

**EVALUATING THE RELATIVE CONTRIBUTION OF CHANGING
FARMING METHODS TO HABITAT LOSS IN THE MID-ZAMBEZI
VALLEY, ZIMBABWE**

By

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Abstract

Agriculture expansion is a major contributor to wildlife habitat loss in the ecological frontier areas. However, little is known about the contribution of different crops to wildlife habitat loss. In this study we evaluated the relative contribution of changes in farming practices, particularly the introduction of cotton (*Gossypium hirsutum L*) to the loss of wildlife habitat with specific focus on the African elephant (*Loxodonta africana*) in the mid- Zambezi Valley, Zimbabwe. First, we developed a remote sensing method based on normalised difference vegetation index (NDVI) derived from 16 day multi-temporal Moderate Resolution Imaging Spectroradiometer (MODIS) remotely sensed data for the 2007 growing period, to test whether cotton (*Gossypium hirsutum L*) fields can significantly ($p < 0.05$) be distinguished from maize (*Zea mays L*) fields, as well as sorghum (*Sorghum bicolor*) fields. Second, we tested whether woodland fragmentation in the study area was best explained by the areal extent of cotton fields than the areal extent of cereal fields. Finally, we tested whether woodland fragmentation resulting from cotton fields explains elephant distribution better than woodland fragmentation resulting from the extent of cereal fields. Results show that multi-temporal remotely sensed data can be used to distinguish and map cotton and cereal fields. Cotton fields contributed more to woodland fragmentation than cereal fields. Also, we found out that woodland fragmentation from cotton fields significantly explained elephant distribution in the mid- Zambezi Valley. These results indicate that the areal extent of cotton fields explains elephant habitat fragmentation more than the areal extent of cereal fields. Thus, we conclude that the expansion of cotton fields contributes most to elephant habitat loss in the Mid-Zambezi Valley. These results imply that elephant conservation policy needs to address the reduction of the negative impact of cash crops such as cotton on the habitat particularly their threat to wildlife habitat which may eventually lead to loss these wild animals. Thus it is important to strike a balance between wildlife habitat conservation and agricultural production as advocated through the Communal Areas Management Programme For Indigenous Resources (CAMPFIRE) policy.

Dedications

To my late father Paggy Hirrin Sibanda: Wish you were here to celebrate this achievement with me!

To my mother Magqu Rosemary Sibanda: You've always been a pillar of strength to me

To ithembalami: You've always stood by me through it all

Thanks for your time I spent on this thesis

To Zoë

Declaration 1: Originality

I hereby declare that this thesis submitted for the Master of Philosophy at the University of Zimbabwe is my original work and has not been previously submitted to any other institution of higher education. I further declare that all sources cited or quoted are indicated by means of a comprehensive list of references.

Sibanda Mbulisi

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Declaration 2: Publication

Details that form part and/ or include research presented in this thesis include publications in preparation, submitted, in pres and published and give details of the contributions of each author to the experimental work and writing of each publication.

Publication 1: Sibanda M ¹, Murwira A ² and Baudron F ³ (Accepted in press, International Journal of Remote Sensing) *“Using multi-temporal MODIS images with ground data to distinguish cotton from maize and sorghum fields in smallholder agricultural landscapes of Southern Africa”*

This work was done by the first author under the guidance and supervision of the second author. The third author provided the data.

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Publication 2: Sibanda M ¹, Murwira A ² and Baudron F ³ (submitted to JAG) *Expansion of cotton fields drives elephant habitat fragmentation in the mid- Zambezi Valley, Zimbabwe*

This work was done by the first author under the guidance and supervision of the second author. The third author provided the data.

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Chapter 1: General introduction

1.1 General background

Wildlife habitat loss in the ecological frontier regions of Africa has generally occurred in association with the introduction of new crops especially after the eradication of tsetse (*Glossina* sp.) (Meertens *et al.*, 1996; Nhira *et al.*, 1998; Reid *et al.*, 2000; Murwira and Skidmore 2005; Symeonakis *et al.*, 2007). Ecological frontiers are zones of transition between two different ecosystems particularly the boundary between agro-ecosystems and natural ecosystems (Moore 1967; MacMillan 2003). In the present study, ecological frontiers are treated as a transitional zone between agricultural areas in a savanna ecosystem.

Wildlife habitat loss in ecological frontier regions of Africa has generated much interest in studies that deal with the interaction between agricultural and ecological systems especially after the eradication of tsetse (Boum 1987; Martzke 2002). For example, Ried *et al.*, (1997) demonstrated that the expansion of agricultural activities into the wildlife habitats of South western Ethiopia was commonly pronounced after tsetse eradication. There is also documented evidence of agricultural encroachment into wildlife habitat around the Garamba National Park in North-eastern Congo (DeMerode and Hillman-Smith 2000) and in Amboseli National Park in Kenya (Gathua 2001). In both Kenya and Congo, agricultural expansion contributed to habitat loss through clearance of forest cover. In Zimbabwe, Cumming and Lynam (1997) as well as Nhira *et al.*, (1998) observed that tsetse eradication facilitated the introduction of cotton farming practice which contributed to habitat loss. In a recent study, Murwira *et al.*, (2010) showed that

eradication of tsetse in the Zambezi Valley led to agricultural field expansion in areas where no crop agriculture existed before the eradication of tsetse. However, to the best of our knowledge the relative contribution of specific crops such as cotton to habitat loss is limited. Thus, developing methods for testing the relative contribution of changing farming practices, such as cotton farming to habitat loss is critical for conservation planning.

1.2 Statement of the problem

The mid-Zambezi Valley experienced an increase in agricultural fields after the eradication of tsetse since the 1980s leading to loss of wildlife habitat. It has been suggested that the expansion in agricultural fields in the Mid-Zambezi Valley has resulted more from cotton cultivation than from cereals crops such as maize and sorghum (Meertens *et al.*, 1996; Cumming and Lynam. 1997; Nhira *et al.*, 1998; Govereh and Jayne. 1999; Chipika and Kowero 2000; CIRAD-EMVT 2000; Gaidet *et al.*, 2003; Baudron *et al.*, 2009; Baudron *et al.*, 2010). However, little is known about how and to what extent cotton has contributed to wildlife habitat loss. This may be due to the paucity of cost effective and fast methods to differentiate and objectively quantify heterogeneous croplands.

Advances in satellite remote sensing have provided the opportunity to map agricultural land by crop type. However, methods of discriminating different crop surfaces from remote sensing are still in their infancy.

1.3 Objectives

The main objective of this study was to evaluate the relative contribution of changes in farming practices, particularly the introduction of cotton (*Gossypium hirsutum L*) to the loss of African elephant (*Loxodonta africana*) habitat in the Mid- Zambezi Valley, Zimbabwe. First, we developed a remote sensing method based on normalised difference vegetation index (NDVI) derived from 16 day multi-temporal Moderate Resolution Imaging Spectroradiometer (MODIS) remotely sensed data, to test whether cotton (*Gossypium hirsutum L*) fields can be distinguished from maize (*Zea mays L*) fields and sorghum (*Sorghum bicolor*) fields to determine whether woodland fragmentation in the mid- Zambezi Valley is better explained by the areal extent of cotton fields than the areal extent of cereal fields; and to evaluate whether woodland fragmentation resulting from cotton fields explains elephant distribution better than woodland fragmentation resulting from cereal fields.

1.4 Justification of the study

An understanding of the nature and mechanisms of habitat encroachment by agricultural fields is critical for purposes of land-use planning in areas regarded as biological diversity hot spots such as ecological frontier zones like the Mid-Zambezi Valley. As agricultural fields increase, there is a likelihood that the quality and quantity of wildlife habitat deteriorates as it gets fragmented into small patches (Templeton *et al.*, 1990; Osborn and Parker 2003). Habitat fragmentation has a high potential of increasing the rate of species extinction (MacArthur and Wilson 1967). The mechanism involves restricting wildlife species into refuges in islands of habitats affecting their spatial distribution as well as decreasing their reproductive success. In this regard, it is important to understand the fragmentation and spatial distribution of wildlife habitat due to the expansion

of cotton cropland in fulfilling environmental management objectives such as wildlife management.

The African elephant was selected as a focal wildlife species in this study because it is a keystone species in the Southern African savannas (Lee and Graham 2006). Keystone species in an ecosystem are those species that directly or indirectly modulate the availability of resources to other species, by causing physical changes in biotic or abiotic materials (Western 1989; Jones *et al.*, 1994; Power *et al.*, 1996). By so doing keystone species modify, maintain and create habitats for other species within the ecosystem (Western 1989; Jones *et al.*, 1994). In addition, African elephants are amongst wild herbivores which have been adversely affected by habitat fragmentation due to the expansion of agricultural activities in Southern African savanna ecosystems (Cumming and Lynam 1997; Hoare and Toit 1999; Murwira *et al.*, 2010). Studies that have been carried out in the African savannas show that the distribution of the African elephant is mainly a function of the seasonal variations of food, water availability, connectedness, diversity; shape, complexity and size of habitat patches due to fragmentation caused by expansion of agricultural land (Parker and Graham 1989; Cumming *et al.*, 1990; Cumming and Lynam 1997). In this regard, it is important to understand the effect of specific crops such as cotton on the spatial distribution of the elephants so as to balance the conservation of wildlife with human activities within the savanna ecosystem (Graham *et al.*, 2009).

1.5 Organization of the thesis

This thesis is divided into six chapters.

Chapter one provides a brief background of how agricultural activities particularly the effect of the area of cotton and cereal fields on woodland fragmentation, and the effect of woodland fragmentation on the distribution of the African elephant (*Loxodonta africana*) as well as the objective and hypotheses guiding this study.

Chapter two reviews literature on the encroachment of agricultural activities into wildlife areas as well as the hypothesised effects of cotton cropland on the wildlife habitat. It also synthesises diverse literature on the effect of woodland fragmentation on the spatial distribution the African elephant.

Chapter three describes the methods used to gather process and analyse data used to distinguish and map cotton and cereal fields. It also gives an outline of how elephant distribution was estimated and the method of quantifying woodland fragmentation in the mid- Zambezi Valley. In addition, the chapter details how cotton crop and/ or cereal crop cultivation is mostly responsible for the fragmentation of woodlands in the mid- Zambezi Valley.

Chapter four presents the results on whether cotton cropland can be significantly distinguished from maize croplands, as well as sorghum croplands in smallholder agricultural landscapes of the mid- Zambezi Valley, Zimbabwe, using temporal series of 16 day MODIS NDVI data.

Chapter five presents the results of determining the effect of crop cultivation on woodland fragmentation as well as the effect of woodland fragmentation on the distribution of the African elephant.

Chapter six provides general conclusions drawn from testing whether cotton fields can be distinguished from maize and from sorghum fields in smallholder agricultural landscapes of the mid- Zambezi Valley. Furthermore, conclusions are made on testing the effect of crop cultivation on woodland fragmentation with specific focus on how woodland fragmentation affects the distribution of the African elephant within a savanna landscape

Chapter 2: Agricultural Encroachment and wildlife habitat fragmentation: A literature review

2.1 Encroachment of agricultural activities into the wildlife areas

Wildlife habitat has been lost through the conversion of woodland to agricultural land and other land cover types in the past decade particularly in the Southern Africa (Nhira *et al.*, 1998; Chipika and Kowero 2000). Wildlife is a significant ecological and economic resource to many countries through tourism and their herbivory, carnivory, and omnivory functions which stabilise the ecosystem i.e., the savanna ecosystem (Pringle 2008). Understanding the drivers of wildlife habitat loss and fragmentation is fundamental for sustainable conservation and management of wildlife. Wildlife habitat is herein defined as a spatial and temporal environmental hyperspace where a particular wildlife species dwells (Darnell 1973). While performing significant ecological functions, wildlife species continue to be threatened by natural and anthropogenic factors that result in habitat fragmentation and loss. Habitat fragmentation is the reduction of woodland patches into smaller isolated patches which are geometrically more complex and are surrounded by different environments (Templeton *et al.*, 1990; Hoar 1999; Harris and Weiner 2003; Osborn and Parker 2003). Fragmentation has a high potential of increasing the rate of species extinction (MacArthur and Wilson 1967).

Globally, habitat loss and fragmentation threaten the existence of wildlife species (IUCN/SARDC/WWF 2000). Rapid human population growth in much of the tropics has also resulted in some protected areas and biodiversity “hot spots” becoming habitat islands

surrounded by a matrix of human-dominated landscapes such as agricultural fields (Nyhus and Tilson 2004). In many parts of the world such as north-west India, protected habitats are becoming isolated primarily because of growing human population, expansion of agriculture land and increasing infrastructure of motor roads, passing through the different protected areas (Joshi *et al.*, 2010). Leimgruber *et al.*, (2003) noted that the Asian elephant populations in Myanmar, India and Thailand were declining due to high population growth which exerted pressure on the wildlife habitat through agricultural expansion and infrastructural development.

Ried and Cathleen (1985) hypothesised that in Africa the eradication of the tsetse fly (*Glossina spp*) for purposes of easing pressure posed by increasing human population on the land has significantly contributed to the fragmentation of wildlife habitats through encroachment of agricultural activities into areas previously designated for wildlife ,(Cumming *et al.*, 1990; Cumming and Lynam 1997; Graham *et al.*, 2009). Eradication of tsetse fly will reduce the prevalence of livestock diseases such as Nagana. Sleeping sickness on dry-land farmers would be reduced hence making the earlier tsetse infested land habitable by humans. Finally, the ability of farmers to keep livestock and plough the land using animal traction will be maximised. Consequently, habitat loss would be increased. Therefore, land shortages drive forward the conflict between utilisation of land through anthropogenic activities such as agriculture and the preservation of natural habitats and wildlife.

