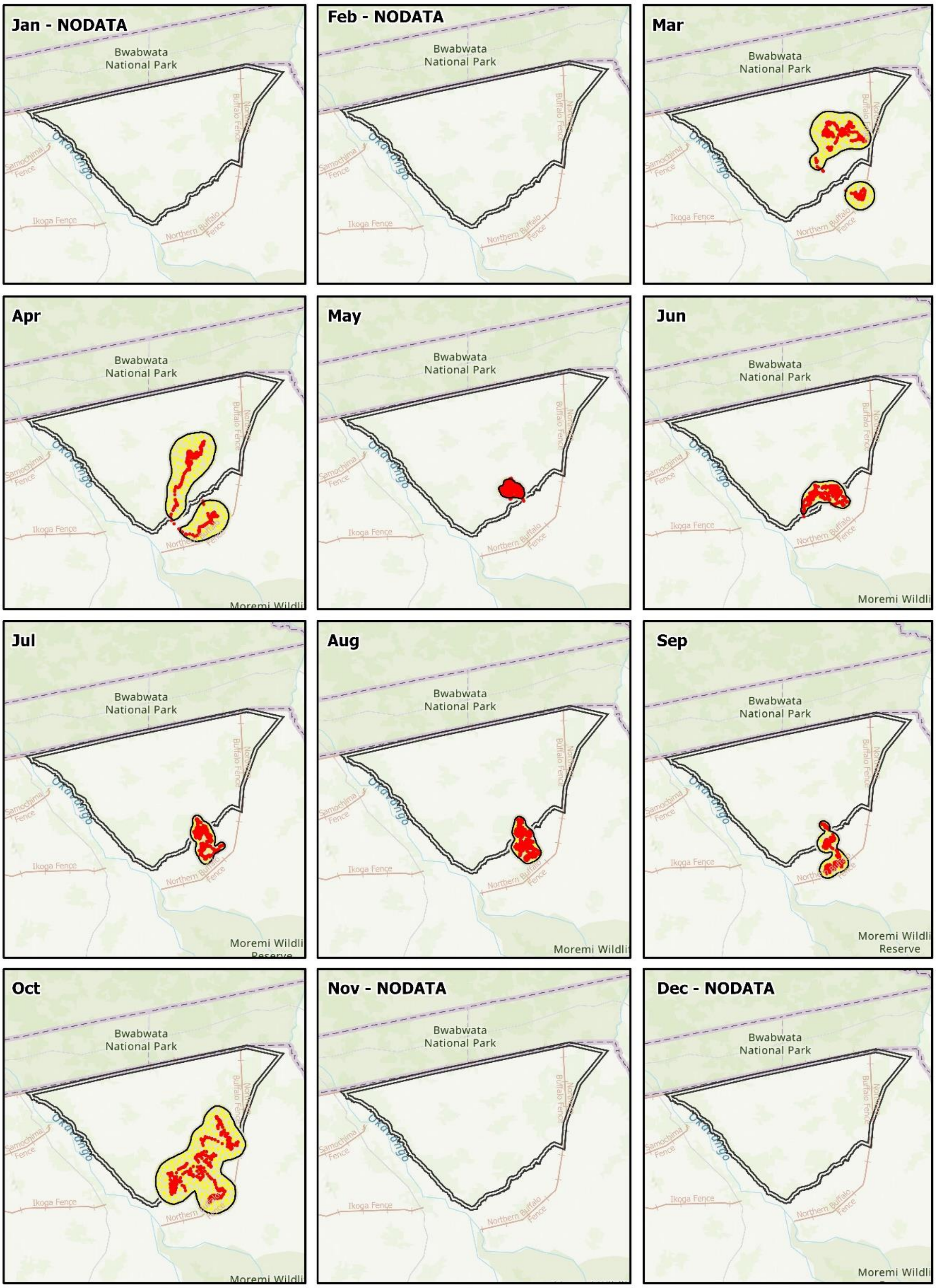
Mpule in 2014



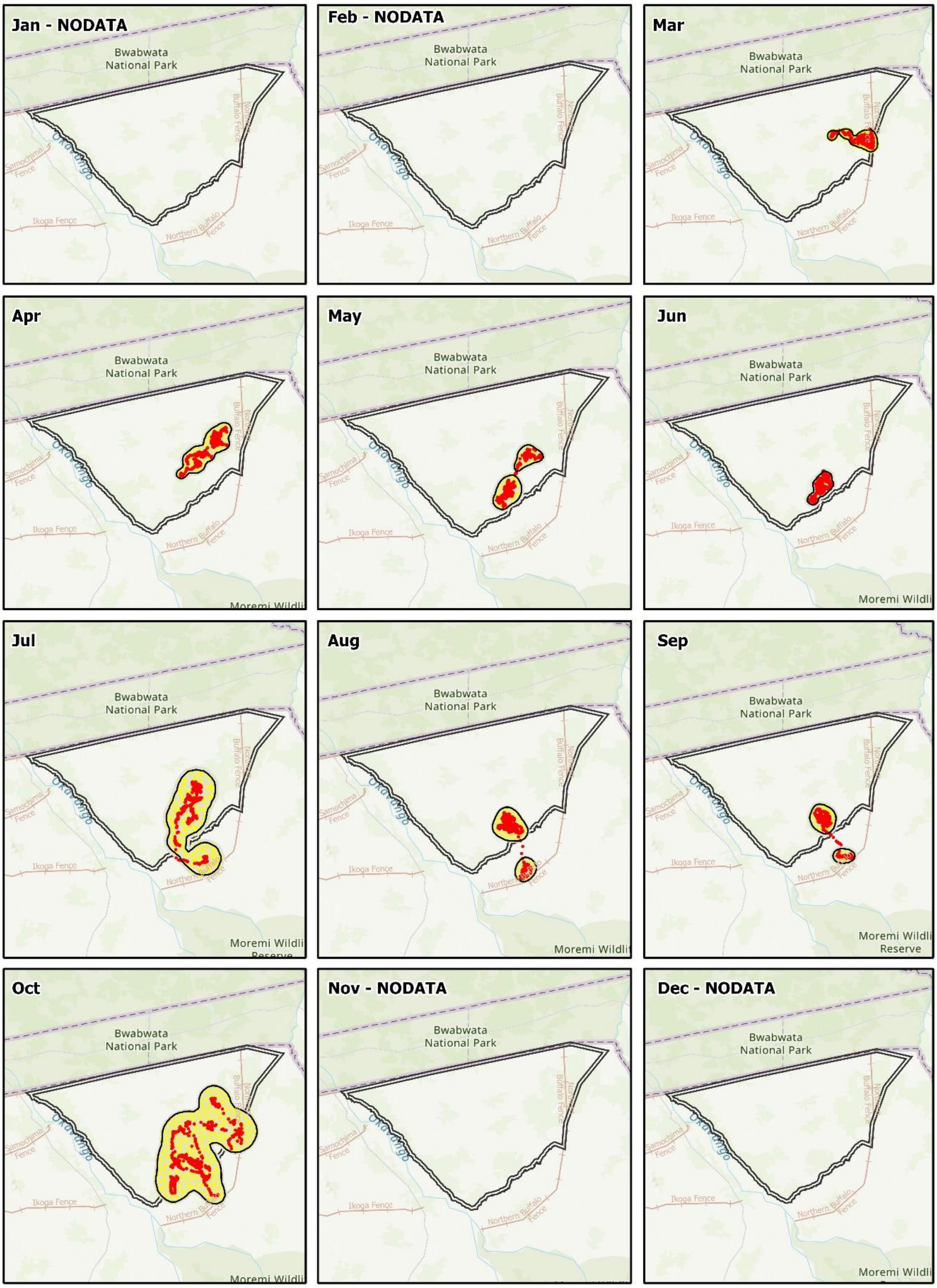
Mpule in 2015



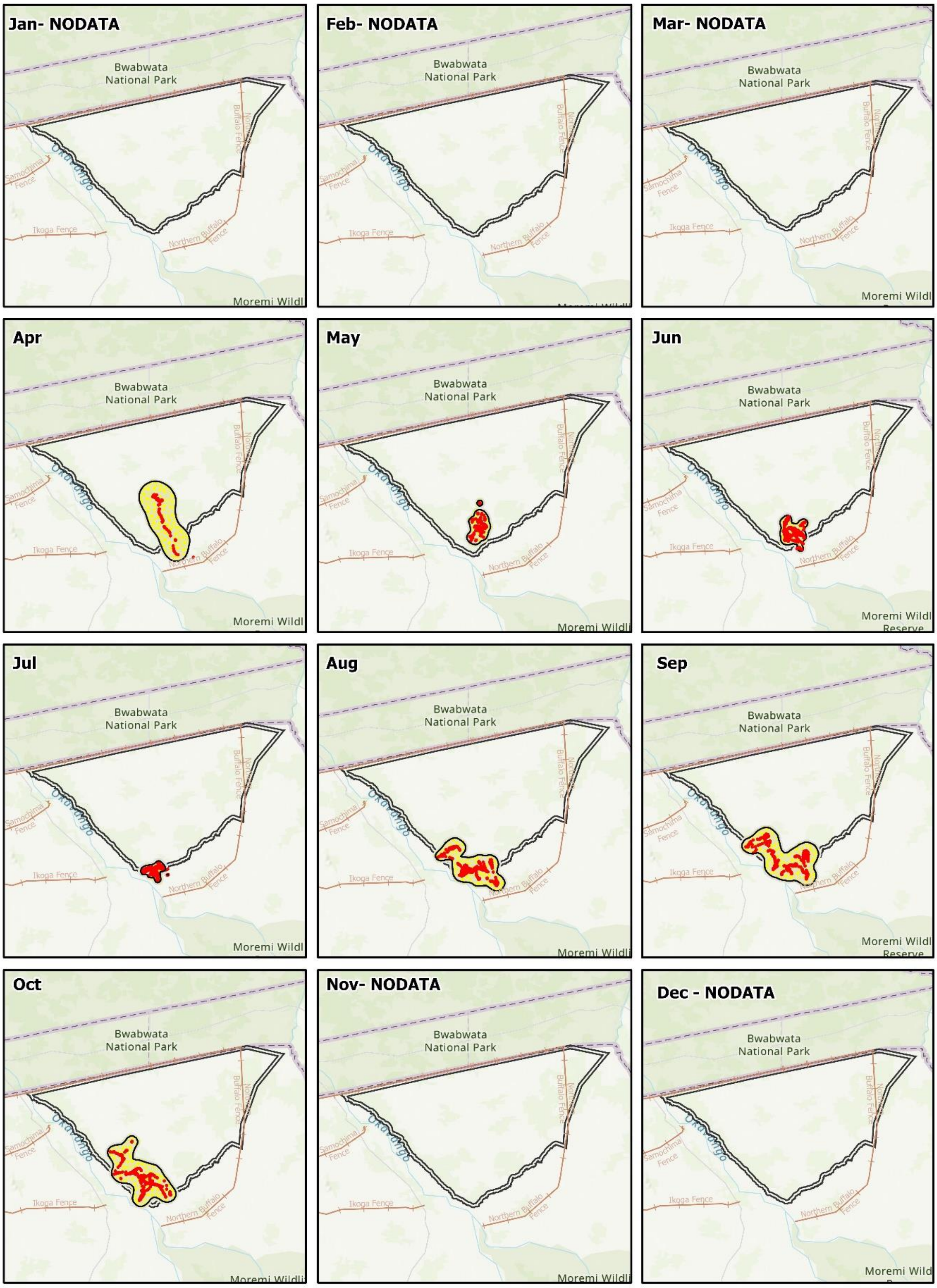
Mpule in 2016



