THE DYNAMICS OF THE *VACHELLIA XANTHOPHLOEA* AND *FAIDBERBIA ALBIDA* WOODLANDS IN THE FLOODPLAINS OF THE MAKULEKE CONTRACTUAL PARK

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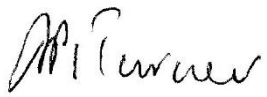
A dissertation submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science

DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

(Signature of candidate)



Signed on 6 July 2021 in Johannesburg.

ABSTRACT

The Makuleke Contractual Park in the far north of the Kruger National Park has a hot, arid climate historically supplemented by variable flooding of the floodplains of the Limpopo and Luvuvhu Rivers. The floodplains form the Makuleke Ramsar Wetlands with diverse vegetation including beautiful monospecific *Vachellia xanthophloea* and *Faidherbia albida* woodlands. A landscape level study examined the dynamics of these woodlands in the chronological order of different phases of establishment, decline and regeneration, and how they were affected by various ecological drivers over a period of half a century. Use was made of aerial photographs, Google Earth imagery and ground survey methods to track woodland changes. Episodic events were key drivers of the woodland dynamics. Anthropogenic factors, geology and soils, climate and hydrology, elephants, mesobrowsers and senescence all played roles.

The Makuleke people lived in the area until they were forcibly removed in 1969, when the area was incorporated into the Kruger National Park. With their departure, and farming activities terminated, the anthropogenic influence shifted to one governed by the conservation policies of the Kruger National Park. This created a changed environment under which most of the woodlands established.

The abiotic template of climate, geology and soils is presented. The average annual rainfall was 437 mm but with a high coefficient of variation. Infrequent flooding of the floodplains from the Limpopo and Luvuvhu Rivers introduced hydrological variability and two large infrequent flood disturbances occurred, dramatically affecting the morphology of the Luvuvhu River and dynamics of the woodlands. How the hydrological regime, large flood disturbances, geology and soils have determined the spatio-temporal distribution of the woodlands in the floodplain is discussed. Under the hot, arid climate premature stress induced senescence in the *V. xanthophloea* woodlands occurred.

The Makuleke elephant population increased from a very low base and exerted an increasing impact on all the phases of the woodlands. Elephants were shown to be the major cause of the decline of the *V. xanthophloea* woodlands but not the *F. albida* woodlands.

The spatial distribution of the areas of regeneration of both woodland species was shown to be influenced by soil form in the floodplains. The role of mesobrowsers, especially impalas, in constraining, and in some cases terminating, regeneration at seedling stage is covered. The concept of a “browse trap” created by mesobrowsers and elephants for both the seedling and sapling stages in the regeneration phase of the woodlands was demonstrated. The area of regeneration was not replacing the area of woodland lost, and reasons are given.

The conclusion highlights the unique characteristics of, and differences between, the two woodland species and how the roles of the key ecological drivers differed in their influence on the dynamics of each of the two woodlands. Their likely influence on the future of the woodlands is discussed. In particular, an increasing elephant population and possible changing flood regime are likely to have major impacts. Recommendations are made for further research that should benefit conservation management of the Makuleke Ramsar Wetlands.

ACKNOWLEDGEMENTS

Both the Limpopo and Luvuvhu Rivers flooded in January 2013 and was the biggest in living memory for the Luvuvhu River. The general impression was that the flood was a disaster with substantial numbers of large riverine and floodplain trees removed. The Luvuvhu River cut a new macro channel along its course.

In September 2013 I was guiding a trail between Rietbokvlei and Nwambi pans when I noticed the emergence of large numbers of *Vachellia xanthophloea* seedlings. That moment was also the germination of this research. The seedlings were a reminder that nature is always in a state of flux, always adapting to survive. The system had been reset by the floods and the process of adapting from a new base state had begun. Prof. Norman Owen-Smith of the University of the Witwatersrand encouraged me in my keenness to study the regeneration of the woodlands.

It became evident that the regeneration of the woodlands was just a small facet of the ecosystem which had been sculptured over time by the forces of nature and man. Drs Corli Coetzee (Kruger National Park (KNP) Scientific Services) and Laurence Kruger (Organisation for Tropical Studies) encouraged me to look at the "bigger picture", and so the scope of the study became "**The dynamics of the *Vachellia xanthophloea* and *Faidherbia albida* woodlands in the floodplains of the Makuleke Contractual Park**".

The structured way to look at this bigger picture crystallised - understand the abiotic template of geology and climate as the base with bottom up influence on the woodlands, and animal agents with top down influence. An important spatially distributed abiotic agent was expected to be the soils. Dr Gerhard Nortje (Solo Vivo) assisted me greatly in understanding soils and accompanied me to Makuleke to help with soils identification. An important anthropogenic episodic change was expected to be the forced removal of the Makuleke people. Through the need to understand this I met Eric Tivani (member of the Makuleke Royal Family). His knowledge and the research into the Makuleke history we did together was invaluable.

Over time the influence of many agents can change spatially, episodically, cyclically, randomly or unidirectionally. The most important unidirectional change was expected to be the impact of a growing elephant population. Dr Michelle Henley (Elephants Alive) reworked her data from the original elephant research in the Makuleke Contractual Park (MCP) to provide key information on the distribution and movements of elephants in the area.

Rudolfe Roussel (from the National Institute of Agronomy of Toulouse, France, while seconded to Elephants Alive) did the digital stitching together of individual aerial photographs.

My wife, Maylene, gets my special thanks. She was supportive and patient while I spent many days away from home and long hours involved in this research.

The final dimension was provided by Return Africa. The management (Godfrey Baloyi) and many guides at Pafuri Camp gave me exceptional support in the field. PJ Massyn, CEO of Return Africa, encouraged me and impressed that the outcome must improve the knowledge base in a way that contributes to science and enhances guest experiences. I hope I have achieved that.

I made new friends. Norman, Laurence, Corli, Michelle, Gerhard, Eric, Rudolfe, Godfrey and PJ – thank you for your great support.

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1. INTRODUCTION

A river floodplain system consists of a flat area of terrestrial vegetation adjacent to the river and stretches from the banks of the river to a surrounding area of higher elevation and is subject to inundation on a frequent or infrequent basis by lateral overflow water from the river (Goudie, 2004). It may contain permanent or temporary bodies of water. The flat profile has been created by deposition of alluvial material from flooding events and is also referred to as the aquatic/terrestrial transition zone (ATTZ).

Natural floodplains are among the most biologically productive and diverse ecosystems on earth but also among the most threatened (Tockner and Stanford, 2002). For millennia floodplains have been used by humans. The major threat to their natural state is anthropogenic through habitat alteration, flow and flood control, species invasion and pollution (Tockner and Stanford, 2002). Floodplain productivity has been harvested since early civilisation by people who have learned to cultivate and use the rich resources of floodplains, and consequently most of the global floodplains have been altered to such an extent that the original natural ecosystem no longer exists. In Europe and North America up to 90% of floodplains are cultivated and the natural state is functionally extinct (Tockner and Stanford, 2002). In Africa more traditional and less intense use has led to a lower level of negative anthropogenic effect. However, many highly modified floodplains exist, such as the Nile River with unnatural flow control from major dams and intensive agriculture in the Egyptian section of the floodplain. After completion of the Aswan High Dam in 1970 all flooding downstream of the dam ceased. In South Africa the Pongola floodplain in KwaZulu-Natal is an example of a modified floodplain system over much of its length (Furness and Breen, 1980).

Where natural floodplain ecosystems exist, there is continual pressure for human occupancy and agriculture, especially in Africa where the population is projected to increase by 207% from 2000 to 2050 (UNPD, 2019). For systems not threatened by land use change there is still increasing universal concern over the degradation of floodplain ecosystems through changing hydrology due to upriver water extraction, changing flooding regimes, climate change and increasing silt and chemical pollution of the river water from agricultural and industrial developments (Louw, 1994; Tockner and Stanford, 2002).

Floodplains are an important component of a landscape's diversity because of a marked difference in the soil and hydrology of the floodplain compared to the adjacent areas of the river and higher elevation. In natural systems in semi-arid areas, they form a distinct ecotone between the fluvial system and surrounding semi-arid savanna (Botha, 2001). They support diverse flora and fauna and have significant ecotourism value. Floodplain vegetation in semi-arid areas is controlled by the extent of depression of the water table distal to the river (Mitsch and Gosselink, 1986) and frequency of flooding (Hughes, 1988). The floodwaters and subsequent groundwater levels are important determinants of the type and productivity of the floodplain vegetation. Floodplain ecosystems are controlled by the flood pulse concept when periodic inundation and subsequent desiccation cause the lateral exchange of water, nutrients and organisms between the river and floodplain (Junk *et al*., 1989). Floodplains are driven by strong periodic abiotic disturbances of wet and dry phases and the stability and resilience of the system is its capacity to fluctuate between these phases (Colloff and Baldwin, 2010). The hydroperiod of the ecosystem, which includes the flooding intensity, duration, and timing, is the ultimate determinant of the ecosystem structure and function (Mitsch and Gosselink, 1986). The absence of floods should be regarded as a system disturbance (Bayley, 1995).