In Zimbabwe, the important issue in wildlife conservation is human-wildlife conflict manifesting in the form of agricultural land encroachment into protected wildlife zones leading to the shrinking of natural habitats. Agriculture is the most extensive land based human activity in the

country contributing to the changes in the land use patterns and fragmenting wildlife habitat into small isolated islands (Chenje and Johnson 1998). The immigration of people into the communal lands for dry land farming purposes has caused a continuous loss of the Southern African rangelands for 45 years (Cumming and Lynam 1997; Cumming and Lynam 1997). In the Mid-Zambezi Valley population growth and pressure resulted in land shortages, particularly for agricultural purposes in the upland (Cumming and Lynam 1997; Cumming and Lynam 1997). This led to the establishment of programmes to eradicate tsetse flies beginning at an area that was settled in 1950 at the foot of the valley escarpment up to the valley floor which coincides with safari areas in the 80s and later (Cumming and Lynam 1997; CIRAD-EMVT 2000; Murwira and Skidmore 2005; Murwira *et al.*, 2010). In other words, there are three zones of human settlement in the mid- Zambezi Valley. The first zone which is at the transition from highland to lowland was settled after the tsetse eradication in the 1950, the second zone is further inland away from the escarpment at the Zambezi Valley, settled in the 1980s and the third zone which was settled later and is at the valley floor. Baudron *et al.*, (2010) noted that after tsetse eradication in the mid- Zambezi Valley land that was converted to agricultural land increased by 263% in areas which had previously been designated for wildlife and safari areas.

2.2 Mapping heterogeneous cropland using crop phenology and Geographic Information

System (GIS) techniques

To quantify agricultural encroachment into natural landscapes, objective methods are needed. Remote sensing the phenology (e.g. green up onset, green peak on set, senescence onset, and length of growing season) of different crop types is an important step towards the mapping of

different crops (Wardlow *et al.*, 2007) particularly in smallholder agricultural landscapes. A number of remote sensing studies have distinguished different crops, as well as vegetation types based on their phenology using multi-temporal satellite data particularly from the near daily satellites such as National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (NOAA AVHRR) with a 1 km to 8 km spatial resolution (Rasmussen 1997; Jakubauskas; *et al.*, 2002; Xiaoa *et al.*, 2005) and a radiometric sensitivity of up to 10 bits. However, the commonly used 1 km spatial resolution and sometimes 8 km spatial resolution AVHRR limits its ability to map complex land cover types in spatially heterogeneous landscapes. This is a result of mixed pixels that generalise spectral responses from multiple land cover types contained within the 1- 8 km footprint (Wardlow *et al.*, 2007). As a result, the coarse spatial resolution makes NOAA AVHRR inappropriate for distinguishing agricultural crops in areas with high spatial heterogeneity such as in smallholder agricultural landscapes in Africa.

The recent deployment of the Moderate Resolution Imaging Spectroradiometer (MODIS) with advanced optical sensors on board the Terra and Aqua satellites which are more sensitive to vegetation reflectance than its predecessors, may have improved the capacity to separate different crop types thereby improving crop type mapping in spatially heterogeneous areas (Sakamoto *et al.*, 2005; Wardlow *et al.*, 2007). Unlike NOAA AVHRR with 1-8 km spatial resolution and radiometric sensitivity of 10 bits, MODIS has a moderate spatial resolution of 250 m, 500 m and 1000 m bands, as well as an improved radiometric sensitivity of 12 bits. A combination of high temporal resolution of a near daily revisit frequency, a high radiometric resolution, as well as a moderate spatial resolution of 250 m may enable differentiation of different crops especially in small holder agricultural landscapes (Chen *et al.*, 2006; Wardlow *et*

al., 2007). The ability to apply remote sensing to distinguish different crop types in smallholder agricultural areas is particularly important as smallholder agriculture constitute the most predominant land use practice in many agriculturally based economies of the world (FAO 2006).

Many approaches have been developed to distinguish crops using remotely sensed data as well as remotely sensed indices particularly following the launch of MODIS (Reed *et al.*, 1994; Fuller 1998; Jakubauskas; *et al.*, 2002; Sakamoto *et al.*, 2005; Doraiswamy and Stern 2007; Wardlow *et al.*, 2007; Simonneaux *et al.*, 2008; Boschetti *et al.*, 2009; Funk and Budde 2009; Doraiswamy *et al.*, 2003). These applications have had various degrees of success. For example, work by Moulin *et al.*, (1998) and Doraiswamy *et al.*, (2003) showed that different crop models may be better understood by combining remotely sensed data with statistical techniques for yield forecasting over large areas based on time series data. In addition, Xiaoa *et al.*, (2005) used MODIS images for identifying inundation and rice paddy fields in southern China. Jakubauskas *et al.*, (2002) applied a harmonic/ fourier analysis of time series of NOAA normalised difference vegetation index data in developing a technique which successfully segregated maize from other crops in large-scale farms of Kansas in the United States of America. In other words, remote sensing is a useful tool for estimating the area occupied by specific agricultural crops in assessing habitat fragmentation and loss.

2.3 Hypothesised effects of specific agricultural crops on wildlife habitat

The introduction of cotton is noted to have paved the way to the expansion of areas under cultivation as a result of tsetse fly eradication in the Zambezi Valley (Cumming and Lynam 1997) resulting in wildlife habitat loss. The success of cotton farming in African savanna

ecosystems is explained by the crop's adaptation to climatic conditions which are marked by dry seasonal hot temperatures that facilitate its growth (Baudron *et al.*, 2009) in the safari area which coincided with tsetse infested, low human population density areas. Cotton is one of the cash crops with a structured market that can be cultivated by dry land farmers in dry areas which are mainly suitable for wildlife and safari areas (Baudron *et al.*, 2009).

2.4: Methods of Measuring Habitat Fragmentation

Clearance of native woodlands for agriculture reduces the integrity of wildlife habitat (Petit *et al.*, 2001; Boutin and Herbert 2002). For example, fragmentation of native woodlands into smaller discrete blocks of remnant forest has a significant effect on the landscape by both increasing the perimeter of forest patches and changing the structural characteristics of the blocks themselves (Templeton *et al.*, 1990; Wauters *et al.*, 1994; Leimgruber *et al.*, 2003; Worden 2007).

Remotely sensed data are handy in testing hypotheses related with crop field expansion and wildlife habitat fragmentation and loss (Zhou *et al.*, 2008). For example Dewider (2004) also used remotely sensed data to detect land use land cover changes and fragmentation of the wildlife habitat following the construction of the international coastal road in the Nile Delta, Egypt. Zhou (2008) integrated the use of remote sensing in developing methods to quantify the spatial patterns of land cover change using fragmentation indices. In habitat fragmentation studies, remotely sensed data are classified into different land cover classes. These land cover classes are used to compute fragmentation statistics also known as patch metrics to quantify the connectedness, diversity, shape complexity and size of land cover patches (Wickham *et al.*, 1997; McGarigal *et al.*, 2002). Patch metrics have mainly been developed to assess the landscape

conditions and inferring ecological processes such as the effects of land cover changes to wildlife distribution (McGarigal *et al.*, 2002). Patch metrics measure the spatial structure or spatial configuration of the landscape, which is an important prelude to understanding spatial ecological processes. However, most studies that have used patch metrics derived from remotely sensed data have mainly focused on temporal land cover change detection. For example, Zhou *et al.*, (2008) used patch metrics based on a temporal series analysis to assess land cover changes in the Tarim basin of China. Crews-Meyer (2003) tested an approach of incorporating the temporal nature of agricultural landscape change as well as the shifting patterns of cultivation using patch metrics in north eastern Thailand. Petit *et al.*, (2001) also used patch analysis to understand land cover changes caused by resettlement in south eastern Zambia based on temporal analysis. The application of patch metrics in assessing the effect of specific cropland encroachment on elephant habitat is critical in understanding the ecological processes triggered by agricultural fields in the landscape.

2.5 Effect of habitat fragmentation on the distribution of wild life: the case of the African elephant (*Loxodonta africana*)

Understanding the way elephants (*L. africana*) persist in human-dominated landscapes particularly fragmented by cotton croplands and the effect of woodland fragmentation on the distribution of the African elephant is important for conservation and wildlife policy implementation in several ways. To begin with, elephants are a species of conservation concern (Graham *et al.*, 2009). Elephants are also keystone species with significant roles in ecological function (Pringle 2008). In the savanna ecosystem, elephants are known for maintaining open wooded grasslands (Pringle 2008). Therefore their persistence outside protected areas is

important for the conservation of other elements of biodiversity. According to the IUCN African elephants are amongst the wild herbivores which are threatened by habitat fragmentation due to the expansion of agricultural activities in the Southern African savannas (Blanc *et al.*, 2007). Thus understanding the relationship between habitat fragmentation due cotton crop cultivation and the spatial distribution of wild elephant is important for striking a balance a balance between effective wildlife conservation and sustenance of human livelihood.

2.6 Studies conducted in the Zambezi Valley

Previous studies (Sinclair and Fryxell 1985; Soderstrom *et al.*, 2003; Lamprey and Ried 2004) hypothesized that the eradication of tsetse fly, to enable agricultural activities contributed to the loss of vegetation cover, extinction of endemic wildlife species, and loss of soil. Hoare and Toit (1999) focused on how human population density and settlement is related to the distribution of wildlife particularly that of the elephant in the Sebungwe, and then Murwira (2005) extended the study of Hoare (1999) by including a temporal investigation in the context of tsetse eradication regime.

Chapter 3: Materials and Methods

3.1 The study area

The study was conducted in the communal lands of the mid- Zambezi Valley in Mbire district, Zimbabwe (Figure 1). Communal lands are a land category characterised by community land ownership and are subdivided into administrative or management units called wards. We focused our study on Chisunga ward 2 and Neshangwe wards 3 and 9 of Mbire district. The study area is located between decimal degrees 30°00' and 31°45' east and 16°00' and 16°30' south. Mbire district has a dry tropical climate, with low and variable annual rainfall of between 450 and 650 mm and a mean annual temperature of 25°C. The soils of the study area vary from eutric leptosols in ward 2, tropically leached iron bearing soils in ward 3 to calcic luvisols in ward 9 (Nyamapfene 1991). The natural vegetation of Mbire district is mainly deciduous dry savanna, dominated by mopane trees (*Colophospermum mopane*) (Gaidet *et al.*, 2003). The local wildlife biodiversity is relatively high, with more than 40 large mammals, 200 birds and 700 plant species (CIRAD-EMVT 2000). Mbire district is habitat to African mega-fauna excluding the Black Rhinoceros (*Diceros bicornis*) which became locally extinct due to extensive poaching between 1989 and 1991 (Cumming and Lynam 1997; Gaidet *et al.*, 2003).

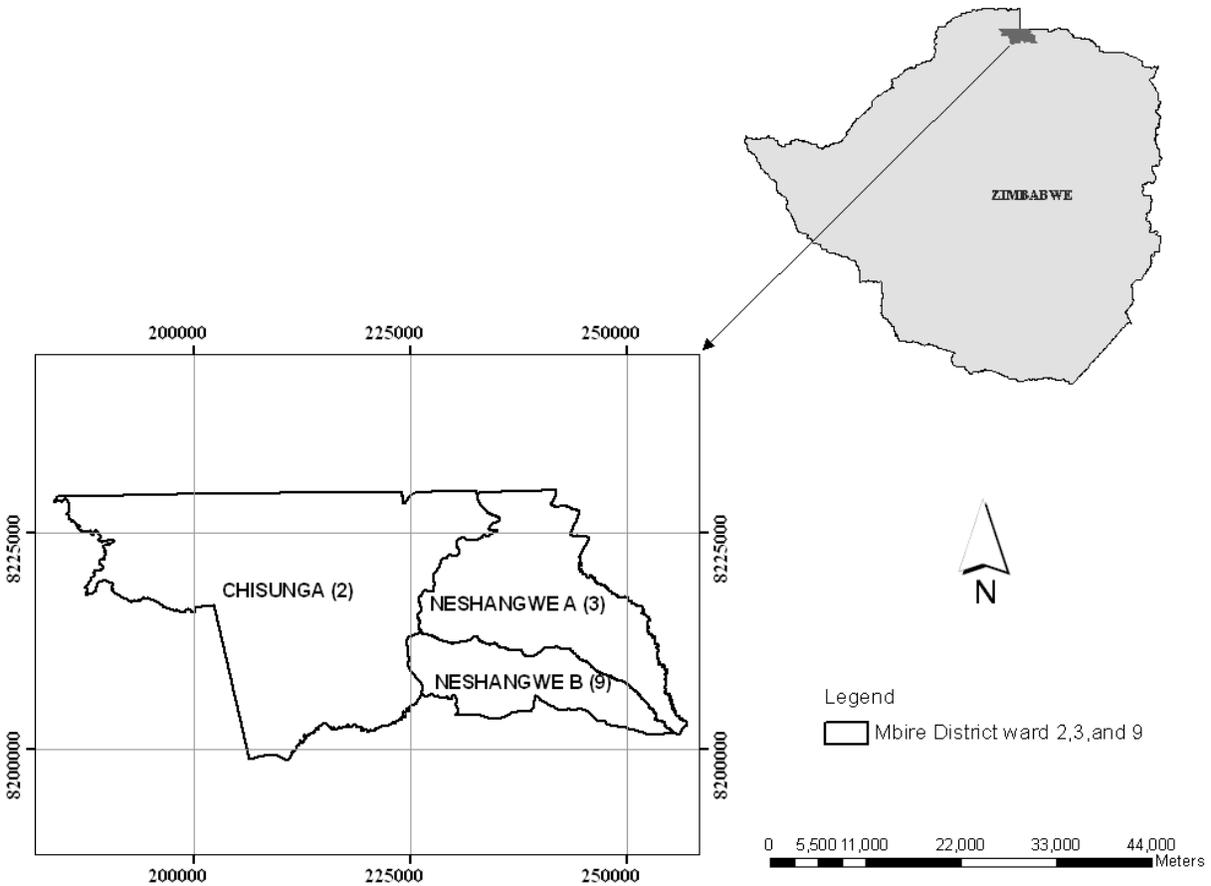


Figure 1: Location of the study area covering Wards 2, 3 and 9 Mbire district in the Mid-Zambezi Valley, Zimbabwe. Map coordinates are in UTM zone 36 south based on the WGS84 reference spheroid.