Mpule in 2017



Nare in 2014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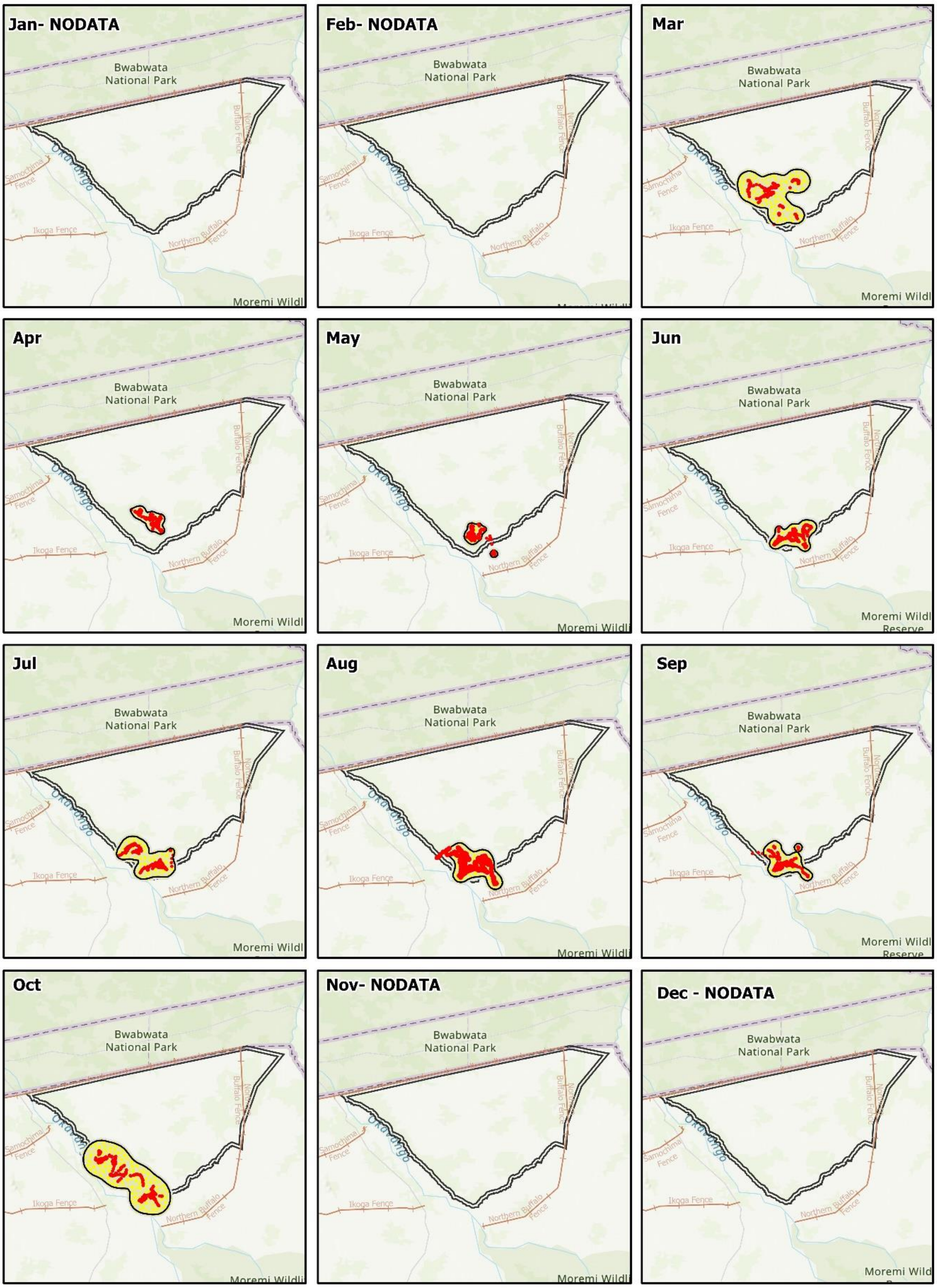
Northern Buffalo Fence
Buffalo Fence
Moremi Wildl