Flooding regimes are central in determining the spatial and temporal dynamics of floodplain ecology. Changes in river flows, water quality and sediment transport can alter habitat and the germination and growth of riparian vegetation (Elderd, 2003; Mallik and Richardson, 2009; Bendix and Hupp, 2000). Studies done on the Tana River floodplain, Kenya (Hughes, 1990) and the Pongola River floodplain (Furness and Breen, 1980) show that the spatial distribution and difference of vegetation communities is determined by the flood frequency, level and duration, which are also a function of elevation differences in the floodplain and distance from the river. These correlate with soil differences with the Tana floodplain being a good example. Hughes (1990) postulated that a change in the flooding frequency would have significant vegetation effects. However, there appears to be a dearth in the literature of life cycle dynamics of recruitment, establishment and decline. Emphasis has generally been focussed on the dependence of floodplain vegetation on the flood regime and soils, a bottom up effect. Other agents not as extensively covered include herbivory by megaherbivores, mesoherbivores and fire (top down). Anthropogenic factors can farther complicate the interrelationships and interactions of all these agents.

Extreme floods can have detrimental effects. Kruger National Park (KNP) rivers have been studied through the Rivers Research Program, which was implemented, inter alia, to understand the ecosystem consequences of their highly variable flow regimes and large infrequent "disturbances events" of flood and drought (Rogers and O'Keeffe, 2003). Using aerial photography after 1940 allowed an assessment of the changes to the Sabie River following the large floods of 1925, 1996 and 2000, and the severe drought of 1991/92. This showed major temporal changes in channel type and major spatial and temporal changes of vegetation in the macro channel and channel bank. However, this river does not have a floodplain which could be studied. The dramatic effect of a 1:200 year flood caused by cyclone Domoina in 1984 on the Umfolozi and Pongola Rivers systems has been well documented (Rossouw, 1985). Large areas of riparian woodland and mangrove swamps were removed.

An excellent example of a floodplain in a semi-arid savanna is the Makuleke Ramsar Wetlands in the Luvuvhu and Limpopo floodplains in the Makuleke Contractual Park (MCP) which is a major component of the diversity of the area. The MCP is situated in the north of the KNP between the Limpopo and Luvuvhu Rivers within the tropics centred at latitude 22.38^{o} S and longitude 31.18^{o} E (fig 1.1). The Makuleke people lived in this area from about 1820. The area was incorporated into the KNP in 1969 when the Makuleke people were forcibly removed. After the first democratic elections in 1994 the Makuleke people were successful in reclaiming the land and title was granted to the Makuleke Communal Property Association (CPA) in 1998. At the same time the CPA entered into an agreement with South African National Parks (SANP) and the South African Government which committed the area to conservation. The MCP was created and remained part of the KNP as a contractual park.

Afforded the protected status of a national park since 1969, the MCP floodplains are unique in South Africa, having escaped the direct impact of human activity for almost 50 years. Prior to 1969 the floodplains were subject to limited small scale agriculture and hunting which would have limited the population of large and small herbivores. Protected as a national park since 1969, herbivores, particularly elephant, were able to immigrate into the area and animal populations, including elephants increased. Elephants are recognised ecosystem engineers and an immense amount of research on their impact on woodlands has been documented (O'Connor *et al.,* 2007). Woodlands were able to establish and go through life cycle phases of recruitment, establishment and decline.

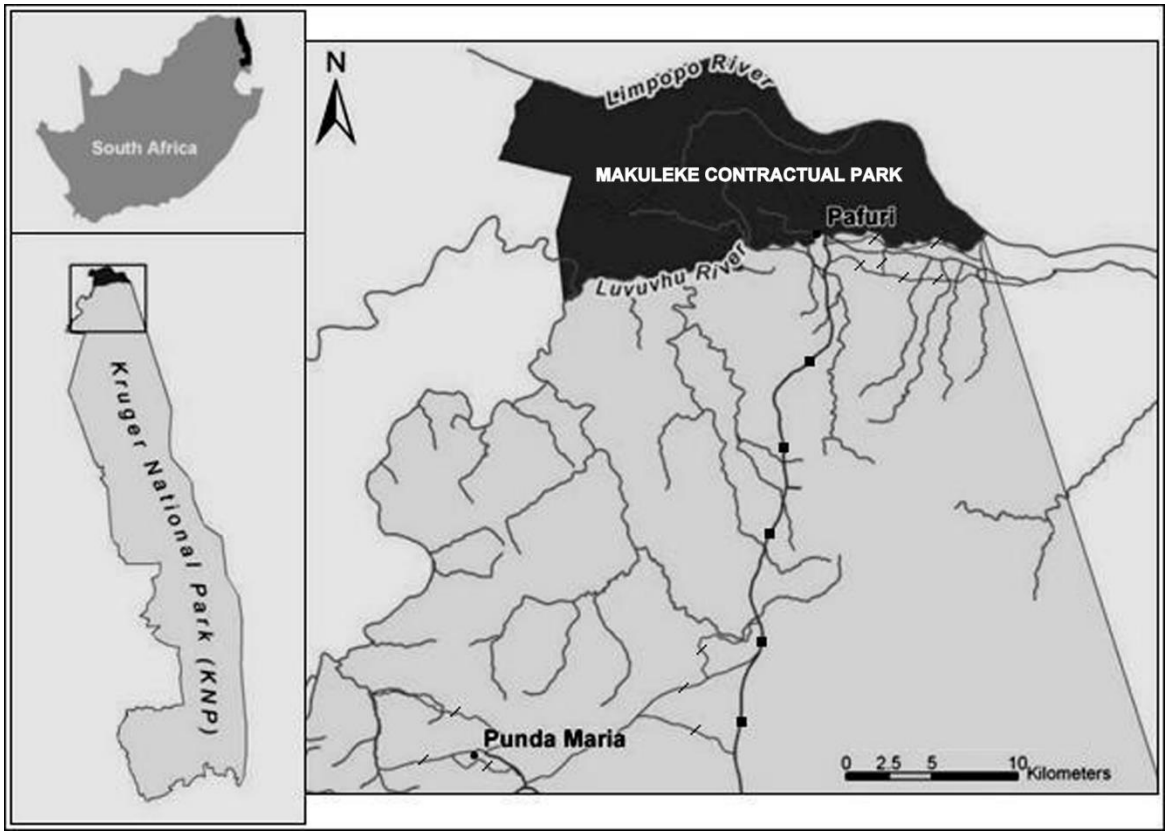


Figure 1.1: **The location of the Makuleke Contractual Park in the north of the Kruger National Park and northeast corner of South Africa between the Limpopo and Luvuvhu Rivers. The centre of the MCP is at latitude 22.38° S and longitude 31.18° E.**

Floods have always been part of the MCP ecosystem with the most recent large floods occurring in 2000 and 2013. These floods were widely reported, and their impact in the Limpopo valley was significant. In recognition of their diversity, uniqueness and importance, the floodplains were declared a Ramsar Wetland on 22 May 2007 (RSIS, 2016). The floodplains (Ramsar site) cover an area of 7750 ha of which about 6800 ha is within the MCP. The balance is in the KNP south of the Luvuvhu River. The Ramsar wetlands consist of the Limpopo and Luvuvhu River floodplains and floodplain pans and are classified as vlei type wetlands. The Ramsar wetlands include a series of 31 named pans and many other unnamed pans. The pans occupy a small percentage of the floodplains and the vegetation consist mostly of a diverse assemblage of riverine forest, riparian woodlands and floodplain grasslands (RSIS, 2016). Monospecific *V. xanthophloea* and *F. albida* woodlands are components of this vegetation diversity. They provide valuable sources of food, shelter, and habitat for wildlife. In addition, they are a tourism drawcard. Ramsar status has as its objective conservation and sustainable use which is achieved through ecotourism. The Makuleke Conservation Development Framework (CDF, 2012) balances the needs of conservation and ecotourism.

Why study the monospecific woodlands?

The main reasons for selecting the monospecific woodlands were:

1. Understanding their dynamics is integral to supporting conservation of the Makuleke Ramsar Wetlands. The monospecific woodlands are an important component of the Wetlands (part of the wetland vegetation classified by Ramsar as riparian woodlands) (RSIS, 2016);

2. The woodlands are tourism icons of the MCP. For some tourists, experiencing these woodlands is the primary reason to visit the MCP. They add to the overall diversity of the MCP. Understanding the woodland dynamics can be used to enhance guest experiences and increase tourism revenues;
3. Observations after the floods in 2013 showed significant flood impact on some of the mature monospecific woodlands and an apparent flood role in initiating the large scale appearance of seedlings. Other large scale flood impact was observed in changes to the channel of the Luvuvhu River and removal of adjacent riverine woodland. The disturbance caused by the floods was an opportunity to study the dynamics of woodlands in one of the most pristine natural floodplain environments that can be found in South Africa. The two monospecific woodlands were an ideal target;
4. There is a general concern about the impact of elephants on woodlands and observations showed elephant impact on many of the MCP tree species. Studying the dynamics of the woodlands would incorporate quantifying the role of elephants.

The MCP is acknowledged as an area of amazing abiotic and herbivore diversity. This study takes a more integrated approach than usual by studying top down and bottom up control of the monospecific *V. xanthophloea* and *F. albida* woodlands over a period of several decades.

Structure of the study.

The study is divided into 6 chapters:

Chapter 1 is an introduction and rationale why the monospecific woodlands are the focus of the study.

Chapter 2 defines the aims and objectives and sets out the research questions. It explains the use of a multi-stage model of woodland life cycle with demographic bottlenecks as the foundation for studying the dynamics of the woodlands in the chronological order of an establishment phase, decline phase and regeneration phase. It also postulates which were the key ecological drivers affecting each woodland phase.

Chapter 3 describes the study site including details of the key ecological drivers.

Chapter 4 examines the demographic character of the monospecific V. *xanthophloea* woodlands in each of the three woodland phases, and the role played by each of the key ecological drivers in affecting the woodland phases. A literature survey and methods used specific to the *V. xanthophloea* woodlands are included.