Most of the human settlements in Mbire district are along Angwa and Manyame rivers in a wildlife conservation frontier. Wildlife is mainly concentrated in areas which are tsetse infested while humans are mainly settled in tsetse free areas (Cumming; and Lynam 1997; Nhira *et al.*, 1998; Murwira and Skidmore 2005). The major human activity in this district is dry land farming of cotton, maize and sorghum, which often results in human-wildlife conflicts. Cultivation of cotton in the Mid-Zambezi Valley increased during the 1980s after tsetse fly eradication (CIRAD-EMVT 2000).

3.2 Distinguishing cotton from maize and sorghum fields in smallholder agricultural landscapes of the mid- Zambezi Valley

3.2.1 Crop data

Sampling was conducted in a SEE-NWW orientation following the direction of tsetse eradication which generally is observed to define the gradient of cropping intensification (Cumming and Lynam 1997) . We used stratified random sampling to select the agricultural fields from which data on crop types were collected. Specifically, we used three spatial data layers, i.e. administrative boundaries (wards), soil types, and cropland patches to define sampling strata. Based on the strata, three transects were randomly generated in a GIS following a SEE-NWW orientation. We selected twenty-five homesteads which intersected these transects. We then used a handheld Global Positioning System Receiver (GPS) to identify the selected homesteads. A farmer from a selected homestead then led us to the agricultural fields where crop type data were collected.

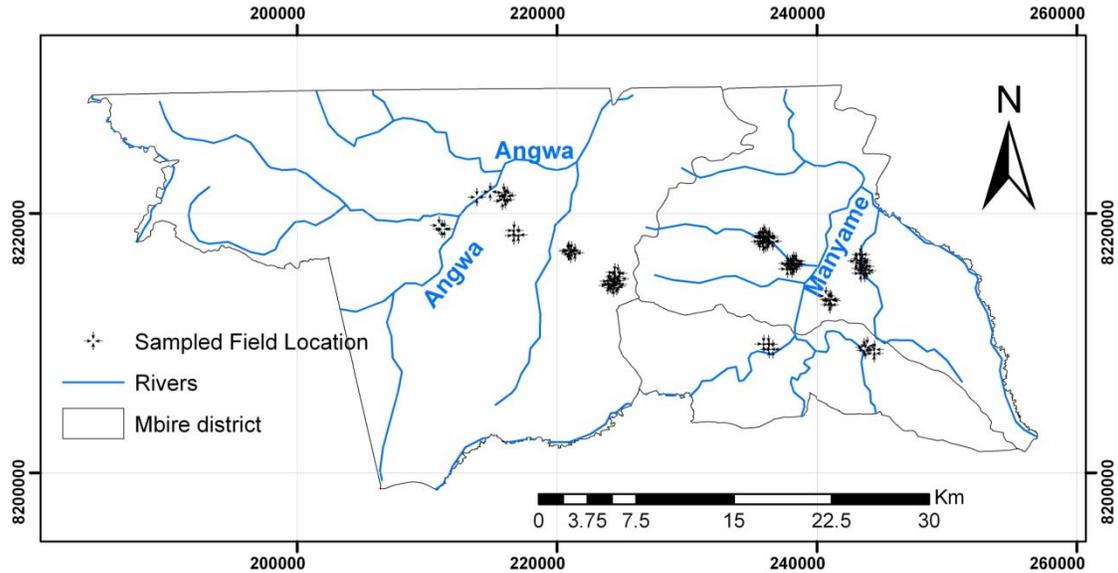


Figure 2: The distribution of the sampled crop fields in wards 2, 3 and 9. Map coordinates are in meters UTM zone 36 south based on the WGS84 reference spheroid.

Figure 2 shows the distribution of sampled fields. As mentioned earlier, crop data were collected in the sampled agricultural fields. In the selected fields, cotton, maize and sorghum stalks were used as an indicators of which crop was cultivated in each field. Presence of stalks was used to verify the information provided by the farmer regarding the type of crops grown because the field survey was conducted during the dry season in October. Next, we used a GPS to locate the centre coordinates of each cotton, maize and sorghum field to minimise the problem of mixed pixels. Finally, we manually digitized fields from Google Earth (Keyhole 2007) (<http://earth.google.com>). The Google Earth image domain is based on the 2.5 m SPOT panchromatic band (Knorn *et al.*, 2009). The digitized fields were later used for distinguishing fields from other land cover types through performing a mask operation in a GIS.

3.2.2 Remote sensing data

In order to characterise crop phenology, MODIS 16-day Normalized Difference Vegetation Index (NDVI) data composites (MOD13Q1) covering the period from early growth to harvesting of all crops, i.e. from the 1st January to 10th of June 2007, in the study area were selected and downloaded from the USGS EROS Data Centre (<https://wist.echo.nasa.gov>). NDVI is estimated by the following equation:

$$\text{NDVI} = (\rho\text{NIR} - \rho\text{RED}) / (\rho\text{NIR} + \rho\text{RED}) \quad (1)$$

where ρNIR is reflectance in the Near Infrared (846–885 nm), ρRED is reflectance in the Red (600–680 nm) reflectance for the respective MODIS bands. NDVI values range from -1 for water up to 1 for healthy vegetation. The NDVI images were then converted from sinusoidal projection to WGS 1984 UTM zone 36 in a GIS. In this study we used NDVI to distinguish cotton from maize and sorghum because NDVI has been widely proven to objectively estimate vegetation greenness, i.e., the total concentration of chlorophyll in vegetation (Tucker and Sellers 1986; Reddy *et al.*, 2001; Zhang *et al.*, 2003; Sakamoto *et al.*, 2005; Xiaoa *et al.*, 2005; Doraiswamy *et al.*, 2003). The relationship between NDVI and green biomass is based on the amount of photosynthetically active radiation absorbed by the crop canopy quantified via this index (Tucker 1979; Tucker and Sellers 1986). NDVI has also been widely used to characterise crop phenology (Jakubauskas *et al.*, 2002; Zhang *et al.*, 2003; Funk and Budde 2009). The MODIS 16-day spectral data composites were improved at the EROS data centre by applying atmospheric distortion adjustment algorithms, cloud removal and bi-directional reflectance distribution function (BDRF) correction (Chen *et al.*, 2006). The algorithms used to generate MODIS composites include maximum value compositing (MVC)

developed by Holben (1986) and view angle constrained for preventing selection of off-nadir pixels for bidirectional reflectance (BRDF) corrected NDVI compositing (Chen *et al.*, 2006). It is for these reasons that we adopted the NDVI product for this study. In addition, we used the MODIS 16-day composites data set as it has a sub-pixel accuracy of 50 m at nadir (Wolfe *et al.*, 2002). Provisional analysis using ground control points computed by the MODIS team after the most recent update of sub-pixel geolocation error correction indicated a mean geolocation error of 18 m across track and 4 m along scan with standard deviations of 34 and 40 m respectively (Wolfe *et al.*, 2002). These errors are less than the sizes of our fields which are at least 7.5 ha hence making the 250 m pixel sized satellite data appropriate for this study.

3.2.3 Analysis of MODIS time series to detect different crops

We extracted NDVI values for different crop types derived from GPS surveyed fields from the near planting period to senescence, i.e. January to June 2007, by overlaying the field maps of crops with MODIS derived NDVI maps for each date in Integrated Land and Water Information System Geographical Information System (ILWIS) (ITC 2005). We used 19 sample fields for maize, 25 sample fields for cotton and 25 sample fields for sorghum. Table 1 shows the descriptive statistics of the sampled cotton, maize and sorghum field sizes. It has to be noted that due to the 250 m spatial resolution of MODIS the number of sample fields is not the same as the number of pixels used for analysis. We selected pixels that were located on the center of the sampled fields only in order to avoid the effect of mixed pixels.

Table 1: Descriptive statistics of area in hectares (ha) for the cotton, sorghum and maize fields in the study area.

Crop	Mean area (ha)	Minimum area (ha)	Maximum area (ha)	Standard deviation of area (ha)	Number of pixels
cotton	7.55	6.27	14.38	1.74	29
maize	8.01	6.28	13.99	1.99	30
sorghum	15.21	6.25	30.40	8.37	56

Next, we used the respective NDVI time series for cotton, maize and sorghum to test whether the three crops could be distinguished based on several steps. Firstly, exploratory statistical data analysis was conducted to test whether NDVI values of cotton, maize and sorghum followed a normal distribution based on Kolmogorov-Smirnov test. The Kolmogorov-Smirnov Test indicated that the NDVI data for the 1st of January to the 26th of June did not significantly ($P < 0.05$) deviate from the normal distribution. Since the data did not significantly deviate from a normal distribution, we used repeated measures analysis of variance (ANOVA) to test whether there were significant ($\alpha = 0.05$) difference among the mean NDVI values of cotton, maize and sorghum at 16 day time intervals (from the early green-up, up to the late senescence period).

3.2.4 Assessing changes in cotton, maize and sorghum NDVI values at different phenological stages

In order to further compare the change in NDVI values among the three crops at different phenological stages throughout the season, we computed the change in NDVI values for each crop per pixel per field by calculating the difference between successive 16 day interval NDVI data. We then used Fourier transformation to test whether and in what form was the change in mean NDVI per pixel between successive image dates for cotton, maize and sorghum a function of different phenological stages using the formula;

$$f(x) = a_0 + \sum_{n=1}^m \left(a_n \cos \frac{n\pi x}{L} + b_n \sin \frac{n\pi x}{L} \right) \quad (2)$$

where $f(x)$ = a best-fit regression line for mean changes in NDVI between successive image dates for cotton, maize or sorghum, a_0 = intercept of the mean change in NDVI between successive image dates for cotton, maize or sorghum, a_n = cosine of the coefficient of change in mean NDVI between successive image dates for cotton, maize or sorghum b_n = is the sin coefficient of change in mean NDVI between successive image dates for cotton, maize or sorghum, L = number of image days throughout the year, π = PI and x = a particular image date. To accomplish this, we fitted regression lines which best described the rate of change in greenness for cotton, maize and sorghum over the growing season based on scatter plots with NDVI change as a the response variable and time of the season as the predictor variable. This was followed by testing whether there was a significant difference in the rates of change in greenness (NDVI values) of cotton, maize as well as cotton and sorghum by comparing the slope and intercepts of the regression functions fitted on the rate of change in NDVI for maize, cotton and sorghum. In the case that the rate of change in greenness between cotton and maize as well as sorghum was not significantly different, we would conclude that these crops have similar phenological rates. On the other hand, if the test of differences between the intercepts of the rate of change in sorghum, maize and cotton greenness yielded significant differences, we would conclude that the regression lines describing the form of the rate of change in the greenness of all the three crops were parallel. We then graphically plotted the gradients of change in NDVI values of cotton, maize and sorghum to facilitate interpretation.

3.2.4 Spatial logistic regression to estimate cotton, maize and sorghum crop

To map cotton, maize and sorghum in a spatial logistic regression, we used a clear single day MODIS satellite image of the 16 of April 2007. The single day MODIS satellite image was selected and used because it was cloud free and taken almost at a nadir position such that there was limited elongation of pixels. The MODIS satellite image was used to derive NDVI data used in a spatial logistic regression. We then used a t-test to test whether there were significant ($P < 0.05$) differences between NDVI values of the 16 day MODIS NDVI data of the 23rd of April 2007 and the single day MODIS satellite image of 16th April 2007. To test for significant differences between the NDVI derived from a single day satellite image and the 16 day NDVI composite data we used 19 sample fields for maize, 25 sample fields for cotton and 25 sample fields for sorghum surveyed using a GPS. The t-test results showed that there were no significant ($P > 0.05$) differences between the single day and the 16 day NDVI MODIS data. Since there were no significant differences between the NDVI data of the single day (of the 16 of April) and the 16 day composite data (of the 23 April) and considering the better quality of the former, image, it was used in mapping the spatial distribution of cotton maize and sorghum crop.

A point map of crop types derived from the fieldwork was associated with the MODIS derived NDVI values of the 16th of April satellite image, for each crop based on an overlay function in ILWIS GIS (<http://www.itc.nl>).

The observed crop type spatial data was converted into binary format in a GIS, i.e., a field with specific crop type such as cotton was given 1 otherwise 0. Three binary maps were produced, i.e., one for cotton, one for maize and the other for sorghum. Each binary map was combined with an NDVI map using an overlay function in a GIS in order to produce three tables where

binary crop data were treated as a dependent variable while the NDVI was treated as an independent variable. The hypothesis we were testing was that there is a significant relationship between crop type and NDVI. The resultant relationships were used to produce statistically significant equations for mapping the probability surface of each of the three crops in a GIS. Prior to mapping, we plotted the equations graphically to explore the nature of the relationships between the three crop types and NDVI.

Details on logistic regression are treated in detail elsewhere (Moore and McCabe 1998). The probability surface maps for each crop were masked using agricultural field maps digitized from Google earth images.

In the following step, we intended to produce a map showing the distribution of cotton and cereals. To do this we classified each pixel as cotton, maize and sorghum in ILWIS GIS. This involved producing a stack of three crop maps in a map list and then for each pixel retrieving the crop with the highest probability. The result was a map showing the relative distribution of cotton and cereals. Accuracy assessment was conducted and a kappa statistic of 51% was obtained using a separate set of cotton, maize and sorghum sample fields.

In order to test whether the area occupied by cotton in 2007 was previously woodland, we classified a Landsat image of 1990 to an accuracy of 0.93 based on the Kappa statistic. The year 1990 was selected since it had the oldest and clearest Landsat image available for the study area. Next, we overlaid cotton, maize and sorghum fields classified in 2007 with the classified woodland cover of 1990 in a GIS in order to extract area statistics for testing whether woodland

that has been converted to cotton fields is more than woodland that has been converted to cereal fields.