Nare in 2015



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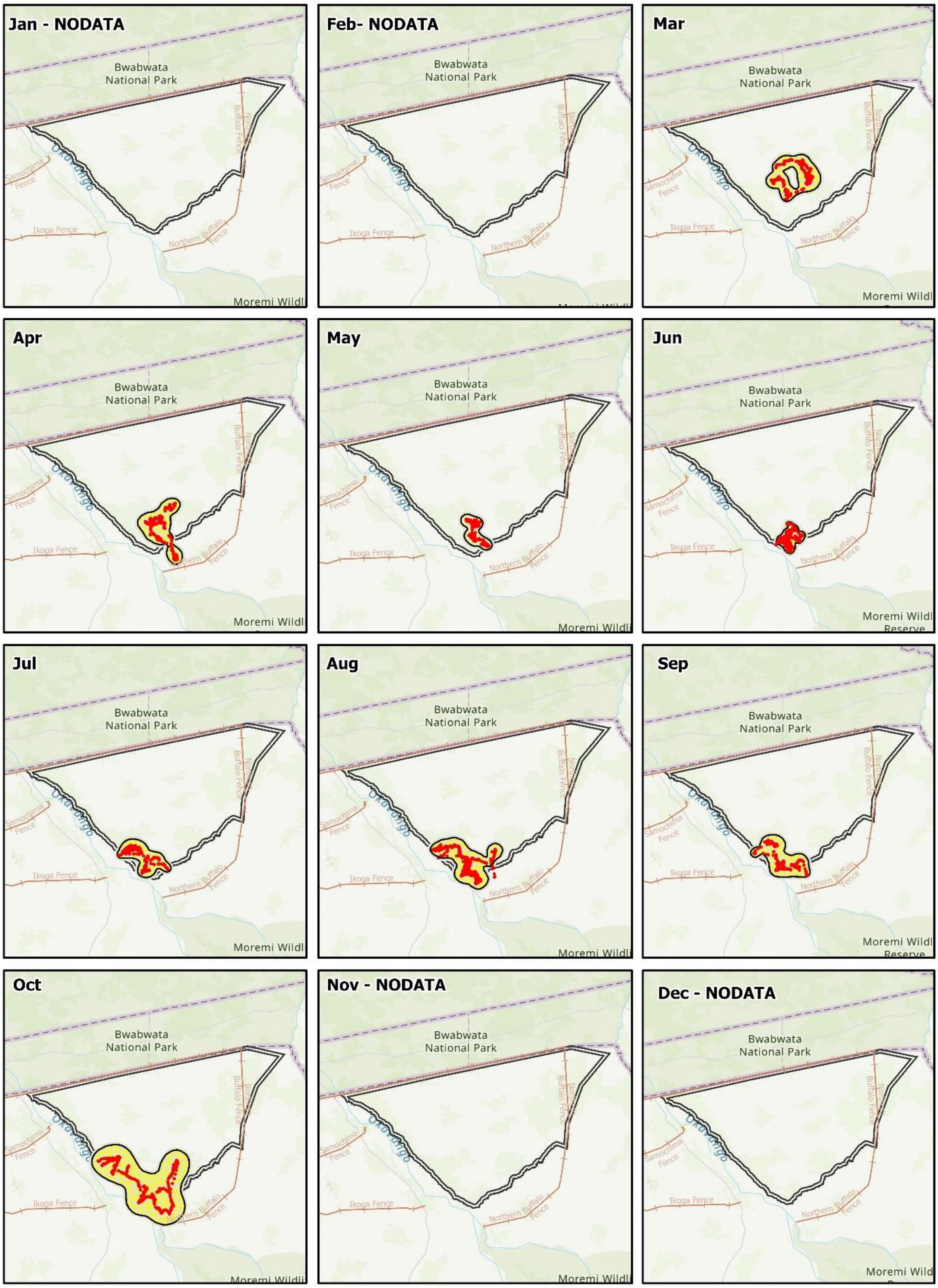
Ikoga Fence
Northern Buffalo Fence
Buffalo Fence

Nare in 2016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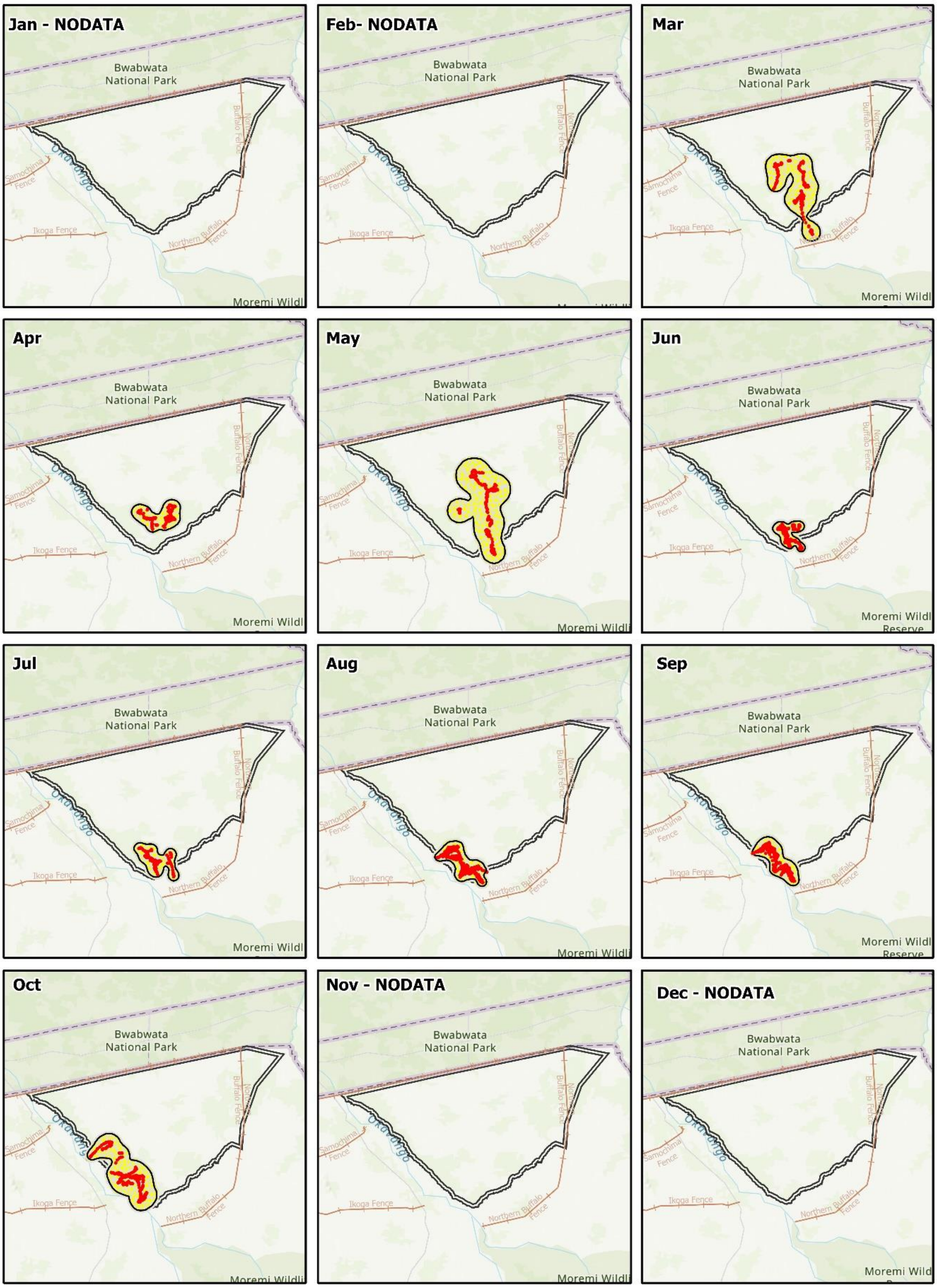
Ikoga Fence
Northern Buffalo Fence
Buffalo Fence
Moremi Wildl