Chapter 5 examines the demographic character of the monospecific F. *albida* woodlands, in each of the three woodland phases, and the role played by each of the key ecological drivers in affecting the woodland phases. A literature survey and methods used specific to the *F. albida* woodlands are included.

Chapter 6 is a synthesis of the functioning of the woodlands. It compares the characteristics of the two woodlands and explains how they differed in their dynamics and responses to the key ecological drivers. Their likely influence on the future of the woodlands is discussed, and recommendations made on future research which would assist in conservation management of the Makuleke Ramsar wetlands.

2. AIMS AND OBJECTIVES

The aim of the research was to contribute to the knowledge of the functioning of the Makuleke Ramsar Wetlands by studying the dynamics of two monospecific woodlands and the ecological drivers impacting their dynamics. The monospecific woodlands are an important component of the Makuleke Ramsar wetlands.

The objective was to identify the main ecological drivers impacting the woodlands and to map the chronology of events of ecological drivers and woodland phases through the broad phases of:

1. establishment of the woodlands. This refers to woodlands that were mature (capable of producing flowers and seed) before 2013, the date of the last major flood;
2. decline of the woodlands. This refers to any decline of the woodlands after their historical establishment;
3. regeneration of the woodlands. This refers to the appearance of seedlings and saplings after 2013 with the potential to grow into mature woodlands.

There are several potential demographic bottlenecks in woodland tree populations (Midgley and Bond, 2001; Sankaran *et al.,* 2005; Bond, 2008; Holdo, 2014; Staver and Bond, 2014; Bond *et al*., 2017.). Life history stages and demographic bottlenecks are explained using a multi-stage model with bottom-up (resources) and top-down (consumers) (herbivores, fire) control of demographic transitions between life history stages. Potential demographic bottlenecks exist at each life history stage. The demographic bottleneck model has five stages:

1. Stage 1. Pollination, seed production and seed dispersal.
2. Stage 2. Seedlings.
3. Stage 3. Saplings.
4. Stage 4. Sub-adults.
5. Stage 5. Adults.

This is represented by the schematic model of figure 2.1 and is referred to as the “demographic bottleneck model” or “Bond model”. “Controller” (or ecological driver, used synonymously) refers to an agent preventing or facilitating movement between life history stages or causing mortality.

Various controllers govern the movement between these stages on a spatio-temporal scale, and cause mortality that occurs within any of the stages. The defining characteristics of stages 2 to 5 are differences in plant height and to a lesser extent stem diameter. Age is not used as a characteristic due to the difficulty in determining age accurately. Movement between stages can be progression (advancing to the next stage through growth) or regression (reversion to a previous stage through height reduction). Plants can also be maintained in a stage for lengthy periods. In the adult stage the plant can produce flowers and fruit. Advancing from one demographic stage to the next is termed “escaping” from a particular “controller trap or traps” (Staver and Bond, 2014; Bond *et al*., 2017). If no individuals escape a controller trap, adult woodlands never materialise. The number of stages was determined by the possibility of different controllers affecting different plant heights. The model is conceptual and using height as the stage characteristic does not accommodate all scenarios. A root that resprouts from below the surface and is seedling height is classified as a seedling (irrespective of age). Reversion to a previous stage applies mainly between the stages 3 to 2 where plants are smaller. Pollarding in stages 4 and 5 does not convert these trees to stages 2 or 3.

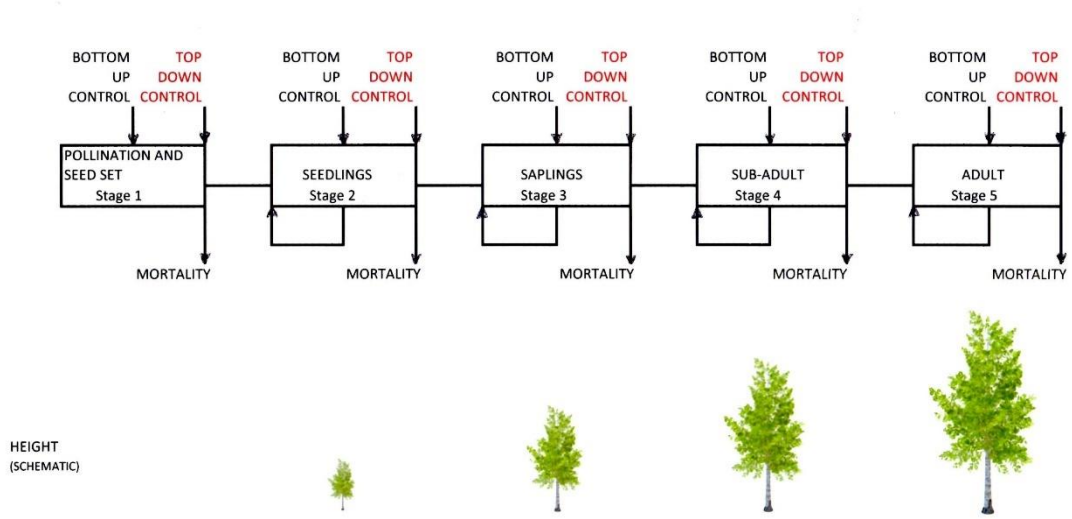


Figure 2.1: **Woodland demographic bottleneck model with different stages ("Bond model"). Bottom up and top down control can prevent or facilitate transitions between stages or cause mortality.**

A natural reduction in population with growth often occurs as individuals compete for light, water and nutrients, which is termed thinning. Inherent in the demographic bottleneck model is mortality causing a population reduction at each stage, which is not natural thinning. The transitions between demographic stages are unlikely to be even and can be temporally lumped due to temporal changes in controller dynamics, often of an episodic nature. The final adult stage of a mature woodland is a result of a complex fine balance of the effect of all the controllers at all the stages. Mortality terminates the final adult stage.

The dynamics of the monospecific woodlands were viewed within the framework of the demographic bottleneck model and referred to movement between the various life history stages under the influence of different ecological drivers, matched to the three phases of establishment, decline and regeneration (fig 2.2).

The monospecific *V. xanthophloea* and *F. albida* woodlands were spatially separate in the floodplains and in line with this, the assumption was made that the dynamics of the two woodlands would be different. This led to setting the same objective and four similar research questions for each woodland.

A monospecific woodland can consist of individuals of the same age (cohorts) or of individuals of different ages (having a wide age distribution). In both cases the principles of the demographic bottleneck model will be valid. The objective and research questions are formulated below. The research questions address the woodland phases in the chronological order of the schematic model of figure 2.2.

OBJECTIVE: To identify the main ecological drivers affecting each of the monospecific *V. xanthophloea* and *F. albida* woodlands.

Research question 1: What were the main drivers of the historical establishment of the mature woodlands?

Research question 2: What were the main drivers of the recent decline of the mature woodlands?

Research question 3: What were the main drivers of the regeneration of the woodlands?

Research question 4: Will the regeneration on a landscape scale replace the declining mature woodlands?

The expectation was that the main ecological drivers which would affect one or more of the phases of establishment, decline, and regeneration of both woodlands but to varying extents, spatially and temporally, would be:

- anthropogenic factors
- climate
- geology and soils
- elephants
- mesoherbivores
- senescence

The dynamics of some of these ecological drivers in the MCP context are covered in the site description in chapter 3.

Senescence is a complex biological process where cells tissues and organs of a plant age and die (Woo *et al.*, 2018; Thomas, 2013). Overall senescence is the age dependent programmed degradation and degeneration process of the entire organism leading to the death of the whole tree. This is a natural process, the timing of which can be advanced when the tree is subject to environmental stress (premature senescence) (Ciesla and Donaubauer, 1994). Whole woodlands can be subject to synchronous overall senescence. Senescence is a term subject to much semantic debate (Thomas, 2013). Premature senescence refers to stress over a lengthy period leading ultimately to premature or early death.

Although fire is ubiquitous in savannas, it is not expected to be important in the context of the MCP woodlands. Most fires in KNP are from external sources. The MCP is largely protected from invading fires by the Limpopo and Luvuvhu Rivers. The fire return period over 66 years (1941 to 2006) was between 12 and 67 years (van Wilgen *et al.,* 2014). Other ecological drivers such as insects, disease, and competition from other vegetation were expected to be secondary.

Woodlands are inherently complex. They can consist of single species (monospecific) or a mixture of species in a spectrum of proportions of different species. They can also comprise cohorts of even age or a distribution of ages. Densities within and between woodlands can vary. Based on personal observations, the woodlands that were the focus of this study appeared to be monospecific and consist of even height (possibly even age) cohorts. Confirming this is inherent in answering the research questions as ecological drivers will determine these demographic characteristics. Even aged woodlands have clear growth and development characteristics (Bettinger *et al.,* 2017). Canopy height is even, increases with age and then plateaus. Average tree diameter increases with age and displays a narrow unimodal distribution.

The research questions do not address the complexity of inter-relationships that would exist between the main ecological drivers, which is beyond the scope of this research.