3.3 Expansion of cotton fields drives elephant habitat fragmentation in the mid- Zambezi Valley, Zimbabwe

The study area was stratified into 5 km distance zones (figure 3). These 5 km strata were used to quantify the area of land under cotton and cereal crops as well as the frequency of elephant occurrence from the foot of the Zambezi escarpment to the valley. A distance of 5 km was selected to stratify the area because this is the average distance between villages in the Mid- Zambezi Valley derived after exploratory analysis in a GIS. In addition, these 5 km intervals are portions of the habitat that are left for elephant habitation in the mid- Zambezi Valley. The direction of stratifying the study area followed the tsetse fly eradication regime.

For purposes of understanding the gradient of agricultural field intensity, the study area was also stratified into regions A, B and C according to the time of settlement. Region A (strata 40 km- 60 km) was settled after the late 1980s while region B (strata 15 km -35 km) was settled in the early 1980s. Region C (strata 0- 10 km) was settled in the 1950s. Thus regions C to A represent a gradient on the timing of tsetse eradication.

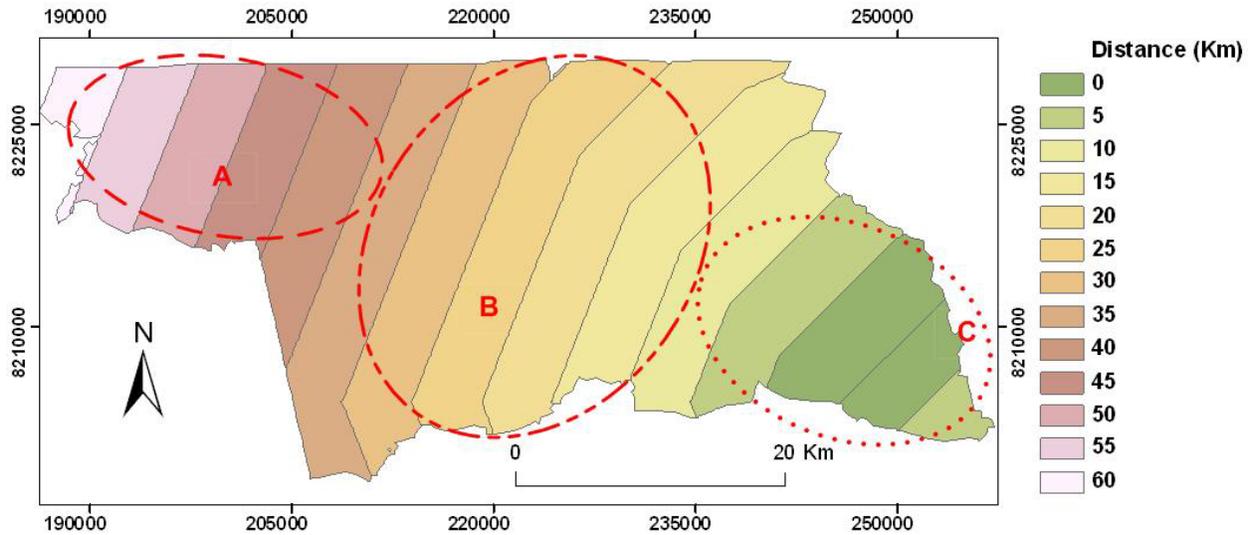


Figure 3: Stratification of the study area into 5 km strata and three settlement zones. A is zone of low agricultural fields intensity which is in the safari areas, B is a zone of medium agricultural fields intensity and C is a zone of high agricultural fields intensity. Map coordinates are in UTM WGS 1984 zone 36 south.

3.3.1 Remotely sensed woodland and agricultural field data

To map the woodland cover, we used a Landsat Thematic Mapper image of 17 July 2007. We georeferenced the Landsat satellite image to UTM WGS 1984 zone 36 south prior to classifying it. We used a supervised classification method, maximum likelihood, to classify the images into woodland and fields cover classes. Google earth was used to derive points for accuracy assessment of the classified map as in Knorn (2009). A kappa statistic of 0.94 was obtained using 130 points.

The extracted woodland cover was used to compute the fragmentation metrics in a GIS. We used woodland cover only to estimate fragmentation because elephants are mainly browsers and their habitat is the woodland. We computed the patch size, density, edge and shape metrics to quantify

the fragmentation of the woodland patches (Wickham *et al.*, 1997; McGarigal *et al.*, 2002). We used these patch metrics to measure woodland fragmentation because they facilitate the comparison of woodland patches loss along the gradient of agricultural fields intensification. Also these metrics have been successfully used to measure habitat fragmentation (Grainger *et al.*, 2005; Beer and van Aarde 2008; Graham *et al.*, 2009). To facilitate mapping and interpretation, we classified woodland patches into three size classes in hectares that is, the small (0.04-1613 ha), medium (1614-3328 ha) and large (3329-5631 ha). The classification was based on the equal class or intervals method which creates numerically equal mapping classes. To do this, we subtracted the lowest woodland patch area from the highest woodland patch area to establish the range of the area of woodland patches. Then, we divided the woodland patches area range by the number of classes (3) to get the area class interval.

We also tested the clustering of the woodland patches along the gradient of high agricultural fields intensity prior to testing whether clustering of woodland patches has any relationship with the spatial distribution of the African elephant. To achieve this, we first determined the centroid of every woodland patch in a GIS for all the 5km strata. Next, we used the nearest neighbour distribution function (G -hat) (Bailey and Gatrell 1995) to quantify the degree and distance of spatial clustering of woodland patch centres along the gradient of crop intensification. Using the G -hat function, an excess of short distance neighbours denotes clustering, while an excess of long distance neighbours denote dispersion. The G -hat function is estimated using the formula;

$$\hat{G}(s) = n^{-1} \#(d_i \leq s)$$

Where n is the number of points, d_i is the i th point to the closest of the other $n - 1$ points, and $\#$ means “the number of” and $s =$ is the nearest event.

3.3.2 Elephant distribution data

We collected elephant data based on transects randomly selected from land cover strata in a GIS (Figure 4). Elephant presence indicators were collected along 36 transects each with a length of 500 m and a width of 45 m. We used a transect width of 45m as it was compatible with remotely sensed data from a Landsat TM satellite image with a spatial resolution 30m. The width of these transects gives an error tolerance of 15m to the remotely sensed data. We used a length of 500m for the transects as we considered it to be closer to the minimum patch dimension (457 m^2) found to be suitable for elephant habitat (Murwira and Skidmore 2005). Transects used in sampling elephant data were oriented in a SEE-NWW direction following the direction of tsetse eradication which generally is observed to define the gradient of cropping intensification (Cumming; and Lynam. 1997).

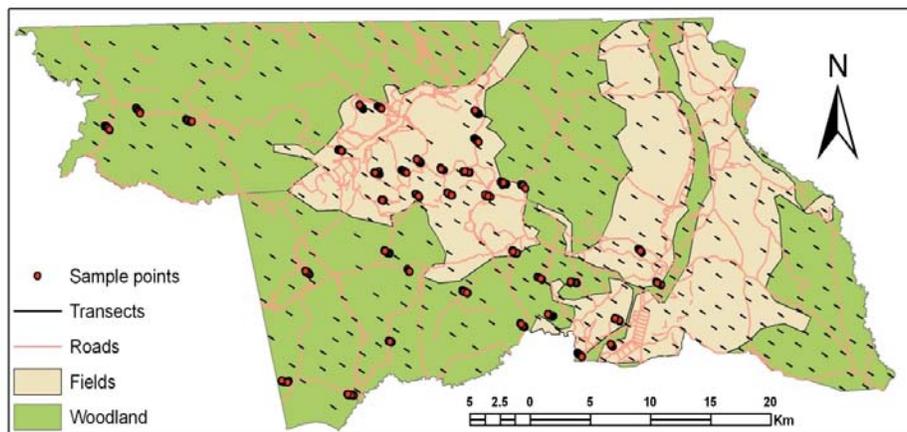


Figure 4: Sampling strata, sample points and transects used in collecting elephant data in Mbire district, Zimbabwe.

Global Positioning System (GPS) receiver was used to navigate to the points marking the beginning of transects. Elephant presence was determined using dung piles, signs of damage to vegetation and spoor (Sutherland 1996). In this survey we assumed the rate of dung decay to be static since we are more interested in the occupancy (presence) of wildlife in relation to human disturbances, though dung decay rates may differ across habitat conditions in the study area (Sutherland 1996). In this study the elephant presence indicators were pulled because we were only interested on the presence of the elephants in the study area.

3.3.3 Analysis of the relationship between elephant distribution and woodland fragmentation

We first used correlation analysis to test the hypothesis that cotton crop intensification significantly related with the spatial structure of woodland patches. Specifically, we used Spearman's rank correlation (ρ) to test whether the areas of agricultural fields, cotton fields and cereal fields significantly relate with woodland fragmentation indices, i.e., woodland class area, woodland patch size coefficient of variation, number of woodland patches, woodland patch size standard deviation, mean woodland patch edge as well as woodland edge density respectively. It has to be noted that high edge density reflects predominance of small woodland patches in the landscape, while low edge density means predominance of large woodland patches in the landscape. We used Spearman's ρ correlation coefficient since most of the fragmentation indices did not follow a normal distribution.

Using regression analysis, we tested whether cotton fields contribute to woodland fragmentation more than cereal fields. To accomplish this comparison, two main criteria were used to compare the regression functions. First, we used the significance of the regression functions. Second, we

used the coefficients of determination (R^2) resulting from the respective regression analyses. The regression function with a higher coefficient of determination was regarded as the best regression function to predict the woodland fragmentation. In this study, only those woodland patch metrics that were significant at $P < 0.05$ and returned higher correlation coefficients were used to test whether it is cotton fields or cereal crop fields that significantly explain woodland fragmentation in the study area.

Regression analysis was used to test whether woodland contributes to the distribution of elephant presence indicators. In other words, we intended to find out whether the woodland fragmentation resulting from encroachment by agricultural fields, particularly cotton significantly predicts the spatial distribution of the African elephant.

Results and Discussion

Chapter 4: Remote sensing of cotton, maize and sorghum fields in smallholder agricultural areas of the mid-Zambezi Valley

4.0 Results

4.1. Separating cotton from maize and sorghum using remotely sensed data

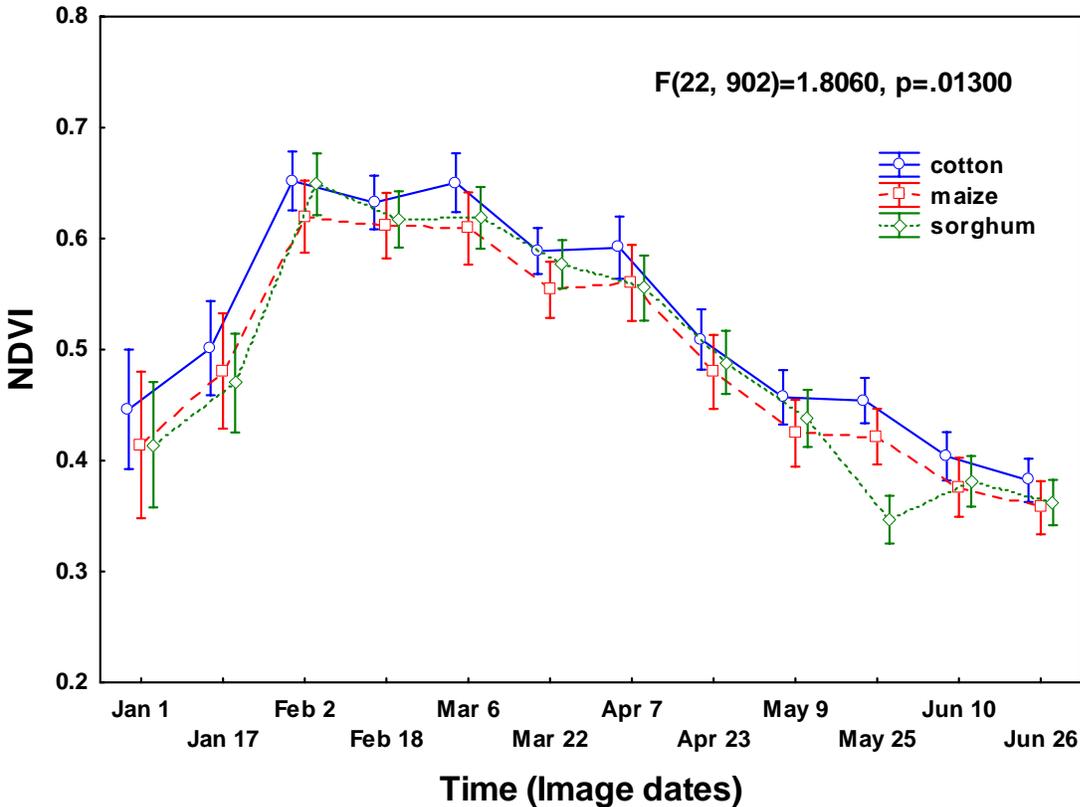


Figure 5: Cotton, maize and sorghum mean NDVI profiles for the 2007 growing season. The bars represent the 95% confidence interval.

Figure 5 shows a comparison of cotton, maize and sorghum NDVI profiles from the beginning up to the end of the 2007 growing season. Results of the repeated measures ANOVA showed

that there are significant differences among mean NDVI values of cotton maize and sorghum during the green-up on set up to the late senescence stage, i.e. from early January to late June as illustrated on Figure 5.