Nare in 2016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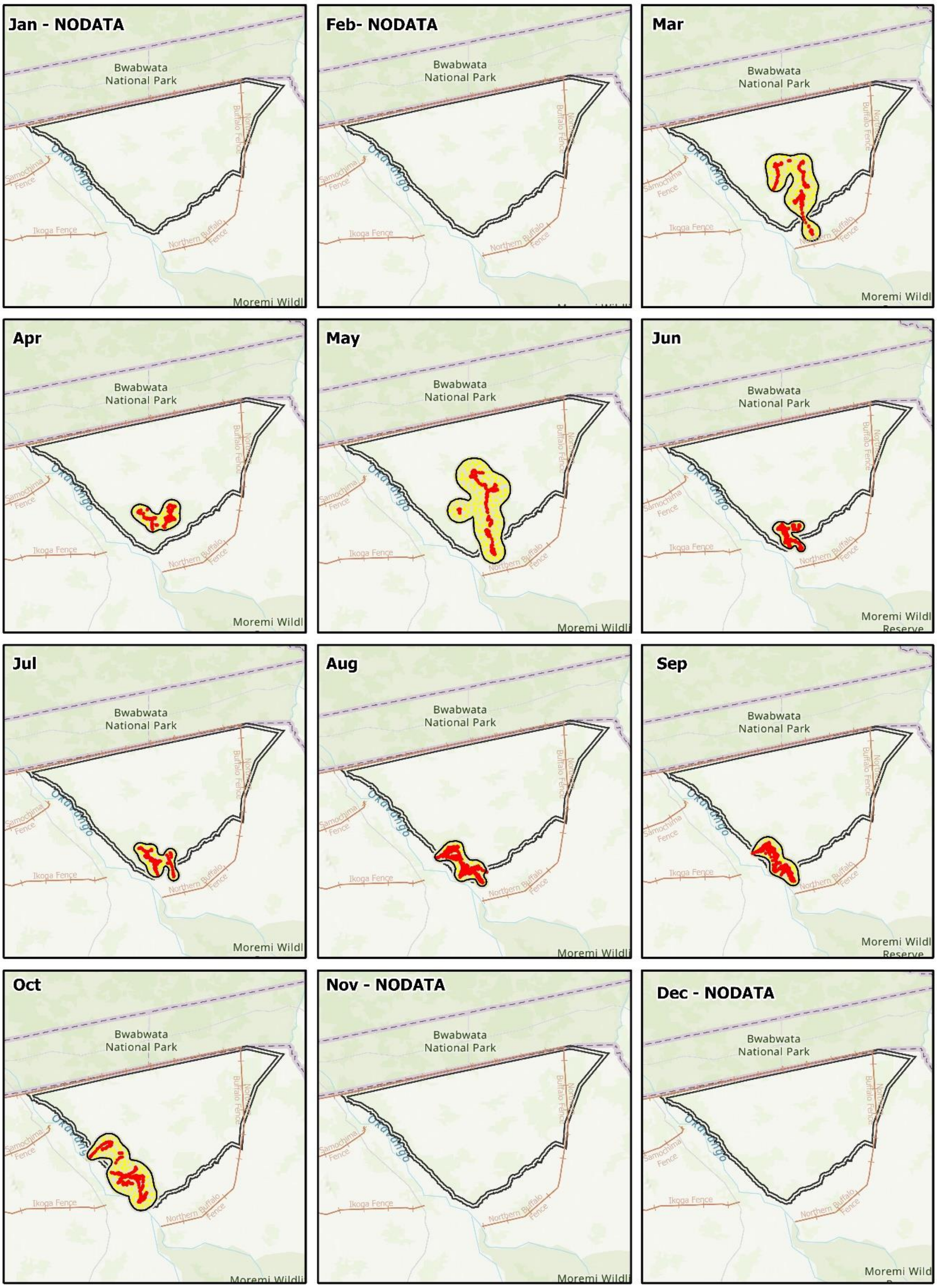
Bwabwata
National Park
Okavango
Buffalo Fence
Samochima Fence
Ikoga Fence
Northern Buffalo Fence

Nare in 2016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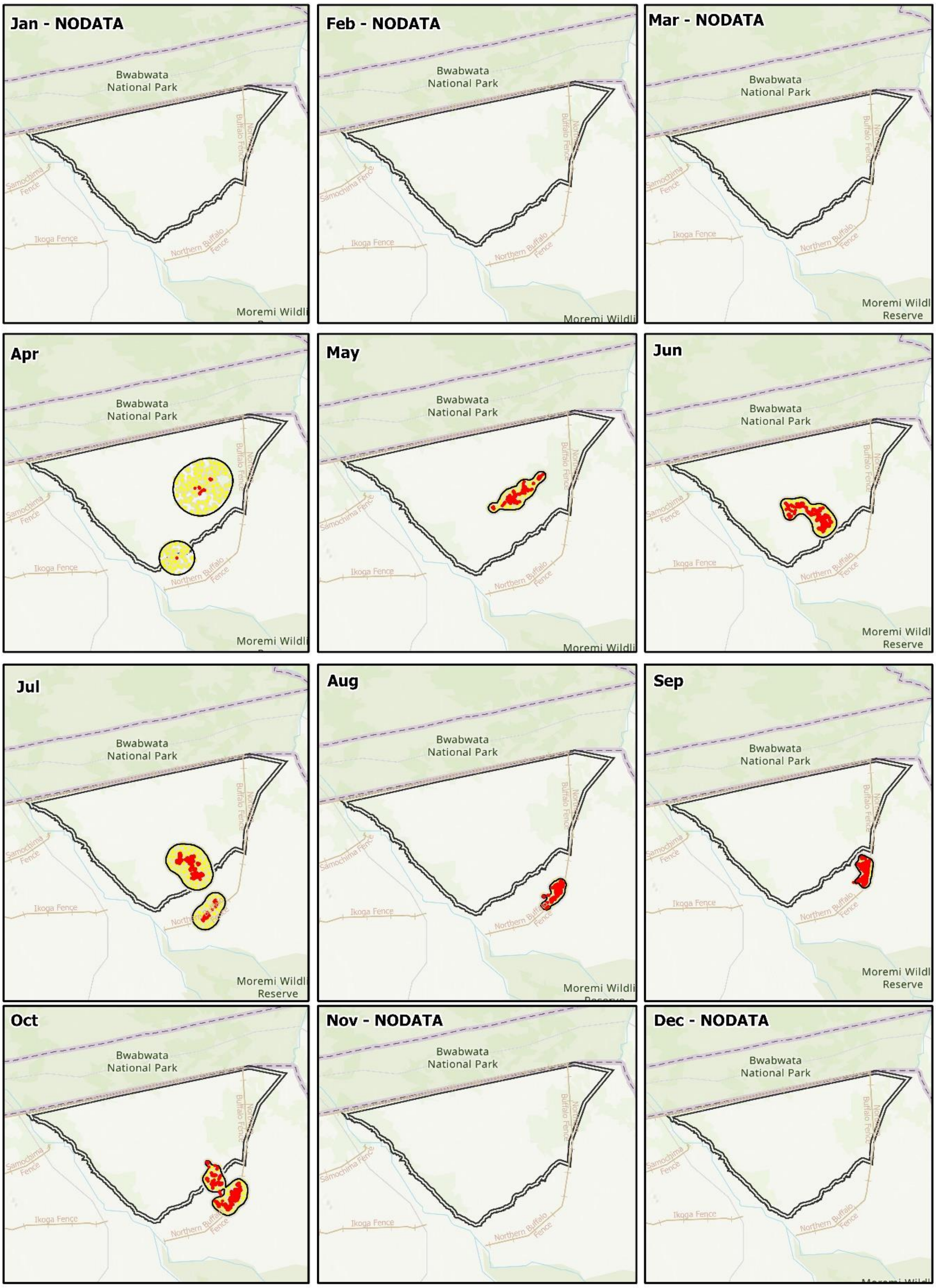
National Park
Okavango
Samochima
Fence
Ikoga Fence
Northern Buffalo
Fence
Buffalo Fence