RESEARCH QUESTION	MAIN DRIVERS		PHASES AND STAGES
1	ANTHROPOGENIC	?	**ESTABLISHMENT OF THE WOODLANDS**
	GEOLOGY	?	
	CLIMATE	?	
	ELEPHANTS	?	
	MESO BROWSERS	?	DEMOGRAPHIC MODEL STAGES 1,2,3,4,5
2	ANTHROPOGENIC	?	**DECLINE OF THE WOODLANDS**
	CLIMATE	?	
	ELEPHANTS	?	
	SENESCENCE	?	
			DEMOGRAPHIC MODEL STAGE 5
3	ANTHROPOGENIC	?	**REGENERATION OF THE WOODLANDS**
	GEOLOGY	?	
	CLIMATE	?	
	ELEPHANTS	?	
	MESO BROWSERS	?	DEMOGRAPHIC MODEL STAGES 1, 2, 3

Figure 2.2: Schematic model of the research questions, and phases of the *V. xanthophloea* and *F. albida* monospecific woodlands.

3. STUDY AREA AND STUDY SITES

3.1. OVERVIEW

The study was conducted within the 23700 ha MCP (fig 1.1).

The Makuleke Ramsar Wetlands exist within the floodplains of the Limpopo and Luvuvhu Rivers which extend along the Limpopo River from Mabiligwe (western boundary) to Crooks Corner (junction of the Limpopo and Luvuvhu Rivers at the eastern extremity) (a linear distance of 43 kms) and along the Luvuvhu River from Mangala to Crooks Corner (a linear distance of 20 kms) (fig 3.1, which includes place names). The floodplains are about 7750 ha in extent. About 6800 ha (88%) is within the MCP, with the balance being the floodplains on the southern bank of the Luvuvhu River. The monospecific *V. xanthophloea* and *F. albida* woodlands and regeneration areas all occurred within these floodplains.

An overall study area of 4000 ha within the MCP floodplains was selected (fig 3.1) which contained *V. xanthophloea* and *F. albida* woodlands and regeneration sites. The study area extended along the Limpopo floodplain from Nhlangaluwe to Crooks Corner and on the Luvuvhu floodplain from Mangala to Crooks Corner. All monospecific V. *xanthophloea* and *F. albida* woodlands and regeneration areas within the 4000 ha study area were studied using individual study sites.

The Ramsar classification of the wetlands is floodplain vlei type, with vegetation comprising riverine forests, floodplain riparian forests, floodplain grasslands and flood pans (RSIS, 2016). In the broad scale vegetation of the CDF (fig 3.2) (CDF, 2012) the floodplain consists of Lowveld riverine forest and subtropical alluvial vegetation. At a finer scale, the vegetation of the Limpopo and Luvuvhu floodplains is more diverse.

The Limpopo River floodplain contains three broad vegetation units (pers obs):

1. A mixed riverine woodland exists on the levee adjacent to the Limpopo River, with beautiful large trees such as *Diospyros mespiliformis, Faidherbia albida, Ficus sycomorus, Vachellia robusta, Hyphaene petersiana, Phoenix reclinata, Vachellia xanthophloea, Trichilia emetica, Xanthocercus zambesiaca and Gymnosporia senegalensis*. The main woodland grasses are *Panicum maximum, Setaria incrassata and Urochloa mosambicensis*. All these grasses are high in nutritional value.
2. Large areas of *Sporobolus consimilis* grasses occur off the levee in the slightly lower and more frequently flooded area of the floodplain. This grass is adapted to the alkaline soil conditions which exist, is tough and unpalatable and utilized almost exclusively by the bulk grazer, buffalo (*Syncerus caffer*).
3. Monospecific stands of *V. xanthophloea* occur off the levee in the *S. consimilis* grasslands in the slightly lower and more frequently flooded area of the flood plains.

The Luvuvhu River floodplain contains four broad vegetation units (pers obs):

1. Adjacent to the Luvuvhu there is no levee and mixed riverine woodland exists, with beautiful large trees such as *Diospyros mespiliformis, Faidherbia albida, Ficus sycomorus, Vachellia robusta, Vachellia xanthophloea, Trichilia emetica and Xanthocercus zambesiaca*.
2. In sections of the floodplain away from the river monospecific stands of *F. albida* occur as a component of the riparian woodlands, mainly in the Hutwini plains area between Mangala and the bridge (fig 3.1).

3. In the slightly lower and more frequently flooded area of the floodplain in the eastern section towards the Limpopo/Luvuvhu junction (Crooks Corner) monospecific stands of *V. xanthophloea* occur. The largest monospecific *V. xanthophloea* woodland in the MCP occurs in the Rietbokvlei/Nwambi pan area (fig 3.1).
4. The greatest area of the floodplain is occupied by open woodland of *Acacia tortilis* and *Urochloa mosambicensis* grasses with large patches of *Azima tetracantha* and *Anisotes formosissimus* shrubs. Unfortuneately, the floods, which are such a key component of the functioning of the wetlands, have also introduced invasive alien vegetation. Extensive areas of the floodplains have been invaded by *Xanthium strumarium* and *Datura* species.

Within the MCP, the floodplains, floodplain study area, and individual study sites form a hierarchy as shown in table 3.1 with spatial distribution in figures 3.3 and 3.4. The nomenclature used to identify study sites is shown in table 3.2 using the following convention:

VW refers to *V. xanthophloea* woodlands

VR refers to *V. xanthophloea* regeneration patches

FW refers to *F. albida* woodlands

FR refers to *F. albida* regeneration patches

with the number of the woodland or regeneration patch identified by an attached numeral (the ID; for example, FW1 refers to *F. albida* woodland number 1). Woodland names are based on local names used by the commercial operators in the MCP. Detail on the rationale of site and patch selections is given in Chapters 4 and 5.

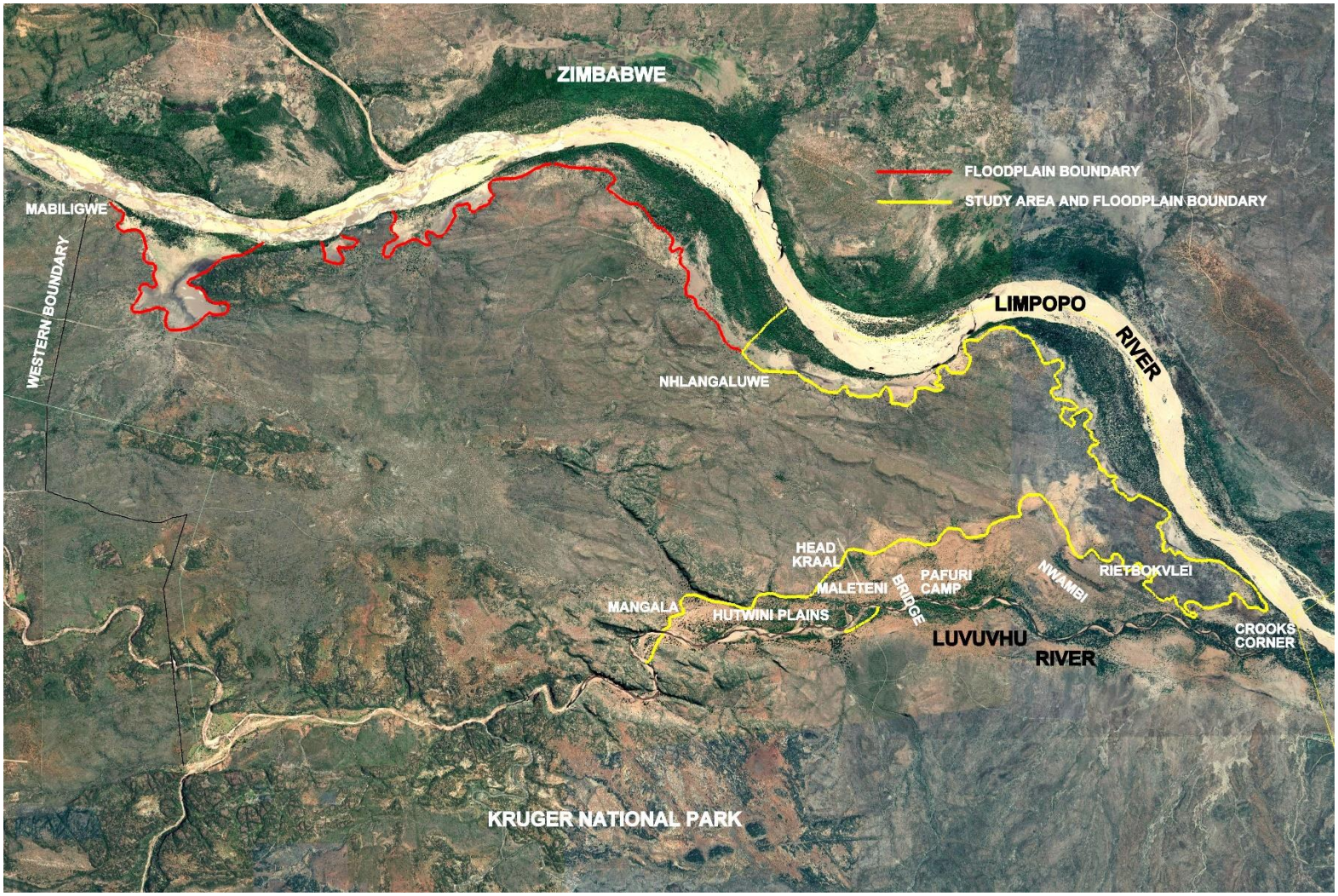


Figure 3.1: MCP floodplain and study area. The floodplain boundary is delineated by the red and yellow lines and the Limpopo and Luvuvhu Rivers. The study area in the floodplains is delineated by the yellow lines and the Limpopo and Luvuvhu Rivers. Place names are marked on the map.