4.2 Temporal changes in the mean NDVI of cotton, maize and sorghum

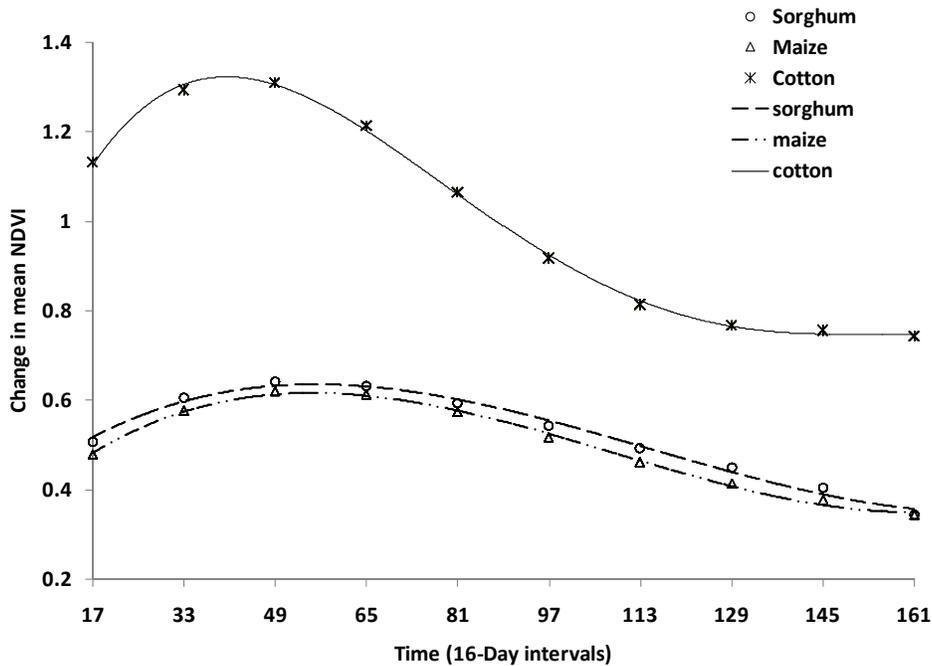


Figure 6: Change in mean NDVI between successive image dates for cotton, maize and sorghum from January 17 to June 10, 2007 (17 = January 17, 33 = February 2, 49 = February 18, 65= March 6, 81 = March 22, 97 = April 7, 113 = April 23, 129= May 9, 145= May 22 and 161 = June 10)

Figure 6 shows that the change in mean NDVI between successive dates for cotton, maize and sorghum through the growing season are each best described by a third order Fourier transformation or hump shaped curve. Specifically, we observe a positive change in the NDVI values per pixel of cotton, maize and sorghum from January to beginning of March (Table 1) which coincides with the green-up onset of all the three crops. This is then followed by a negative change from February to early June for cotton, maize and sorghum. The dip in the rate of change in mean NDVI between the period mid-March to early June coincides with the senescence of all the three crops. Statistical comparison of the rates of change in the greenness

(mean NDVI) between successive image dates for these three crops during the green-up period shows that there is a significant ($P < 0.05$) difference between cotton and maize as well as cotton and sorghum i.e. late January to early March. The rate of change in mean NDVI for cotton during the green-up stage is significantly ($P < 0.05$) higher than the rates of change in mean NDVI for maize and sorghum. Slope coefficients (b_1) of the rate of change in mean NDVI for cotton, maize and sorghum during the green-up period are 0.021, 0.012, and 0.011 respectively. We also observed a significant ($P < 0.05$) difference between the rate of change in the greenness of cotton and the rate of change in the greenness of maize as well as sorghum (Figure 7). Significant ($P > 0.05$) differences were observed again between the rate of change in the greenness of (mean NDVI values) of cotton and maize, as well as sorghum during the senescence stage, i.e., late March to early June 2007. Also, it can be observed that the change in mean NDVI values for cotton during the senescence is different from that of maize and sorghum (Figure 7). Cotton has a slope of 1.155 compared with a slightly higher slope of 4.58 and 3.63 for maize and sorghum respectively. Figure 8 also shows that there were significant ($P < 0.05$) differences between the slopes and intercepts of the rate of change in the greenness of cotton and maize. We further observed that the level at which the rate of cotton greenness changes is higher than that of maize as well as sorghum (Figure 6 and 7). However no significant differences were observed between the rate of change in mean NDVI for cotton; maize and sorghum during their green peak. The slope coefficients (b_2) rate of change in the mean NDVI for cotton, maize and sorghum are 0.00 (Figure 8).

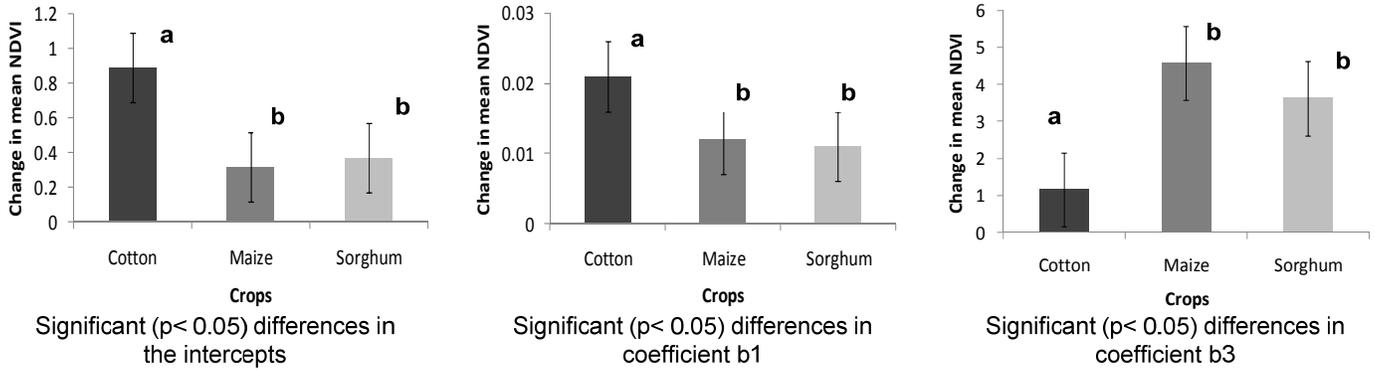


Figure 7: Significant ($P < 0.05$) differences in the intercepts and slope coefficients of the change in mean NDVI between successive image dates for cotton maize and sorghum. The slope coefficients (b2) of the change in mean NDVI between successive dates for maize, cotton and sorghum equations were equal to 0 hence they are not shown.

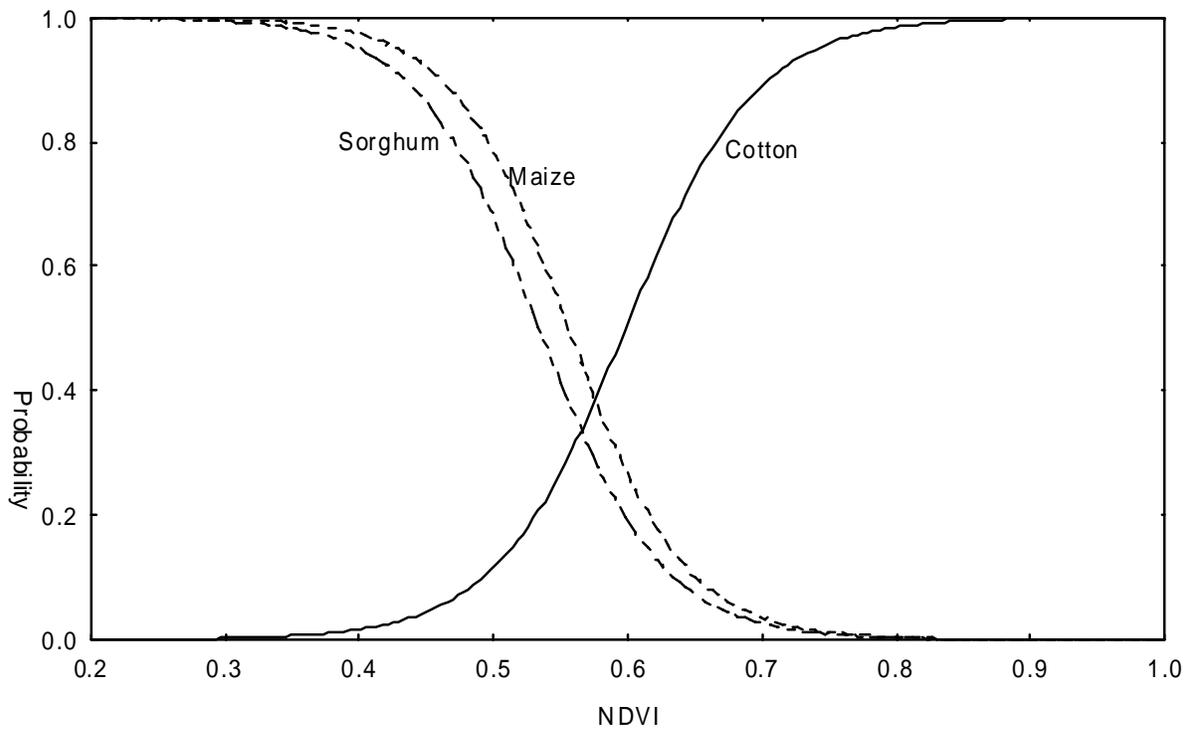
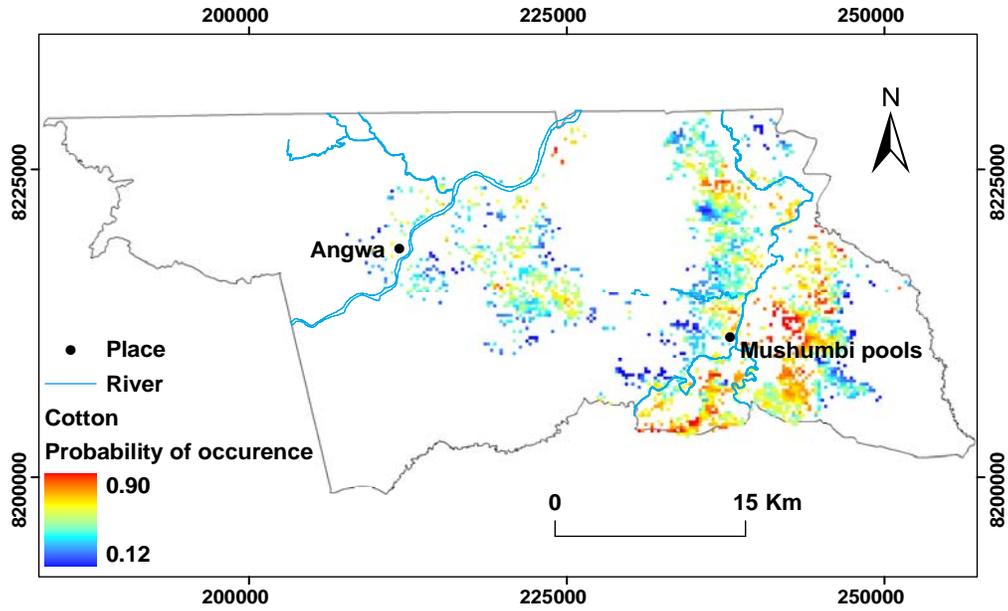
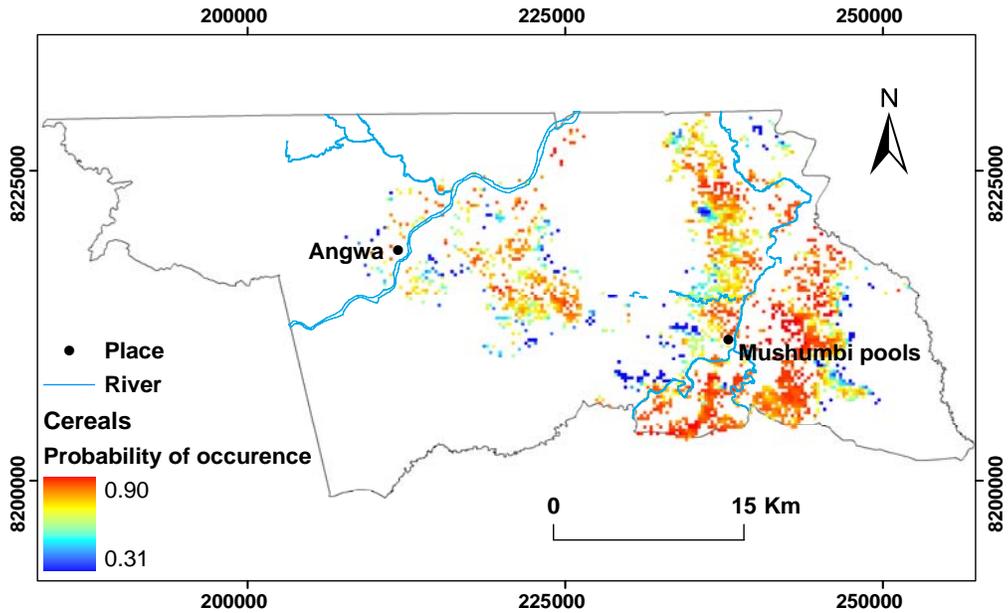


Figure 8: Significant ($p < 0.05$) logistic functions for cotton ($Y = \exp(-12.379 + (X * 20.689)) / (1 + \exp(-12.379 + (X * 20.689)))$), and cereals (maize ($Y = \exp(11.698 - (X * 21.905)) / (1 + \exp(11.698 - (X * 21.905)))$) and sorghum ($Y = \exp(12.835 - (X * 23.091)) / (1 + \exp(12.835 - (X * 23.091)))$)) crops towards the end of the farming season (16 April 2007).

Figure 8 shows that during the senescence period of cereal crops the probability of a crop being cotton sharply increases with the increase in NDVI. Cereal crops show the inverse of cotton. As NDVI increases the probability of a crop mapped being either maize or sorghum decreases.



A) Cotton probability of occurrence



B) Cereals probability of occurrence

Figure 9: Surfaces of probability of occurrence of (A) cotton and (B) cereals. Crop probability of occurrence is expressed in percentage and the coordinates are in UTM zone 36 south.