Rain in 2014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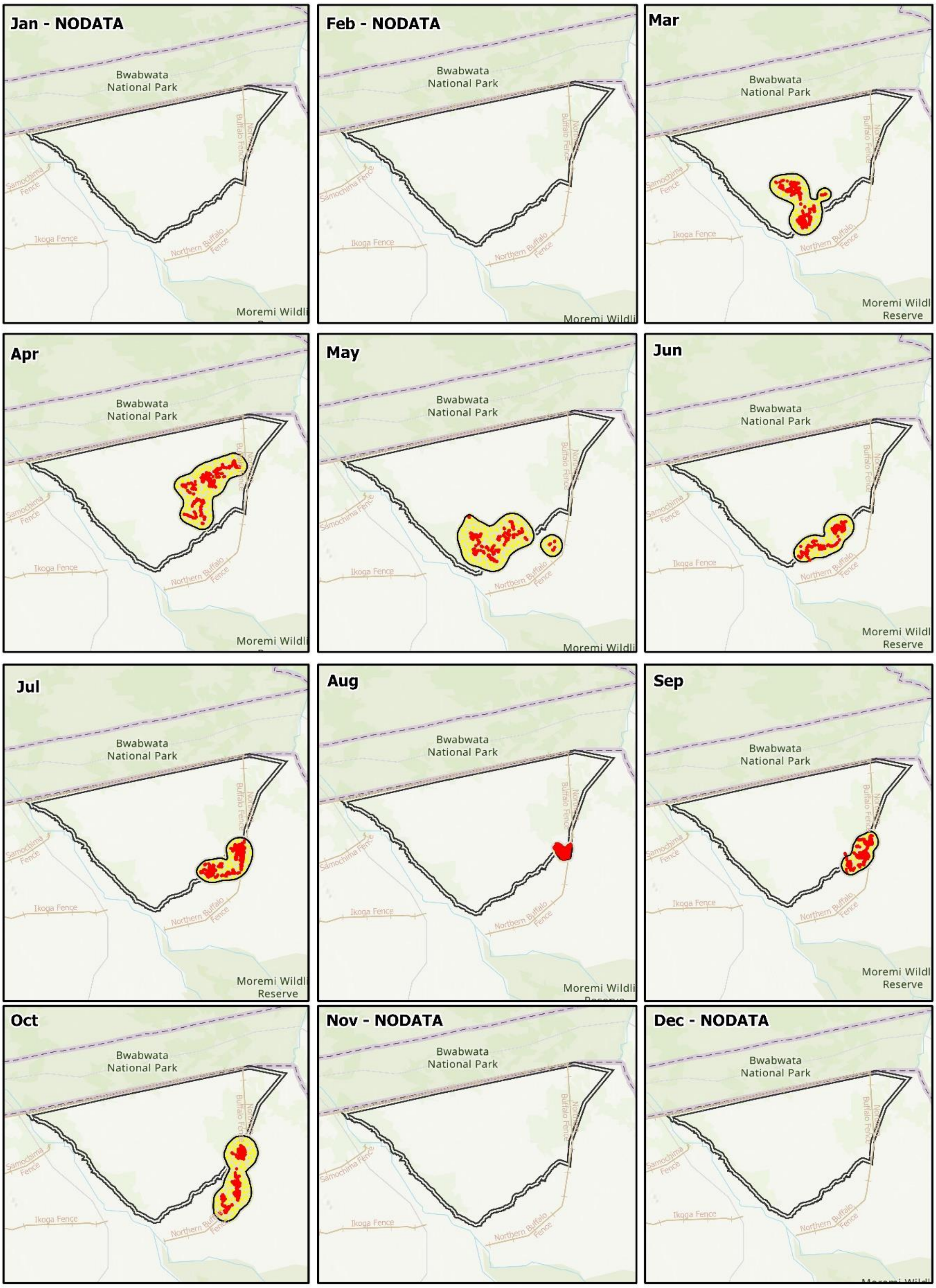
Moremi Wildl
Reserve
Ikoga Fence
Northern Buffalo Fence
Samochima Fence
Buffalo Fence