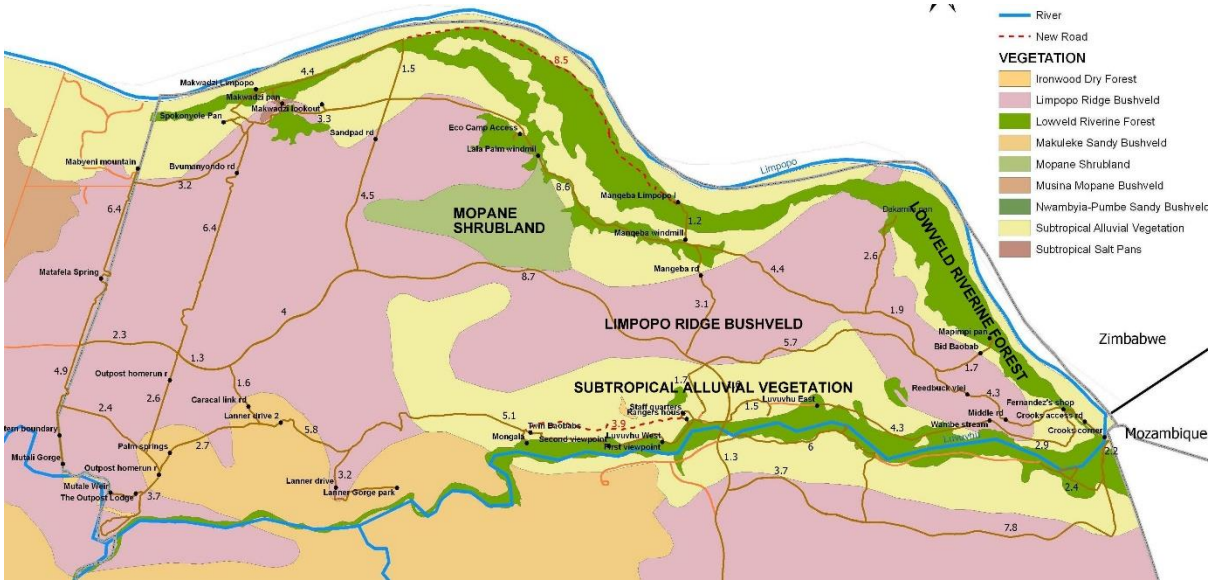


Figure 3.2: The broadscale vegetation of the MCP (Kai Collins, CDF 2012). The floodplains are within the areas shown as Lowveld riverine forest and subtropical alluvial vegetation.

Table 3.1: Hierarchy of the MCP and study site area

LEVEL	STUDY AREA OR SITE	AREA HA	COMMENT
1	Makuleke Contractual Park	23700	
2	Floodplains	7000	Within the MCP
3	Floodplain study area	4000	Limpopo floodplain Nhlangaluwe to Crooks Corner Luvuvhu floodplain Mangala to Crooks Corner
4	*V. xanthophloea* woodlands		
4.1	Sites of establishment of mature *V. xanthophloea* woodlands		Ten sites within floodplain study area
4.2	Sites of decline of mature *V. xanthophloea* woodlands		Ten sites within floodplain study area
4.3	Sites of regeneration of *V. xanthophloea* woodlands		Twenty sites within floodplain study area
5	*F. albida* woodlands		
5.1	Sites of establishment of mature *F. albida* woodlands		Ten sites within floodplain study area
5.2	Sites of decline of mature *F. albida* woodlands		Ten sites within floodplain study area
5.3	Sites of regeneration of *F. albida* woodlands		Eight sites within floodplain study area

Table 3.2: Name and identification (ID) of individual woodlands and regeneration patches

NAME	*VACHELLIA XANTHOPHLOEA* *V. xanthophloea* woodlands	*V. xanthophloea* regeneration patches
Nhlangaluwe 1	VW1	VR1
Nhlangaluwe 2		VR2
Ukangwa 1	VW2	VR3
Ukangwa 2	VW3	VR4
Ukangwa 3	VW4	VR5
Limpop east	VW5	VR6
Limpopo west	VW6	VR7
Limpopo central		VR8
Bvekenya		VR9
Mapimbi west	VW7	VR10
Graveyard	VW8	VR11
Rietbokvlei-Nwambi	VW9	
Rietbokvlei HG 1		VR12
Rietbokvlei HG 2		VR13
Rietbokvlei HG 3		VR14
Rietbokvlei central		VR15
Rietbokvlei west		VR16
Rietbokvlei-Nwambi		VR17
Nwambi central		VR18
Nwambi north		VR19
Nwambi north west	VW10	VR20
Number of sites	10	20
	Fig 3.3	Fig 3.3

NAME	*FAIDHERBIA ALBIDA* *F. albida* woodlands	*F. albida* regeneration patches
Mangala south	FW1	in KNP, not studied
Mangala	FW2	FR2
Oxbow		FR3.1
		FR3.2
Island	FW4	
		FR4.1
		FR4.2
		FR4.3
Main	FW5	FR5
Maleteni	FW6	no regen
Airstrip	FW7	no regen
Trails Camp south	FW8	in KNP, not studied
Trails Camp		FR8
Gwalala	FW9	no regen
Luvuvhu Camp	FW10	no regen
Mixed riverine	MRW	no regen
Number of sites	10	8
	Fig 3.4	Fig 3.4

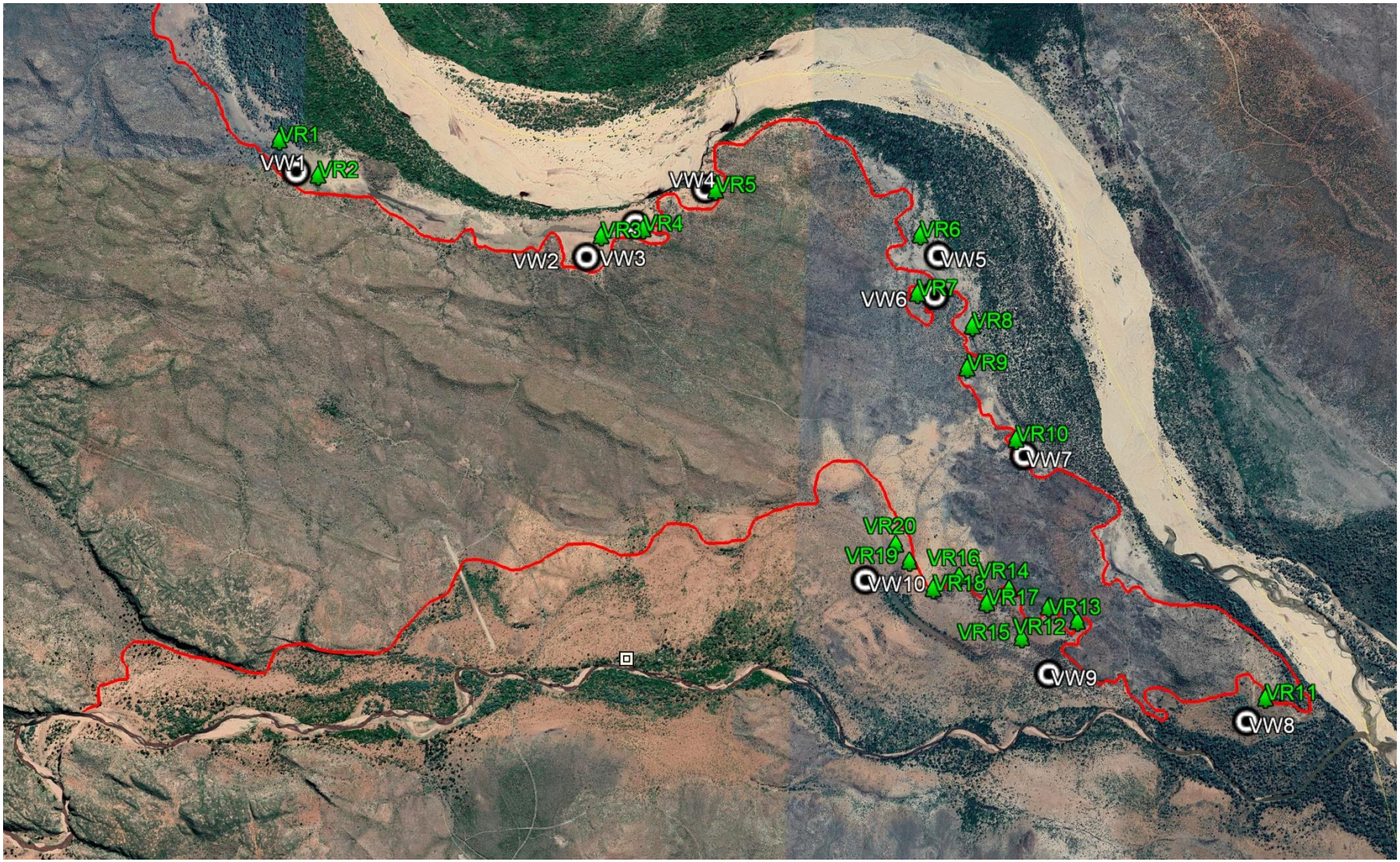


Figure 3.3: ***Vachellia xanthophloea*** **woodlands (VW, black circles) and regeneration patches (VR, green icons) study sites in the floodplains of the Limpopo and Luvuvhu Rivers. Note the different spatial distribution compared to the** ***F. albida*** **woodlands (fig 3.4).**