Figure 9 shows the probability of occurrence of cotton and cereal crops. It can be observed on figure 9 that cereal crops have the highest probability of occurrences towards the Manyame and Angwa rivers and have lower probabilities of occurrence at the edges of the cultivated area and their probability of occurrence increases with the increase in the distance away from the edges of the cropland area. Cotton is mainly concentrated on the edges of maize and sorghum fields expanding along the direction of tsetse eradication zone in Mbire. Figure 10 shows the spatial distribution of the mapped cotton, maize and sorghum in the Mbire district. It can be observed that maize and sorghum are mainly concentrated along the rivers while cotton follows the gradient of crop intensification.

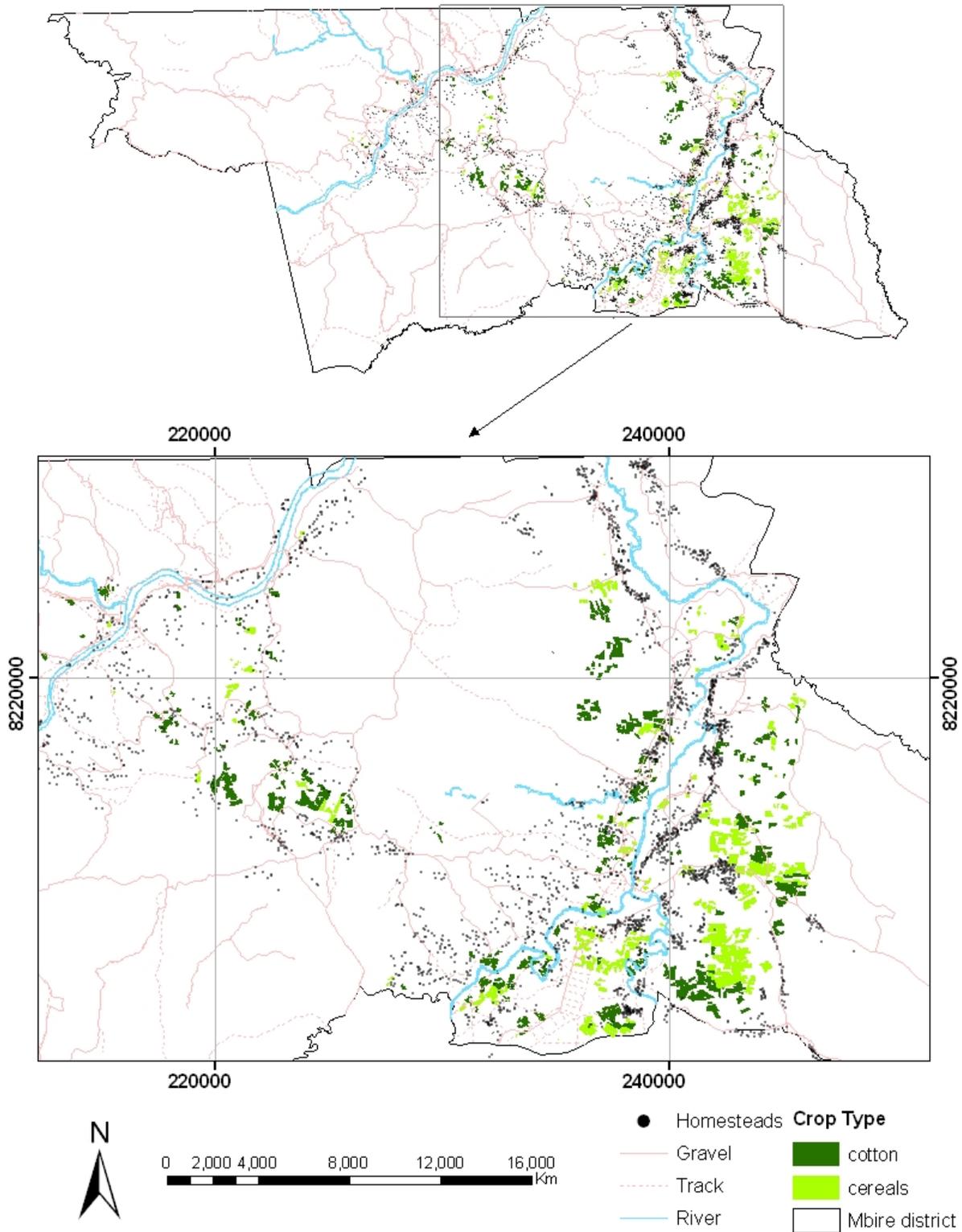


Figure 10: The spatial distribution of cotton and cereals (maize and sorghum) in Mbire district. Map coordinates in UTM zone 36 south.

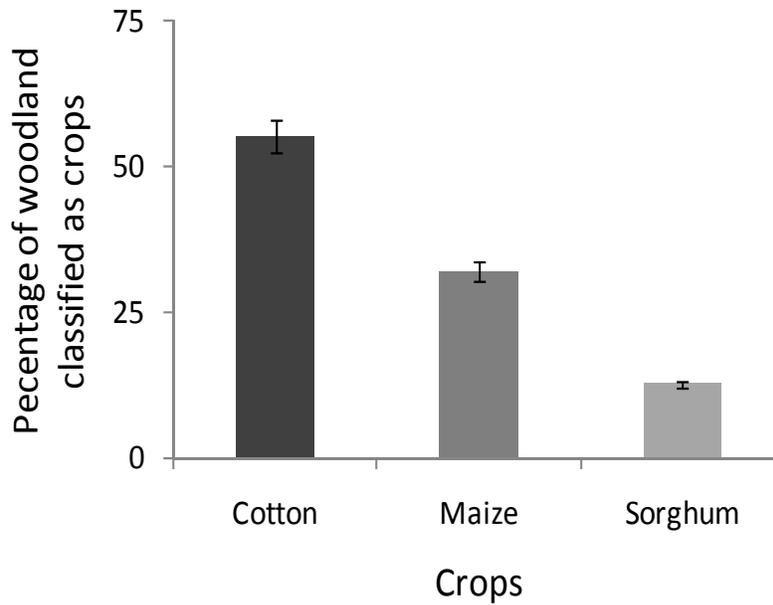


Figure 11: A comparison of the woodland area that has been converted to cotton with that converted to maize and sorghum.

Figure 11 shows woodland area that has been converted to cotton compared with that which has been converted to maize and sorghum. Most of the area classified as cotton fields 2007 was woodland in 1990.

4.2. Discussion

Results of this study indicate that using NDVI time series derived from MODIS satellite imagery, cotton can be distinguished from cereals. Results also indicate that the best phenological stage at which to distinguish maize and sorghum from cotton is during the early senescence period of the three crops as well as during the green peak stage of these crops. We make a claim that this is explained by the different growing periods of the three crops. Although cotton, maize and sorghum are grown almost at the same time, cotton has a longer growing period of up to 250 days while maize and sorghum have a shorter growing period of around 125 days. The relatively shorter growing period for maize and sorghum means that they are senescing earlier (in March) than cotton, which senesces in June. When maize and sorghum are at their

senescence stage in March, cotton is still at its green peak. This explains why NDVI values of maize and sorghum dip steeply in March while cotton NDVI values remain relatively higher than the two cereal crops during the same time thereby giving an opportunity to distinguish cotton from these cereals using remotely sensed data.

Although, we found the same hump shaped relationship between the rate of change in the greenness of cotton, maize, as well as sorghum, which is consistent with normal hump shaped seasonal crop growth progression from the green-up onset through the green peak to the senescence, we found a significant difference in the rate of change in the greenness of cotton and maize during the green-up period. Cotton has the highest rate of change followed by sorghum and lastly maize. We thus deduce that cotton can be distinguished from maize and sorghum at the green-up onset mainly due to its relatively faster rate of change in the greenness. However, we could not find a significant difference between the rate of change in the greenness (NDVI values) of cotton and maize as well as sorghum during the late senescence period suggesting that cotton maize and sorghum have similar rates of senescence but that these occur at different greenness levels.

During the early green-up and the late senescence stage, results indicate that there are no significant ($P > 0.05$) differences in the mean NDVI values for cotton and sorghum. We advance two reasons for this phenomenon, particularly during the senescence period (March 22 to June 10, 2007). Firstly, unlike the way maize is harvested, the harvesting of sorghum does not involve complete removal of the sorghum plant but just the seed-bearing part. Secondly, sorghum tends to reshoot after harvest, thus resulting in high NDVI values. Therefore due to the non-removal of

the sorghum plant during harvesting, as well as the tendency of sorghum to resprout, sorghum tends to regain high NDVI values thereby making it difficult to distinguish from cotton during the senescence stage. This result is consistent with the findings of Warldlow and Egbert (2007) that sorghum has a gradual decline in NDVI during the senescence but maintains a higher NDVI than both maize and other crops towards the end of the growing season.

Results indicate that most of the area that is occupied by cotton fields in 2007 was woodland in 1990. In addition, results also suggest that the area occupied by cotton fields is greater than that occupied by cereal crop fields in the mid- Zambezi Valley from 1990 to 2007. Our results are in agreement with Baudron *et al.*,(2009) who noted that the expansion of cotton in the mid-Zambezi Valley is the major driver of land-use change and loss of wild life habitat.

Results of this study are an important foundation for further studies seeking to enhance understanding of the spatial distribution of different crop types in relation to changes in farming methods in smallholder agricultural landscapes of Southern Africa, particularly in the mid-Zambezi Valley. However, the main challenge in using MODIS is the negative effect of cloud cover especially in December and January which leads to loss of key information relevant for distinguishing different crop types.

Chapter 5: Comparing the effect of cotton and cereal cultivation on the distribution of the African elephant (*Loxodonta africana*) through woodland fragmentation

5.1 Results

5.2 Relationship between area under cotton and cereals and woodland fragmentation.

Figure 12 shows the relationship between woodland edge density and agricultural fields area in the mid- Zambezi Valley. It can be observed that woodland edge density negatively correlates with the area occupied by agricultural fields (Figure 12).

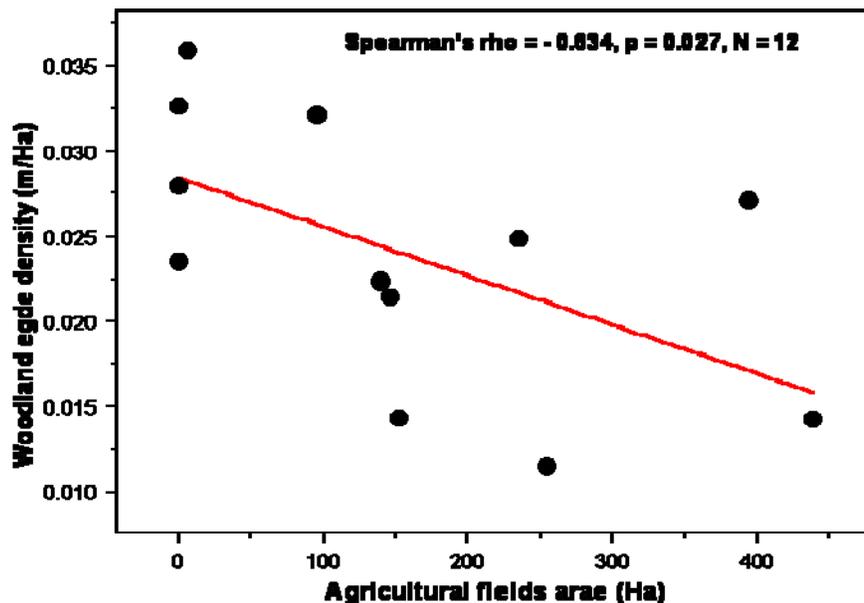


Figure 12 : Correlation between agricultural fields area and woodland edge density in the mid-Zambezi Valley.

Graphs detailing correlation analysis results between cotton, cereal crop fields, and woodland fragmentation indices, i.e., woodland class area, woodland patch size coefficient of variation,

number of woodland patches, woodland patch size standard deviation, mean woodland patch edge as well as woodland edge density respectively are detailed in Appendix 1 and 2. We selected edge density for use in regression analysis to test whether it is cotton fields or cereal crop fields that significantly explain woodland fragmentation in the study area based on the significance of its correlation functions and its high coefficients of determination (rho).

Figure 13 shows a significant ($P < 0.05$) negative relationship between the edge density of woodland and the area of cotton fields as well as between the edge density and the area of cereal crop fields in the mid- Zambezi Valley. It can be observed that the edge density of woodland patches decrease in size as the area of both cotton and cereal crop fields decrease. However, cereal field areas explain only 5 % of the woodland edge density while cotton field area explains 62% of the woodland edge density.

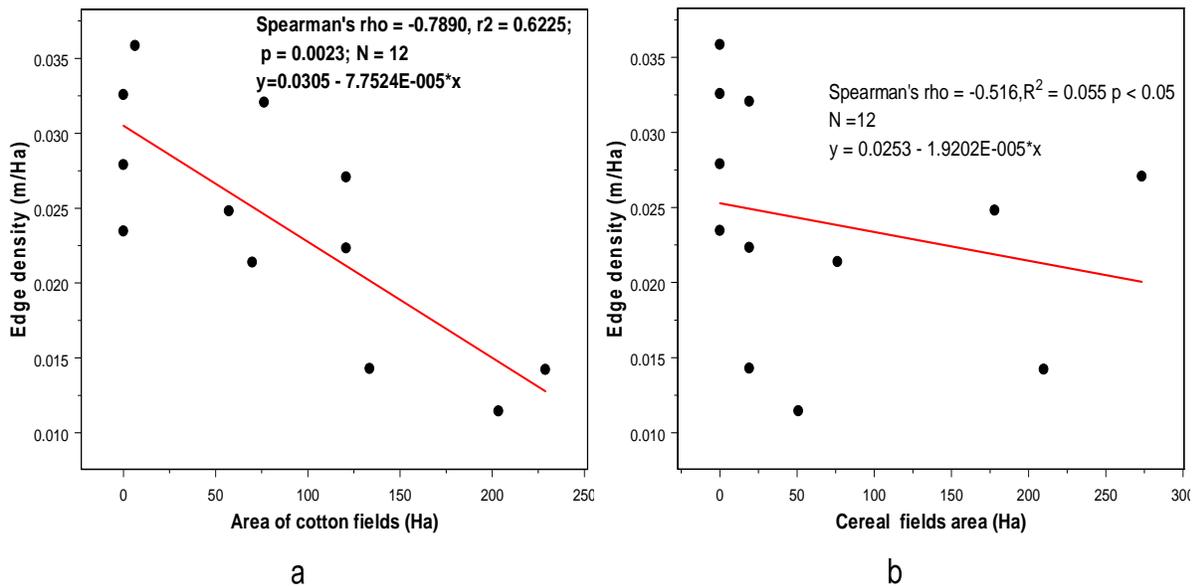


Figure 13: Significant ($P < 0.05$) relationships between (a) cotton fields area and woodland edge density, as well as (b) cereal fields area and woodland edge density in the mid- Zambezi Valley.