Rain in 2015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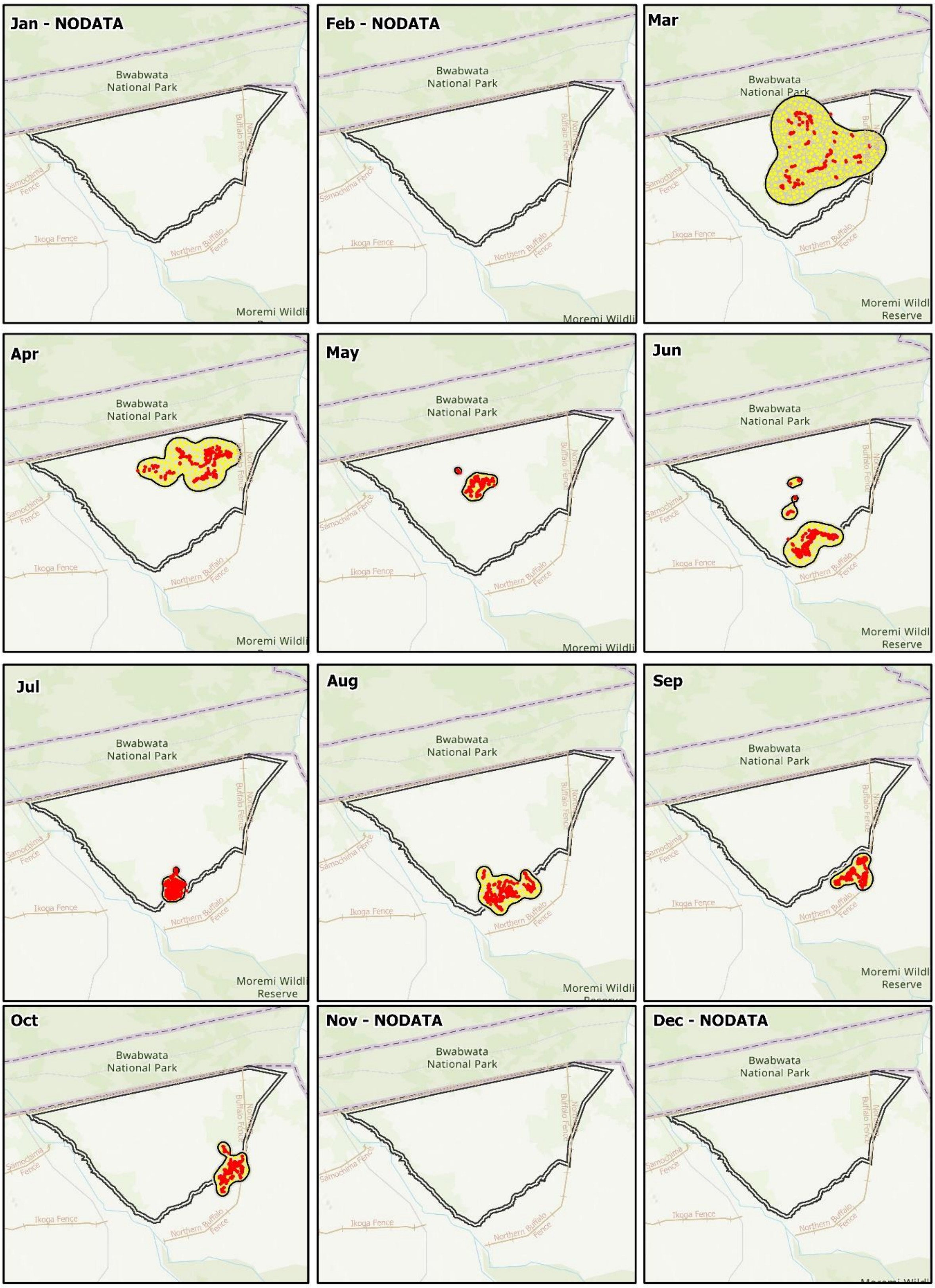
Ikoga Fence
Northern Buffalo Fence
Buffalo Fence
Moremi Wildl
Reserve

Rain in 2016



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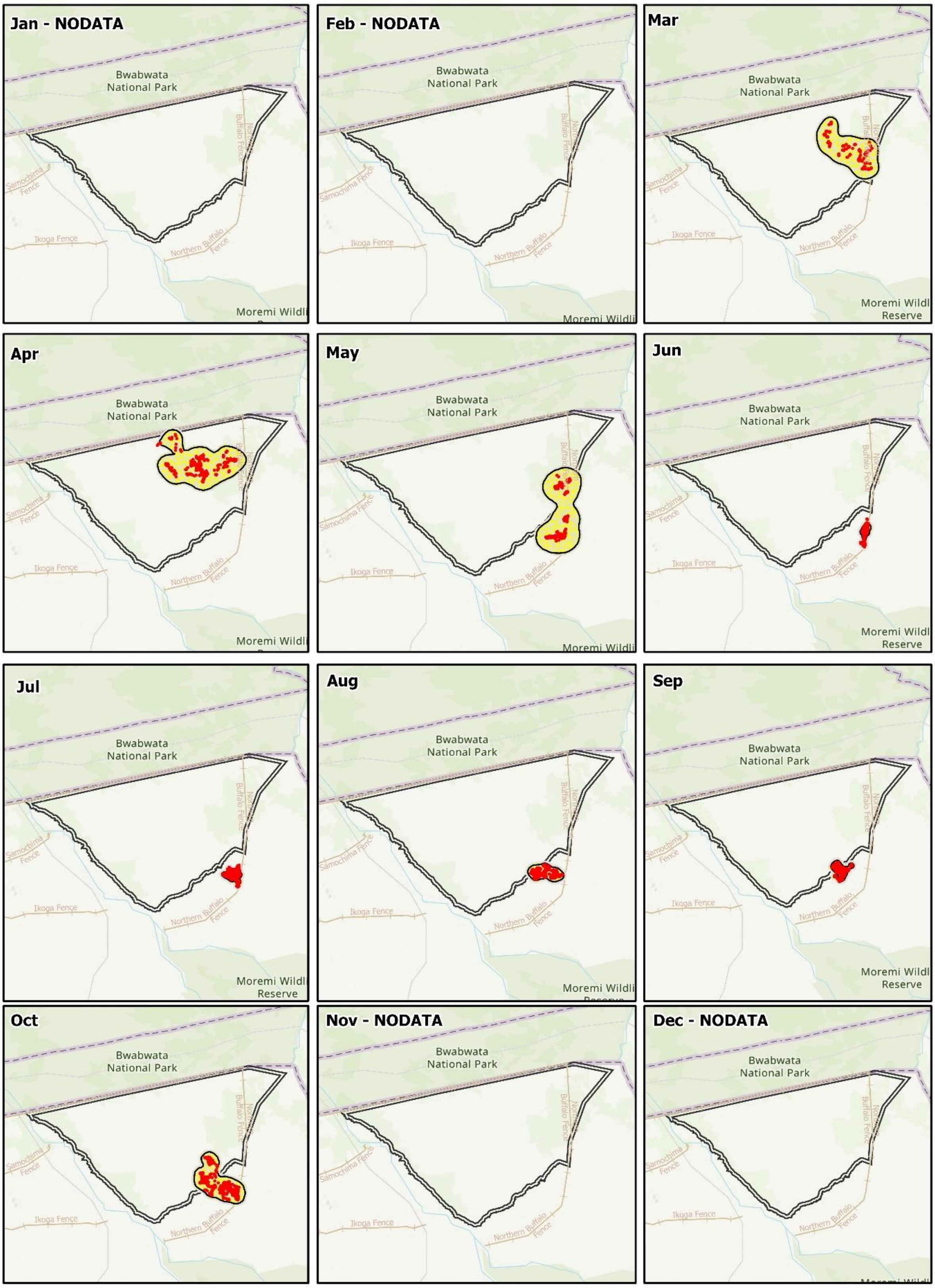
Samochima Fence
Ikoga Fence
Northern Buffalo Fence
Buffalo Fence
Moremi Wildl Reserve