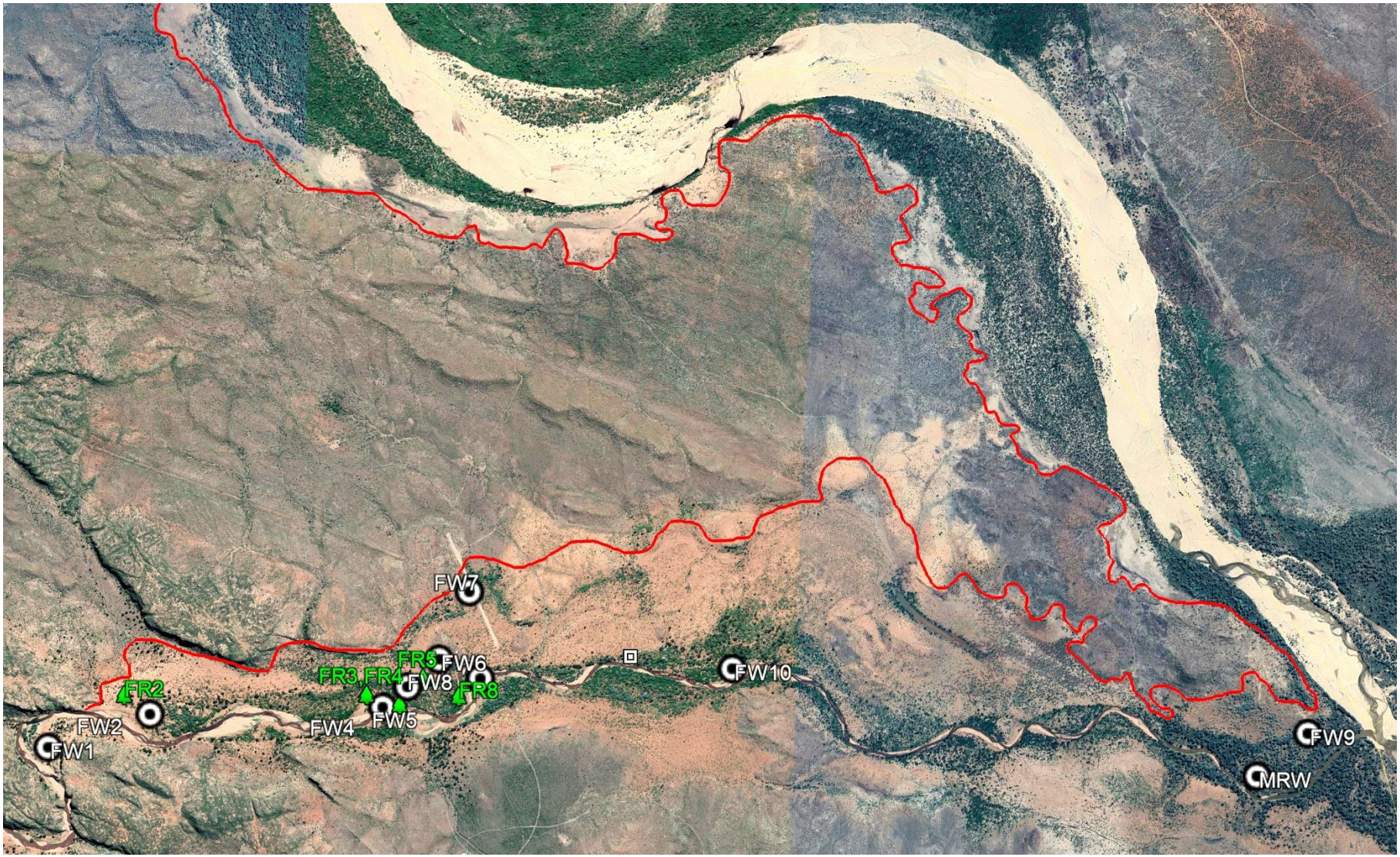


Figure 3.4: ***Faidherbia albida*** **woodlands (FW, black circles) and regeneration patches (FR, green icons) study sites in the floodplain of the Luvuvhu River. Note the different spatial distribution compared to the V.** ***xanthophloea*** **woodlands (fig 3.3).**

3.2. GEOLOGY AND SOILS

The two main abiotic vegetation drivers are geology (through the soils) and climate. Soils control the type and spatial distribution of vegetation (Cole, 1982; Gertenbach, 1983). The relationship between geology (as reflected by soils) and vegetation has been well studied in the KNP (Venter *et al*., 2003). Soils exert an influence on terrestrial plants in three ways through their ability to provide plants with water, nutrients, and their physical and/or chemical condition which controls access by plant roots to water and nutrients. The Venter land classification system for the KNP (Venter, 1990) is based on the relationship between geology, terrain, soils, and woody vegetation. The same general relationship is expected to exist in the MCP and the floodplain woodlands, although the Venter classification is too broad scale to adequately address the floodplain woodland dynamics.

The geology of the study site (Geological Survey, 1981) is presented in figure 3.5. The extensive floodplain alluvium is a key feature of the geology. The backbone of the MCP geology is the basalt ridge which runs down the centre and is the dominant geological feature and is adjacent to the floodplains. Ridges of Clarens Sandstone abut the western end of the Luvuvhu floodplain.

A soil map of the study site (CDF, 2013) is shown in figure 3.6. The Limpopo floodplain soils are classified as Dundee, Arcadia, Inhoek and Bonheim forms, and the Luvuvhu floodplain soils are Oakleaf and Arcadia forms.

The floodplains of the MCP are very flat. The floodplain altitude varies between 239 metres above sea level (m asl) (at Mabiligwe) and 210 masl (at Crooks Corner), a drop of 29 m over a linear distance of 43 kms.

The soils of the floodplains are derived from two major influences. Firstly, the alluvial soils originate upstream, with the Limpopo catchment being more granitic and the Luvuvhu catchment more basaltic (Nortje, 2013; RSIS, 2016; Tinley, 1978). Secondly the catena effect from the adjacent basalt ridges has a much greater influence on the Limpopo floodplain than the Luvuvhu floodplain (which is also influenced by sandstone geology).

The soils in numerous study sites in the study area were examined through site inspections with the assistance of Dr Gerhardt Nortje. The topography of the floodplain influenced the soils. Both floodplains contained shallow depressions in the floodplains, possibly paleo-channels which generally run parallel to the rivers. On the Limpopo side a levee has built up and the depressions are mainly on the distal side of the levee separated from the river. On the Luvuvhu side there is no levee, but depressions still occur. The wetland pans are scattered mainly in shallow depressions in the floodplains.

The study site soils can be broadly classified as follows:

1. The Limpopo levee has a neutral, deep, fine sand or loam soil, free draining and supporting mixed riverine woodlands. Soils are Dundee (Orthic) soil form (stratified alluvium). Paleo-channels are Arcadia soil form.
2. The Limpopo floodplain distal to the levee and adjacent to the basalt ridge has alkaline, high clay soils generated by alluvium from the Limpopo River and the catena effect from the basalt ridge. Soils are Arcadia (Vertic) and Inhoek (Melanic) soil form in the core of the plains, flanked by Dundee soil form on the levee and Willowbrook and Mayo (Melanic) soil forms at the base of the basalt ridge. The alkalinity is due to the influence of the basalt ridge which is composed of Olivine rich Letaba Basalts (Venter, 1986), containing embedded lime concretions (Nortje, 2018). No information on soil depths was available.

Figure 3.5: The geology of the MCP is dominated by floodplain alluvium, Letaba basalt and Clarens sandstones (Geological Survey, 1981). The study site roughly coincides with the floodplain alluvium.

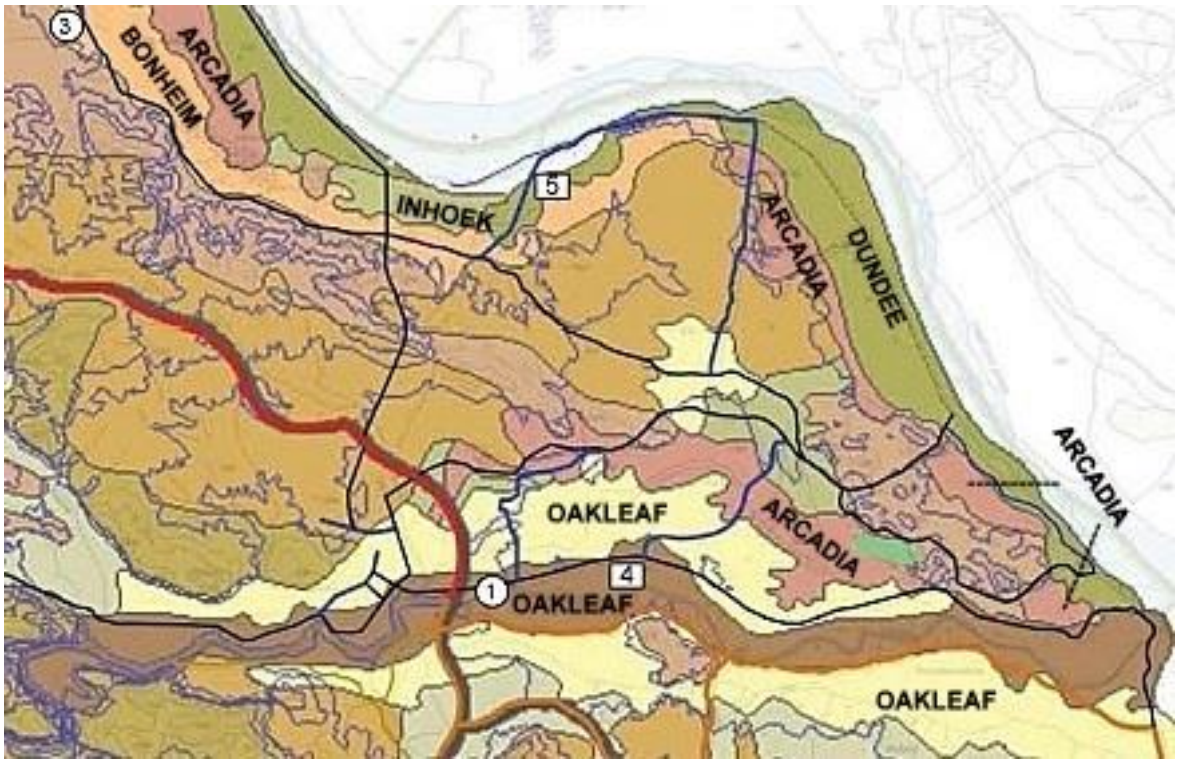


Figure 3.6: The soil forms of the floodplains which cover the study site (CDF, 2012). Two series of Oakleaf soils exist; Limpopo series (yellow) and Makuleke series (brown).