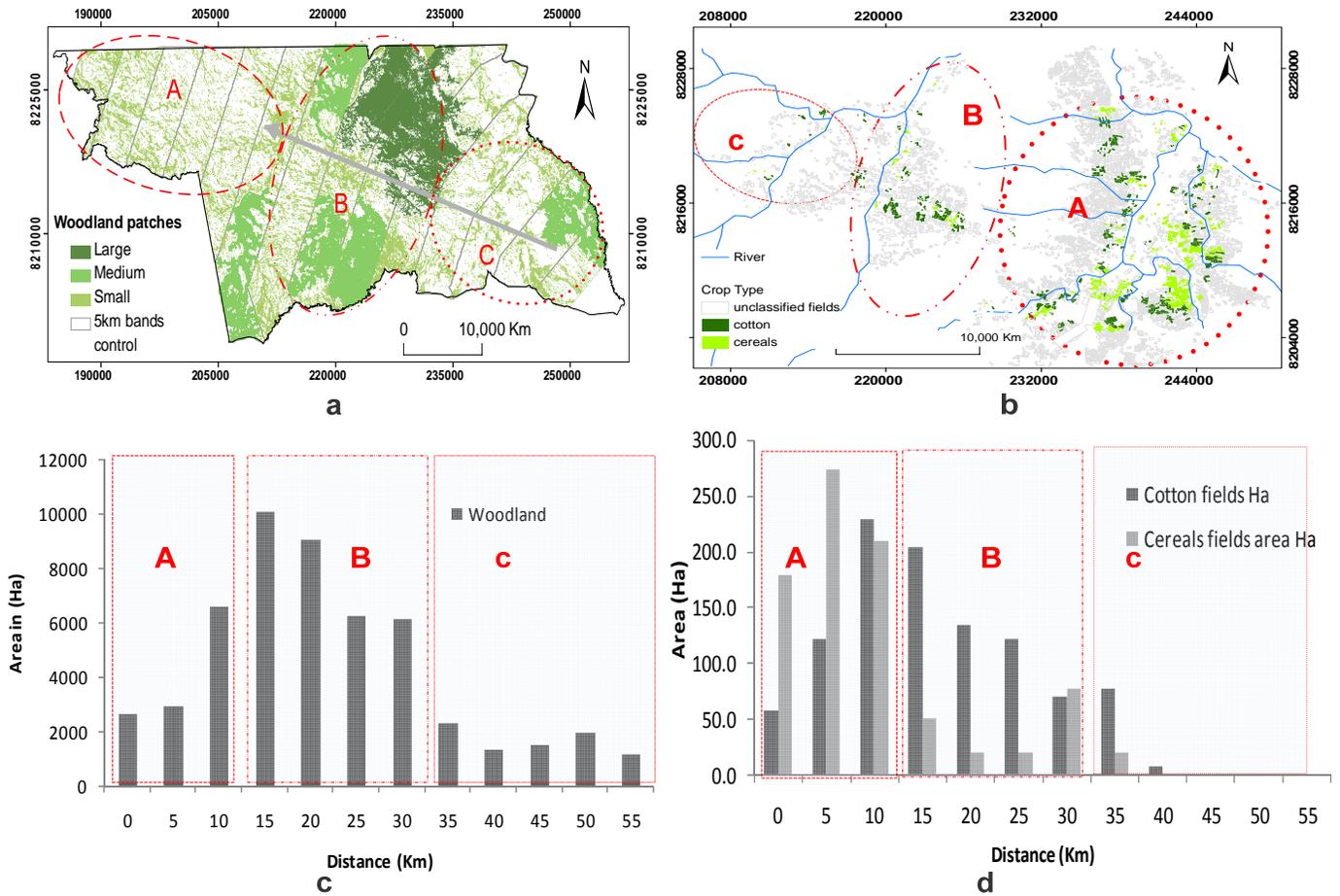


Figure 14: The spatial distribution of (a) woodland (b) cotton and cereal fields including the variations in the area of occupied by (c) woodland as well as (d) cotton and cereal fields in the mid- Zambezi Valley.

There are differences in the area occupied by agricultural fields and woodland in region C which was settled in the 1950s, region B settled in the 1980s and region A which was settled later (Figure 14). Specifically, it can be observed that the area occupied by cereal fields in region C is higher than the area occupied by cotton fields compared with the reverse in regions A and B where cotton dominates (Figure 14). Overall, it can be observed that cotton dominates in recently

settled regions compared with the earlier settled regions. On the other hand, the distribution of woodland area follows a different pattern, with higher woodland area in region B settled in the 1980s compared with the recently settled and earlier settled regions A and C respectively (figure 14).

5.3 Relationship between woodland fragmentation and elephant distribution

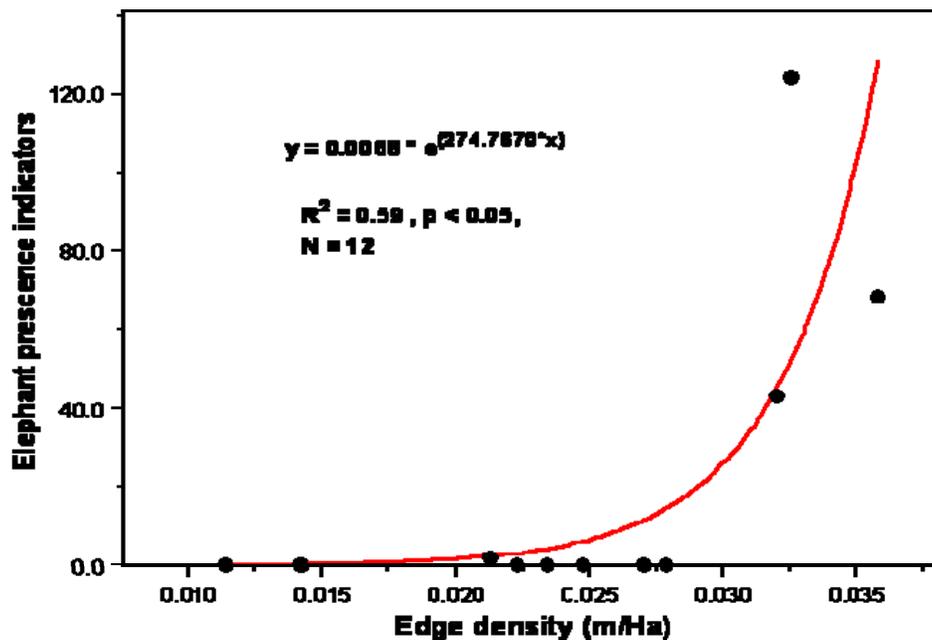


Figure 15: Relationship between the edge density and the elephant presence indicators.

Figure 15 shows a significant ($P > 0.05$) positive exponential relationship between the woodland edge density and the frequency of elephant presence indicators. It can be observed that as small woodland patches become predominant in the landscape elephant presence indicators also increase. Furthermore, we observe that the area which has a high edge density and is associated with relatively high elephant presence is within the recently settled region that is closer to the safari area (55 km).

Figure 16 shows the first order nearest neighbour distribution function G hat function (G -hat). The G -hat neighbourhood function show that woodland patches close to the safari area show evidence of clustering at shorter distances although they are relatively small in size compared with those in the region B (25 km) and C (5km) with high to medium and agricultural field intensity respectively. In fact we observe that the G -hat function of the woodland patches at 55 km strata rise steeply at a distance of 50 m up to a distance of 108 m, while woodland patches at 25 km strata gently rise from a distance of 50 m up to a distance of 315 m. Simply stated, woodland patches become more clustered as one moves from region B and C to region A which is closer to the safari areas coinciding with a region of low agricultural intensity. Specifically, we observe that although the woodland patches in region A (55 km) are predominantly small they have relatively shorter inter-patch distances compared with those in region C (5 km) and region B (25 km) of the gradient of agricultural fields intensity (Figure 15). Regions C and B coincide with the areas which were settled in the 1950 as well as in the 1980s (Figure 13).

In summary, edge density has a relatively stronger negative relationship with cotton compared with cereals. This observation leads us to a further observation that elephant presence tends to be higher where woodland edge density is high but cotton area is high. Overall, we observe that elephant presence is higher at the wildlife frontier where small woodland patch sizes dominate but tend to be relatively closer together compared with low elephant presence in relatively large woodland patch sizes with relatively longer inter-patch distances found in the middle (25km) and beginning (5km) of the gradient of agricultural fields intensity.

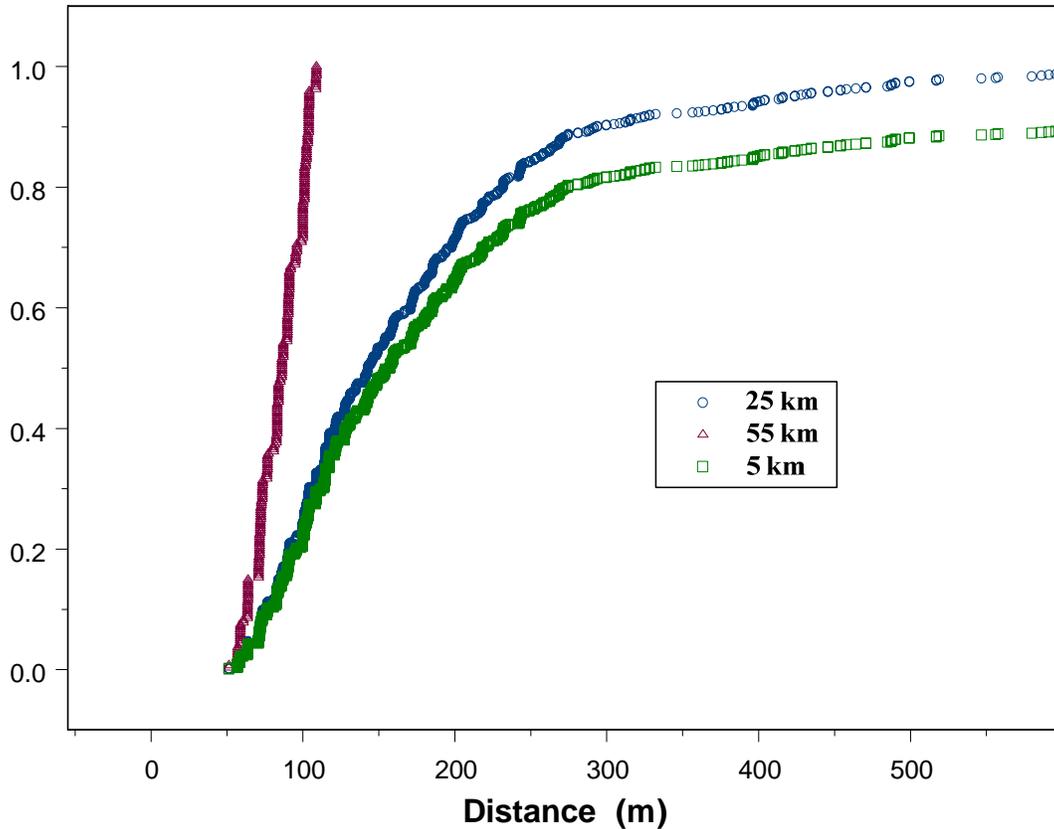


Figure 16: Clustering of woodland patches at 5 km settled since, 1950, 25 km settled since the 1980s, and 55 km strata which were settled since the 1980s and later.

5.2 Discussion

Results of this study demonstrate that cotton fields have led to the clearance of larger areas of woodland than the cereal fields in regions that have recently been settled, i.e. after the late 1980s. These findings suggest that cotton contributes more to the reduction of wildlife habitat especially in newly opened up agricultural areas of the Mid-Zambezi Valley, Zimbabwe. The regression results indicate that although cotton and cereal crops each contribute significantly to the fragmentation of the woodland, cotton fields contribute more significantly to woodland fragmentation than cereal fields. These results are supported by those of Baudron *et al* (2010),

who showed that the expansion of cotton cultivation resulted in a 263% increase of land that was converted from wildlife habitat to agricultural land between 1993 to 2001 in parts of Mbire district which are at the interface of wildlife and agricultural activities. Thus, we put forward a claim that cotton is the main driver of woodland fragmentation in the Mid-Zambezi Valley particularly in newly settled areas.