Rain in 2017



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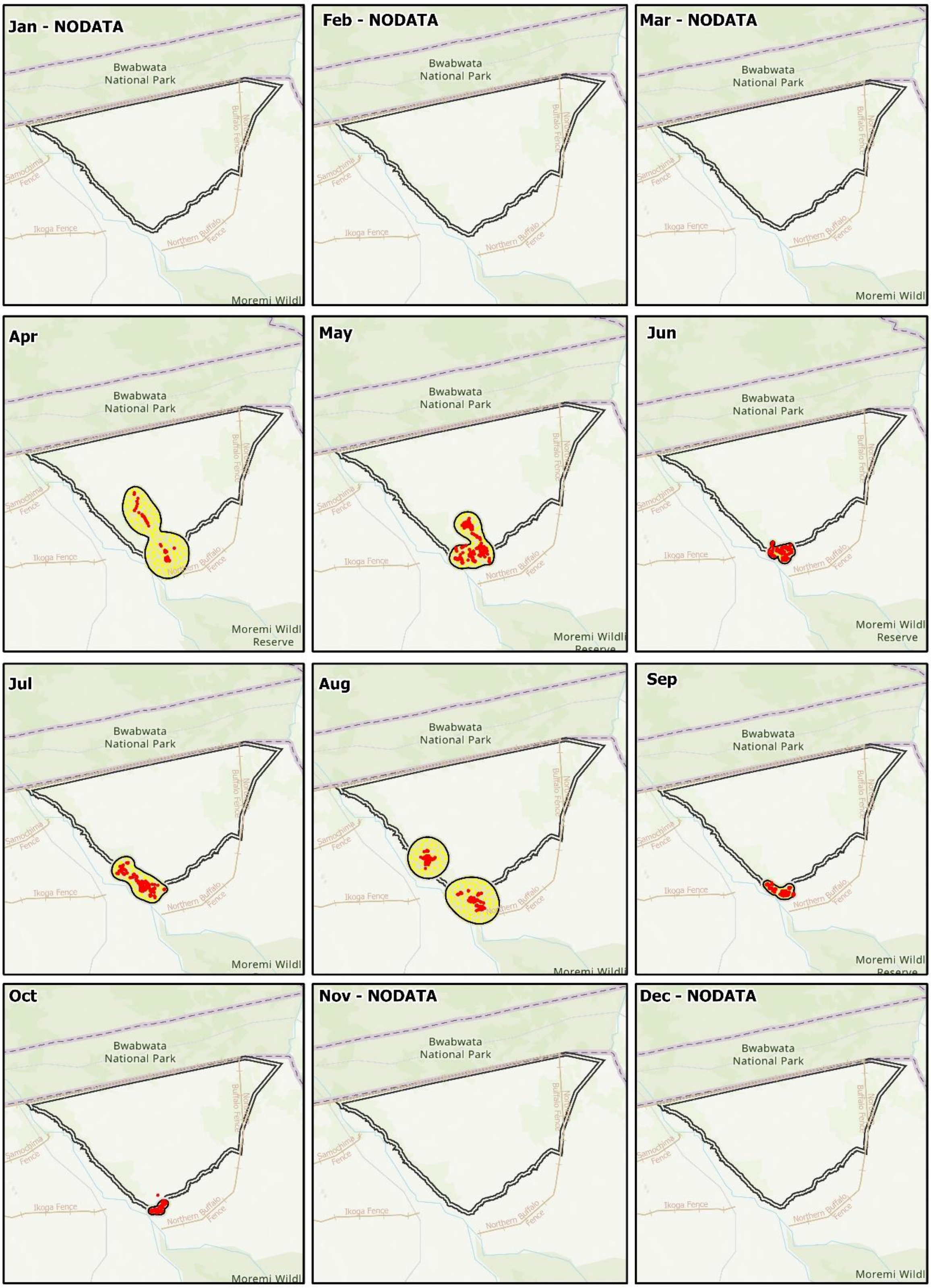
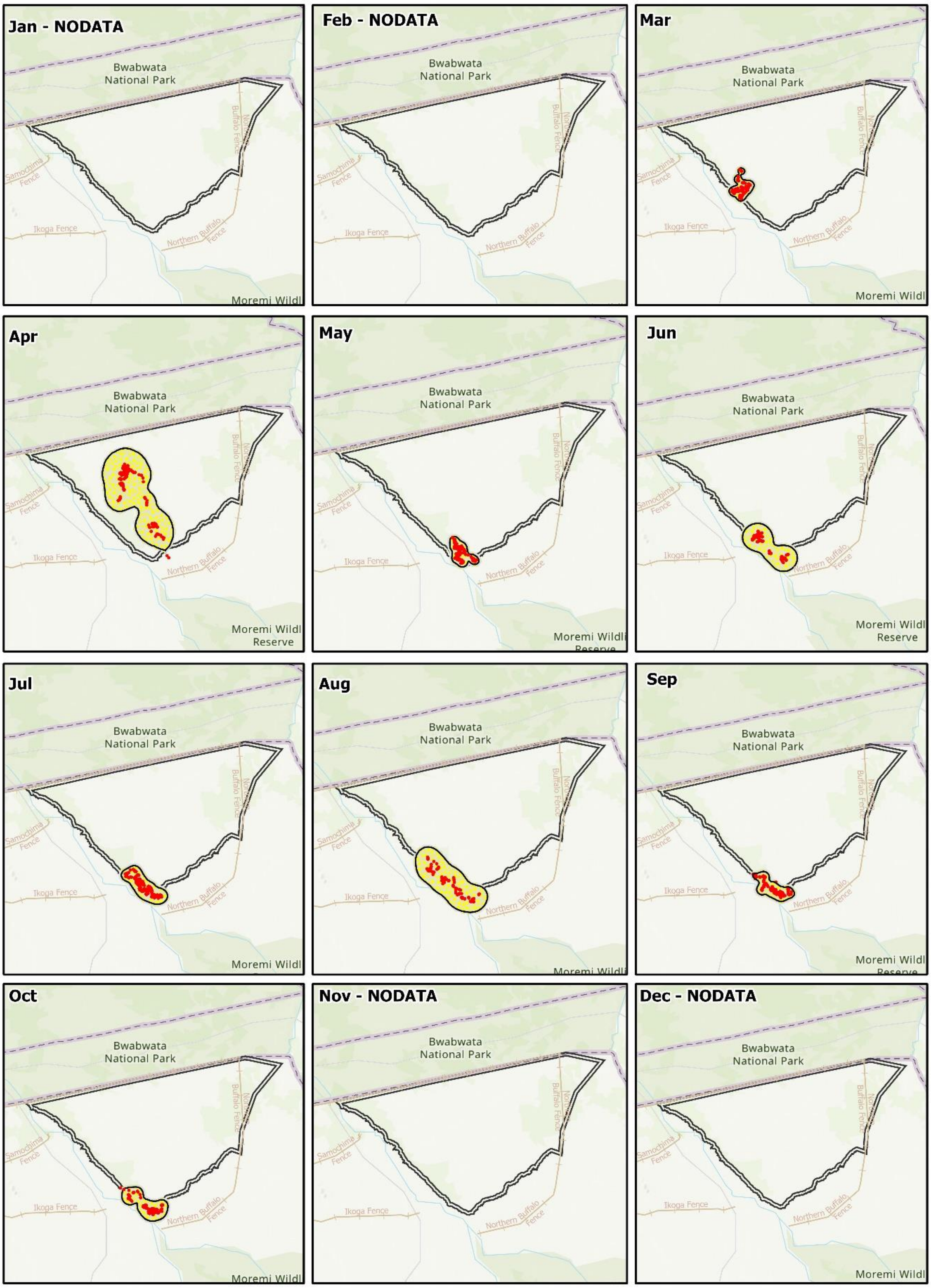
National Park
Samochima
Fence
Ikoga Fence
Northern Buffalo
Fence
Reserve