3. The Luvuvhu floodplain has red neutral loam soils which originated from alluvium from the Luvuvhu River, and which trend towards higher clay and higher alkalinity moving downstream and transecting away from the river due to the influence of the basalt ridge. Towards the western end of the floodplain the flanking ridges are Clarens sandstones. The soils are mainly Oakleaf soil form with recent alluvial deposition along the first terrace of the river being Dundee soil form (Nortje, 2018). Towards the eastern end of the floodplain (Nwambi, Rietbokvlei towards Crooks Corner) Arcadia soils occur. In some areas recent floods have deposited silt to form a Duplex soil – silt over an Arcadia horizon. The alluvium is more than 30 m deep over much of the floodplain and consists of a highly complex layering of coarse and fine sediments (Department of Water Affairs (DWA) boreholes, reported in Botha, 2001). The pans and paleo-channels are Arcadia soil form.

The water table in the Limpopo floodplain ranged from 2,4 to 6,9 m below surface depending on the history of flooding and rainfall (from boreholes, reported in KNP Game Ranger diaries (RSIS, 2016)).

The deep soils of the Luvuvhu floodplain are accompanied by a depth to the water table which varied between 11,6 m (in the 1992 drought) and 6,8 m (in the dry 1988/99 season) for four boreholes on the southern bank of the Luvuvhu River and ranging from 120 to 1400 m from the river (reported in Botha, 2001). Similar soil and water table depths would be expected on the Luvuvhu floodplain on the northern bank in the MCP.

3.3. CLIMATE AND FLOODPLAIN HYDROLOGY

Climate mainly controls the temporal dynamics of establishing or established vegetation. Seasonal variation controls vegetation and structure (Venter et al., 2003). Daily weather variation imposes pulses on the vegetation especially in regions of high evaporation, through the effect on the soil moisture. Arid areas have a higher coefficient of variation of rainfall (Mucina and Rutherford, 2006). In semi-arid systems floodplains are more dependent on the river influence than in mesic systems and flooding variability has a greater influence on vegetation communities (Hughes, 1988).

Long term cycles of dry and wet periods have been linked to the Oceanic Nino Index (ENSO, or El Nino and La Nina phenomena) (Gertenbach, 1980) but also reported to have an inconsistent effect (Howison *et al*., 2017). Measured as sea surface temperature oscillations in the eastern Pacific Ocean, these bring a dynamic of wetter and dryer summer rainfall conditions to the whole of southern and eastern Africa.

The hydrological regime of the MCP floodplains is controlled by the local climate in periods when flooding does not occur, and the regional climate which is responsible for the rivers flooding. Flooding is due to rainfall in the catchment of the Limpopo and Luvuvhu Rivers. The Limpopo catchment (about 110000 km^2) includes large areas of Zimbabwe, Botswana and South Africa as far inland as the Witwatersrand much of which is semi-arid. The Luvuvhu River, and its tributary the Mutale River, have a significantly smaller catchment (about 6000 km^2) in the Soutpansberg Mountains which is one of the higher rainfall areas of South Africa.

MCP local climate. The MCP is situated marginally within the Tropic of Capricorn and at an altitude ranging from 200 to 400 m asl. To the east are the lowlands of Mozambique and the nearest point of the Indian Ocean and warm Mozambique ocean current is 450 km away. These conditions create a

climate characterised by high temperatures in summer, moderately warm frost-free winters, summer rainfall and high levels of evaporation.

Rainfall in the MCP is extremely variable. The (75 year) long term annual average is 437 mm (SAWB and Pafuri Camp records) (fig 3.7) with a coefficient of variation of 40%. Extended periods of above and below average rainfall have occurred. The monthly rainfall distribution is shown in figure 3.8. Eighty five percent of the rain falls in the five months of November to March with monthly averages above

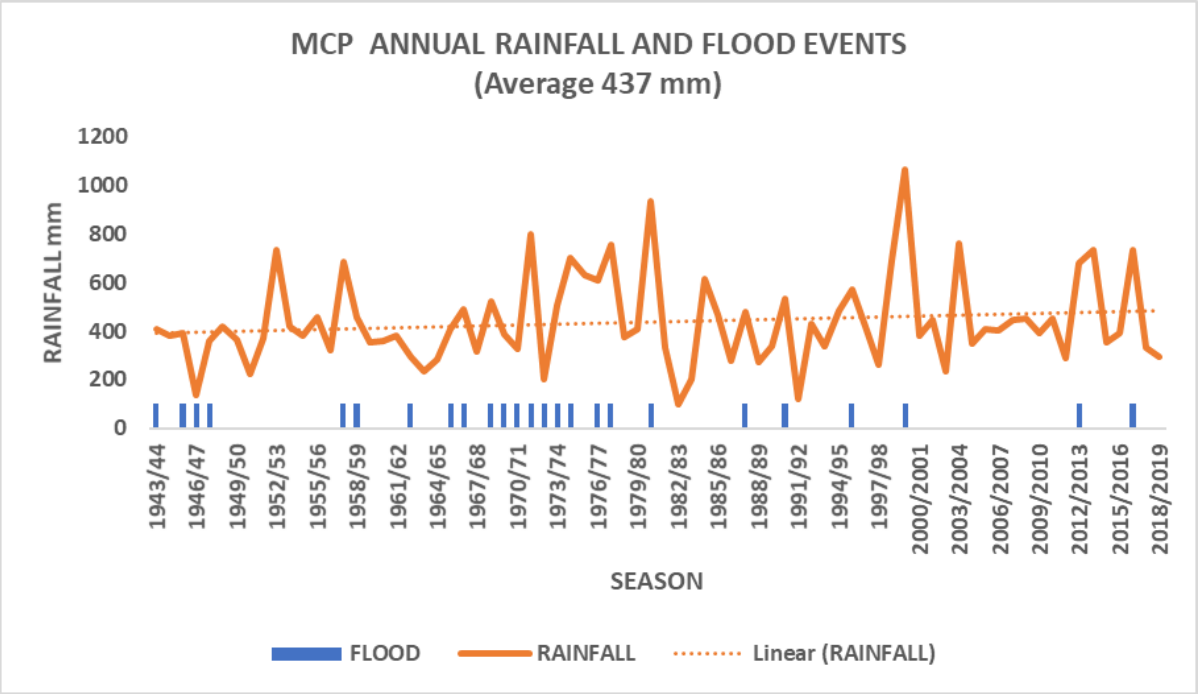


Figure 3.7: Seventy five year rainfall (SAWB (Pafuri) and Pafuri Camp) together with seasons with flood events (Harries, 1999; Joubert, 2007; other miscellaneous sources). Flood events were when the Limpopo and/or Luvuvhu Rivers broke their banks. Some flood data between the 1948/49 and 1964/65 seasons was missing. The average rainfall over the period was 437 mm. Periods of several years of above and below average rainfall have occurred.

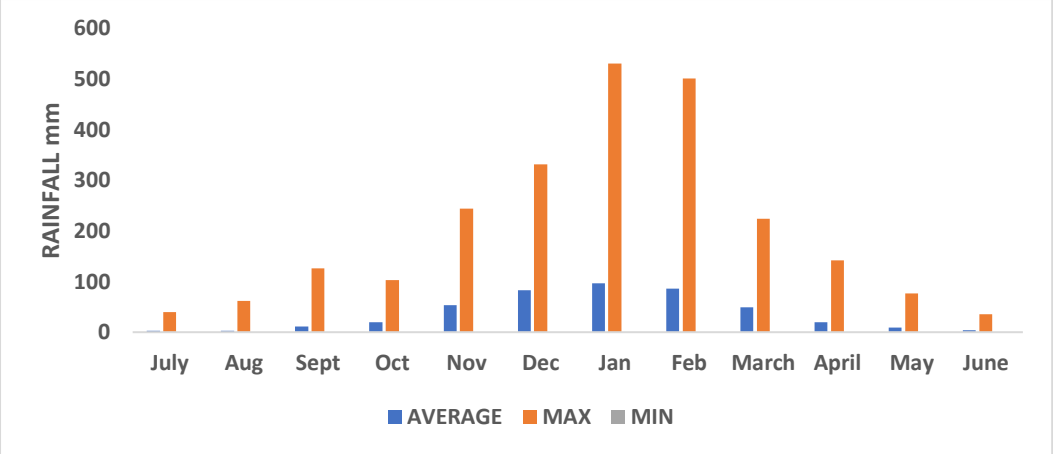


Figure 3.8: Monthly rainfall distribution over the 75 year period from 1943/44 to 2018/19 showing average, maximum and minimum rainfall. During this period, a minimum of zero rainfall was recorded in every month of the year. The average rainfall was 437 mm.