The findings in this study also indicate that the frequency of the African elephant increased where woodland patches were smaller but clustered, as well as where cotton fields occupied more area than cereal fields in the landscape. This suggests that cotton cultivation directly contributes to the spatial distribution of the elephants by fragmenting their habitat (woodland) which then directly negatively affects their spatial distribution in the African savannas. In other words, cotton cultivation occupies most of the expansive agricultural land in the zones settled from the early 1980s and this tends to 'discourage' elephants to roam in this zone. These results are supported by the findings of Murwira and Skidmore (2005) which demonstrated that the redistribution of elephants is in response to the expansion of agricultural land and fragmentation of the woodlands into the mid- Zambezi Valley that follows the direction of tsetse eradication and is then related to agricultural expansion which dates back to the 1950s. In addition, Guy (1976) also noted that an elephant can stay for more than 5 hours in small natural woodland patches of about 0.25 km² or alternatively woodland patches with a linear dimension of 0.5km (500m²) as those noted at the wildlife frontier. However, our findings differ from those of Murwira *et al.*, (2005) who noted that agriculture in general affects the spatial distribution of the elephants. In this study we have demonstrated that cotton cultivation is the most important driver

of habitat fragmentation, although agriculture in general contributes to habitat fragmentation. Thus, we claim that our result is more specific and may lead to better policy interventions.

Although results of this study show that elephant frequency is high where patches are smaller, the inter-patch distances between woodland patches in recently settled areas that are close to the wildlife frontier are shorter than the inter-patch distances in areas settled in the 1950s and the 1980s. This indicates that the woodland patches in recently settled areas tend to be much closer together simulating a near homogenous habitat where elephants are “free to roam” unlike the woodland patches in the region which was settled earlier (in the 1950s) which are distantly spaced thereby repelling the elephants. Our results are supported by those of Murwira and Skidmore (2005) who also concluded that closer woodland patches of up to 457 m² are the lower limit of the optimal range where elephants can thrive in agriculture-dominated environmental conditions in the Zambezi Valley. Leimgruber *et al.*, (2003) noted that woodland fragmentation caused by expanding human populations and agricultural lands restricted elephant populations to small and isolated habitat fragments in Asia. Beer and van Aarde (2008) also noted that African elephants located their home ranges in areas with relatively high patch density, as well as, high fragmentation (high landscape shape index and relatively low largest patch index) in Etosha national park, Khaudum game reserve and Ngamiland District. Thus, we make a claim that the frequency of the African elephant increases where woodland patches are smaller but clustered and where cotton fields also occupy more area than cereal fields in the landscape.

Where this study differs significantly from those studies that have focused on the effect of agricultural fields on habitat fragmentation (Templeton *et al.*, 1990; Wauters *et al.*, 1994;

Cumming and Lynam 1997; Grainger *et al.*, 2005; Lee and Graham 2006; Zhou *et al.*, 2008) is in our demonstration of the effect of crop specific fragmentation on elephant habitat. Specifically, we have demonstrated that mostly the cultivation of cotton contributes more than the cultivation of maize and sorghum to woodland fragmentation which in turn affects the habitat of the African elephant.

Chapter 6: General Conclusions

6.1 Specific conclusions

6.1.1 Cotton and cereals fields can be mapped in small holder agricultural areas using remote sensing

The first objective of this study was to test whether we can significantly distinguish cotton from maize and sorghum, as well as map these three crops in smallholder agricultural landscapes of the Mid-Zambezi Valley using high temporal resolution remotely sensed data such as MODIS. From the results we concluded that NDVI temporal images can be used to distinguish cotton from maize, as well as map them in small holder agricultural areas. These findings are an important preamble that enhances the understanding of the spatial distribution of different crops as well as quantify their relative contributions to wildlife habitat fragmentation in ecological frontier areas.

6.1.2 Cotton fields expansion is mostly responsible for fragmentation of woodland

In respect to furthering our understanding of the effect of specific crop farming on woodland fragmentation in the mid- Zambezi Valley, findings of this study suggest that cotton fields occupy a larger area compared with cereal fields (maize and sorghum) in regions that have recently been settled, i.e. after the late 1980s. We noted that cotton contributes more to the fragmentation of woodland especially in newly opened up agricultural areas. In this regard, we conclude that the cotton crop farming contributes more than cereal crops farming to the fragmentation of woodlands in the Mid-Zambezi Valley.

6.1.3 Habitat fragmentation as a result of cotton fields expansion is responsible for the African elephant distribution in the mid- Zambezi Valley, Zimbabwe

We also found that the frequency of the African elephant increased where cotton fields occupy more area than cereal fields in the landscape. These findings suggest that increased woodland inter-patch distances due to fragmentation by cotton fields significantly repel elephant occupancy in the mid- Zambezi Valley.

6.2 Overall conclusions

Overall, results of this study suggest that it is mostly the cotton farming that contributes more to woodland fragmentation. This in turn affects the spatial distribution of the African elephant in the mid- Zambezi Valley, Zimbabwe. In other words, we conclude that the changes in farming practices, particularly the introduction of cotton significantly contributes to the loss of habitat for the African elephant in the mid- Zambezi Valley. However, in order to understand the effect of specific crops such as cotton on the wildlife spatial distribution, we recommend more laboratory based experimental research to enhance techniques for distinguishing cereal crops such as maize and sorghum so as to quantify their separate contributions to habitat fragmentation. These results imply that elephant conservation policy needs to address the reduction of the negative impact of cash crops such as cotton on the habitat particularly their threat to wildlife habitat which may eventually lead to loss these wild animals. Thus it is important to strike a balance between wildlife habitat conservation and agricultural production as advocated through the Communal Areas Management Programme For Indigenous Resources (CAMPFIRE) policy.

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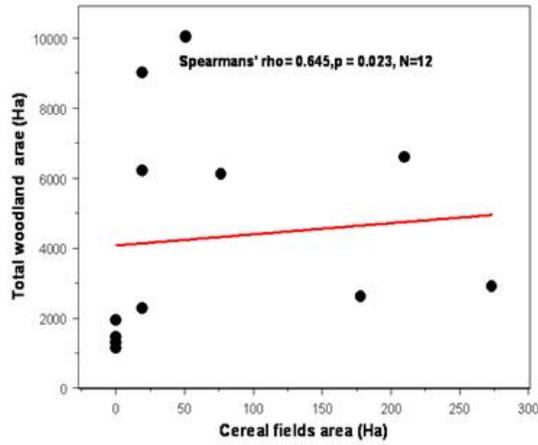
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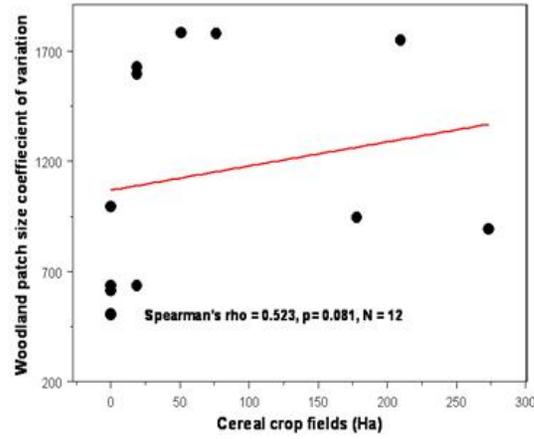
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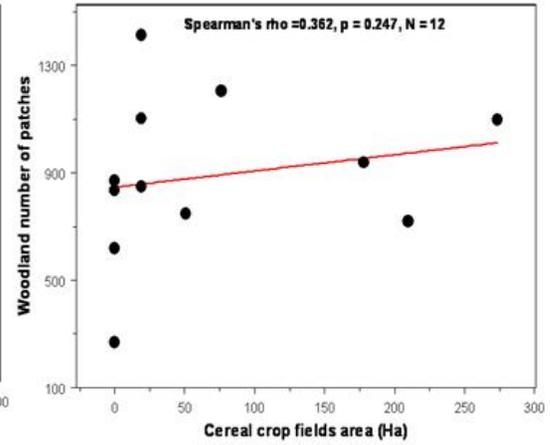
APPENDIX



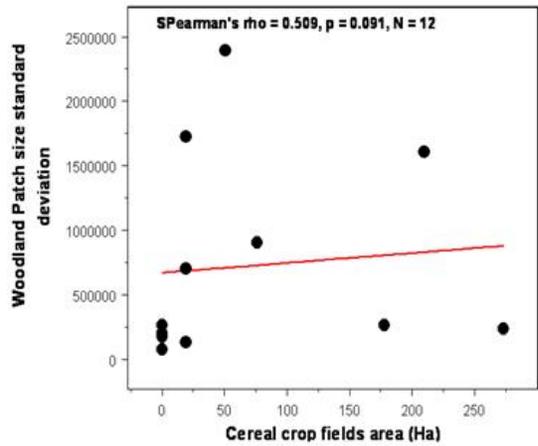
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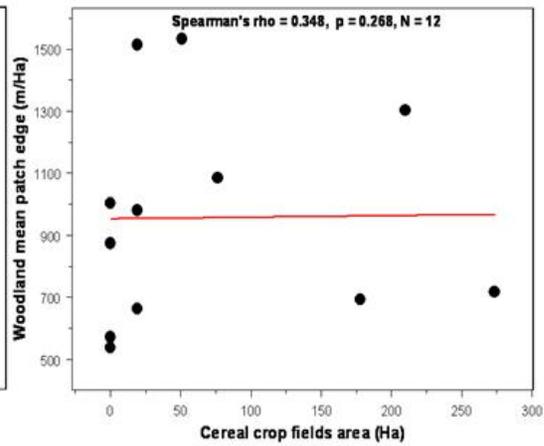
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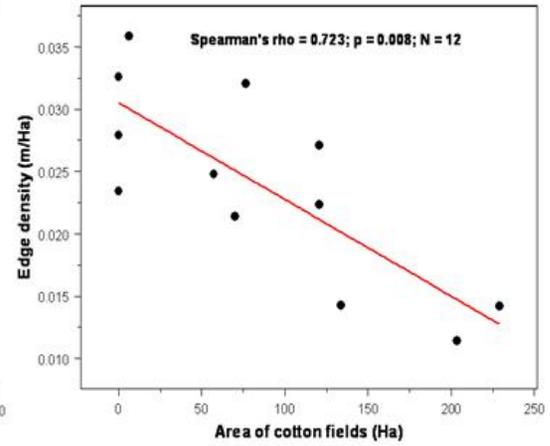
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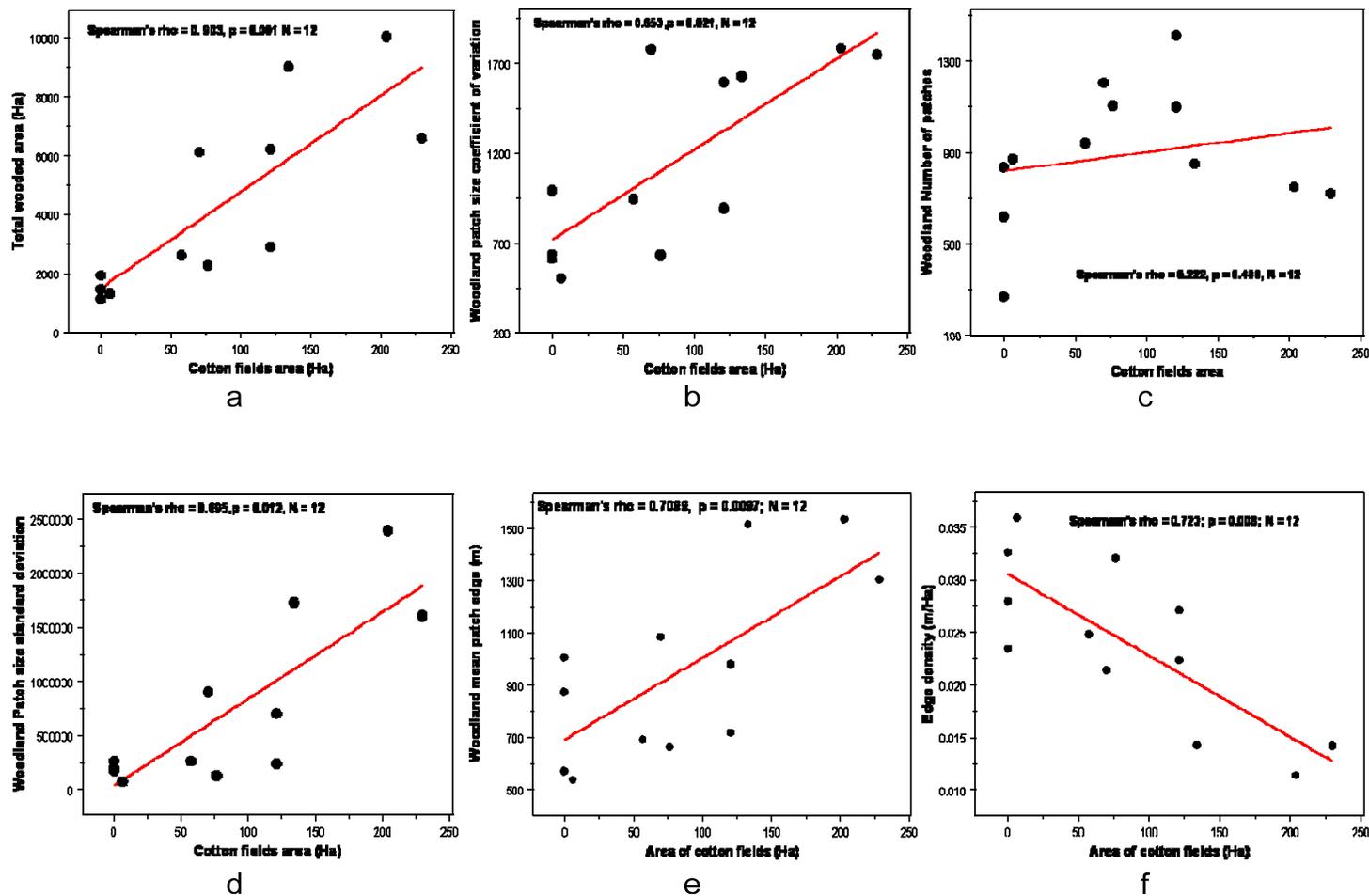


e



f

Appendix 1: Correlations showing relationships between the area of cereal crop fields and the habitat fragmentation indices



Appendix 2: Correlations showing relationships between the area of cotton fields and the habitat fragmentation indices.