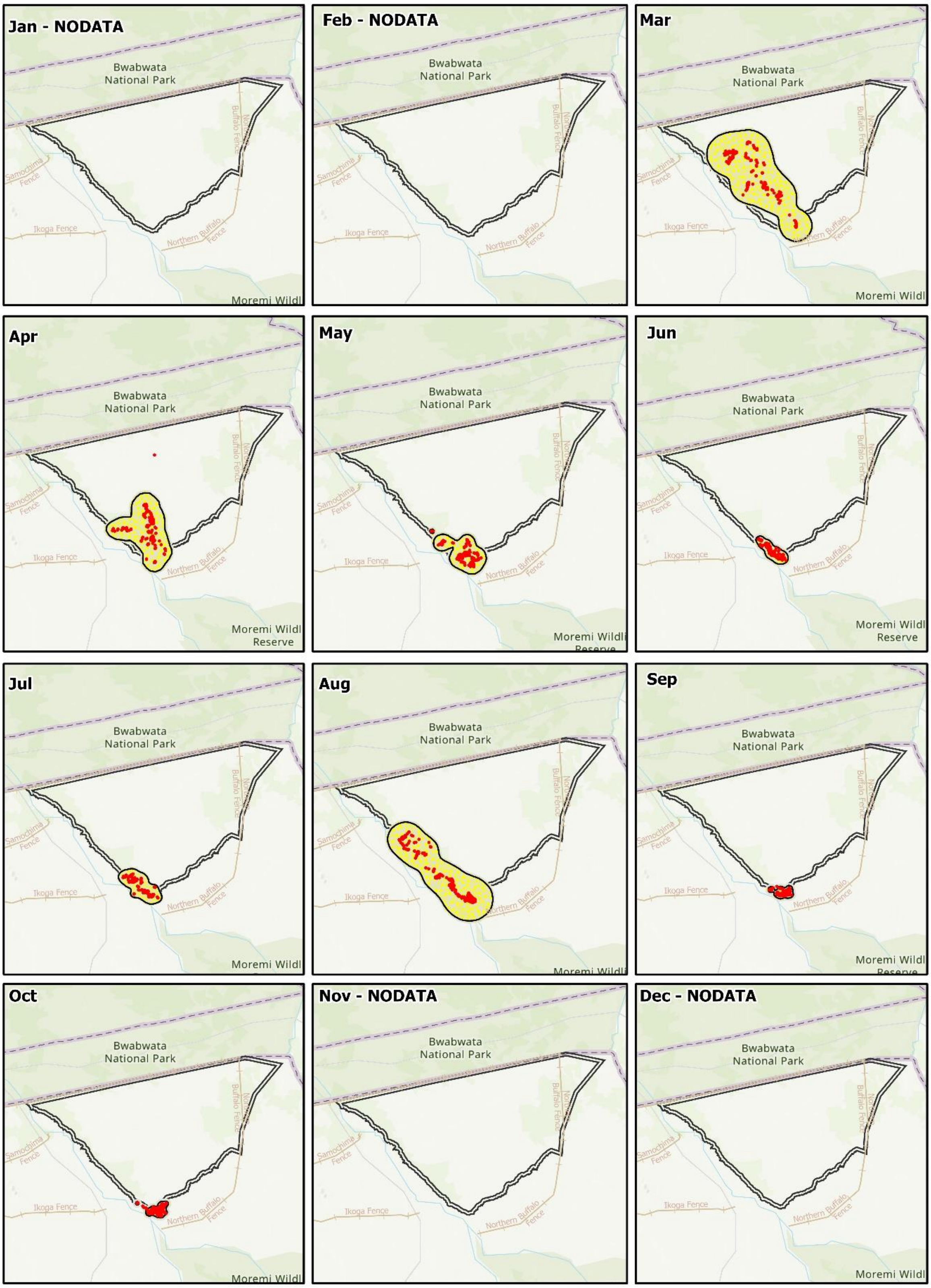
Whisper in 2014

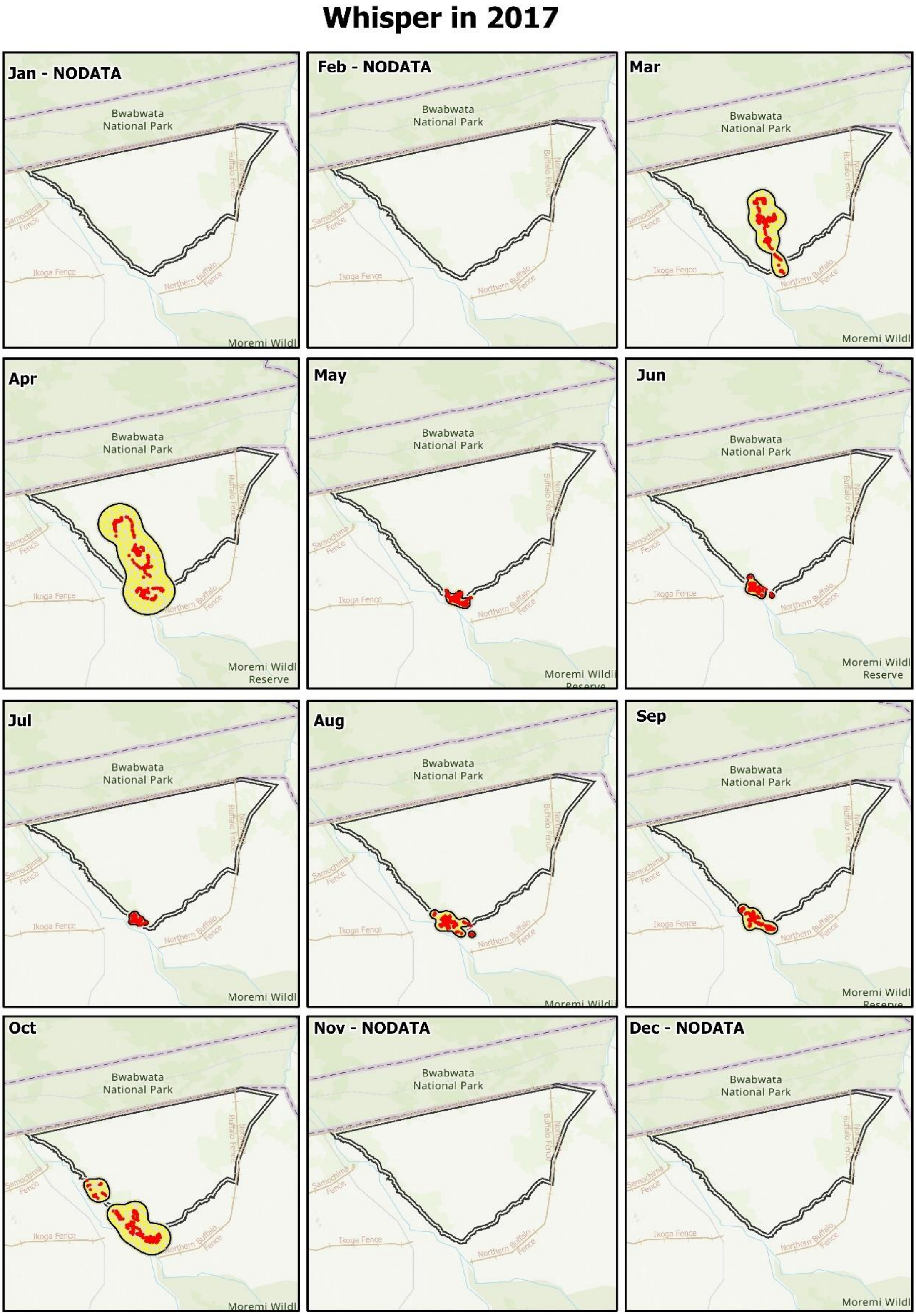


Whisper in 2015



Whisper in 2016





Appendix 8. An example of female elephants (Mbamba, Pille, Amantle, Ann, Ebby, Koo, Mpule, Nare, Rain and Whisper) monthly home ranges. The data was derived in preparation for the Resource selection function analysis using R statistics between 2014.- 2017. Red dots denote to actual fixes whilst the yellow dots indicate random fixes over a month for example in 2014 (April-October) and from 2015 -2017 home ranges were generated from March -October. Months with no data are also shown