50 mm. Individual maximum monthly rainfall is significantly higher than the monthly average. Minimums of zero rainfall have occurred in every month.

Typical temperatures are shown in figure 3.9, which records the average maximum and minimum monthly temperatures (ranging from 39°C to 7°C respectively) at Pafuri Camp over a four year period (2008 to 2011). Daily temperatures as high as 45° C have been recorded. The mean annual potential evaporation measured at Musina (140 kms west of the MCP) is 2268 mm (Mucina and Rutherford, 2006). It is expected that a similar rate would apply to the MCP, which indicates evaporation potential of about five times the MCP average annual rainfall.

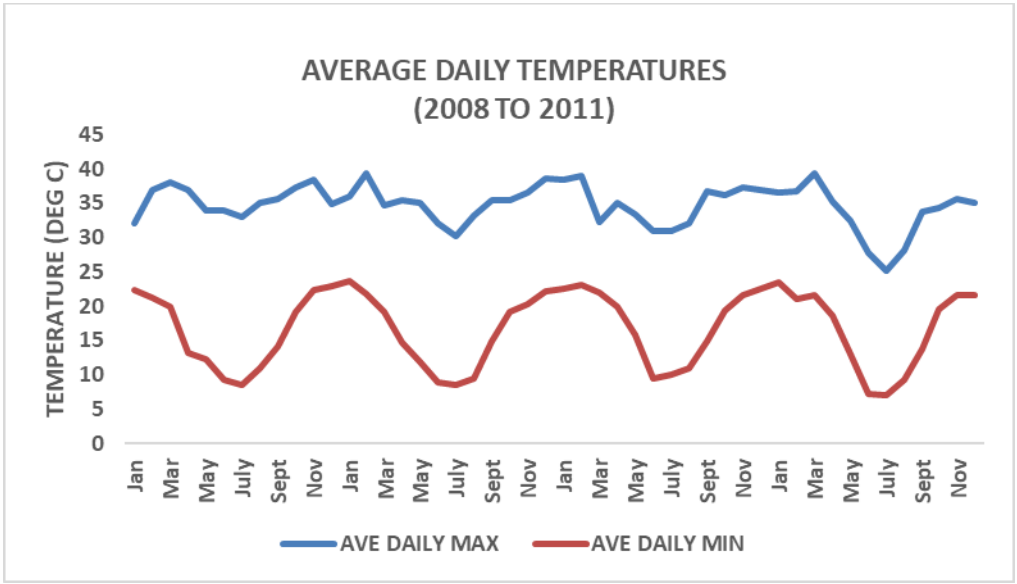


Figure 3.9: Average monthly maximum and minimum temperatures (Pafuri Camp) over a four year period 2008 to 2011. The absolute maximum and minimum temperatures over the same period were 45°C and 5°C.

Regional climate. Although the regional climate affects the local climate, its greatest effect on the hydrological regime of the floodplains is through flooding. This needs to be appreciated in the context of semi-global weather systems affecting the regional climate in the river catchments:

1. The Oceanic Nino Index (ENSO) affects regional weather. The effect of the Oceanic Nino Index on rainfall in the MCP can be seen in figure 3.10. Using a linear least-squares regression, the extreme El Nino and La Nina events cause on average a 28% decline and 26% increase in annual rainfall respectively, which is considerably less than the actual annual rainfall variability. Only about 10% of annual variability can be explained by ENSO (R^2=0,09 fig 3.10). The ENSO effect on rainfall is not consistent, a phenomenon reported in the Hluhluwe-iMfolosi Park, KwaZulu-Natal (Howison *et al.,* 2013) and cyclonic events affecting the MCP appear to be independent of the Oceanic Nino Index.
2. The Intertropical Convergence Zone (ITCZ) has a strong influence on the rainfall in the MCP and much of the rainfall in the catchments of the two rivers. The ITCZ is the ascending arm of the Hadley Cell of global atmospheric circulation within the tropics which moves north and south of the equator in an annual oscillation causing convection in a low-pressure zone and tropical rainfall. In South Africa, the warm Mozambican current and summer low

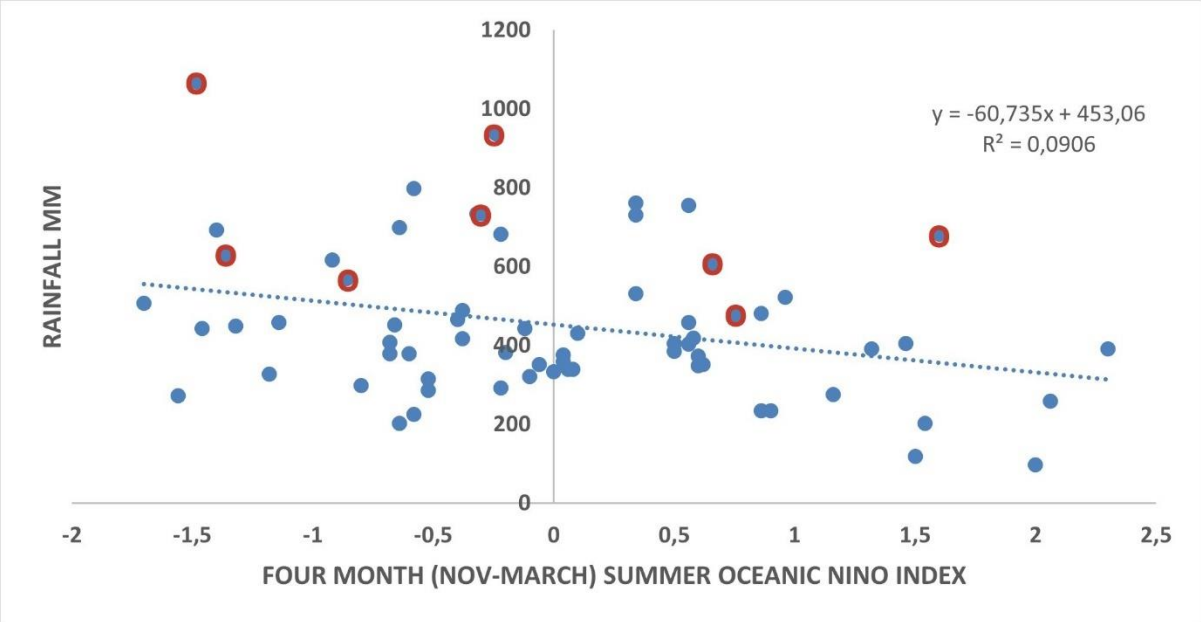


Figure 3.10: Annual rainfall and the Oceanic Nino Index (ONI) for the period 1943/44 to 2017/18 (Null, 2017). The ONI for the months November to March have been used to coincide with the months when most of the MCP rainfall occurs. Years when cyclones caused floods are marked with red circles. The linear least-squares regression is shown.

pressure zone in the central interior draw the ITCZ south. The MCP is marginally within the tropics and on the southern edge of the ITCZ in mid-summer. The ITCZ is the main cause of rainfall in December, January and February, bringing moist tropical air from the north and northeast. This coincides with the summer solstice with a climatic inertial lag. The MCP and broader region receive more rainfall when the ITCZ moves farther south than normal. Often a westerly weather wave across southern Africa combines with the ITCZ to form a tropical-temperate trough.

Five of the nine major floods in the last 60 years were associated with the ITCZ (table 3.3).

3. The Southwest Indian Ocean (SWIO) tropical cyclones that make landfall east of the MCP influence regional rainfall in the catchment of the Limpopo and Luvuvhu Rivers. The Indian

Ocean produces about 11 tropical systems a year in the December to March season (Malherbe *et al*., 2012). Only about 40% of these tropical systems develop into tropical cyclones or intense tropical cyclones. Only a few of these tropical cyclones make landfall, but then start to lose energy and downgrade as they move inland. They, however, can drop significant amounts of rainfall in the areas where they penetrate the continent. The continental area vulnerable to cyclones stretches about 1600 kms from 13.50° S (cyclone Kenneth 2019) to 28.60° S (cyclone Domoina 1984) and the MCP (21.38° S) is in these latitudes but 450 kms inland. Four of the nine major floods in the last 60 years were caused by five tropical cyclones (table 3.3). From 1948 to 1999 there were 37 tropical cyclone systems that made landfall over the Limpopo basin that potentially could have caused flooding of the Limpopo and Luvuvhu Rivers (Malherbe *et al*., 2012). However, most tropical systems that reach the Limpopo basin bring rainfall that does not cause flooding. The contribution of MCP rainfall from SWIO tropical systems is episodic but less than 10% and their greatest impact is the large infrequent floods (Malherbe *et al*., 2012).

Table 3.3: The eight floods recorded at the Wenela pump house (Crooks Corner) and Baobab Hill House (Maleteni) and the cause of the floods. Cyclones are highlighted in red. The height of cyclone Claude was not recorded at Crooks Corner, but the Makuleke people recall it as a large flood (Tivani, E.V., member of Makuleke Royal Family, pers comm)

FLOOD RANKING	DATE	CAUSE	MCP RAINFALL FOR THE SEASON JULY-JUNE mm
1	Jan 2000	Tropical depression followed by Cyclone Eline.	1068
2	Jan 1958	Cyclone Astrid.	683
3	Feb 1981	No cyclone. Probably the ITCZ.	937
4	Jan 1977	Cyclone Emilie.	607
5	Feb 1975	No cyclone. Probably the ITCZ.	700
6	Feb 1996	No cyclone. Probably the ITCZ.	570
7	Feb 1988	No cyclone. Probably the ITCZ.	479
8	Jan 2013	Deep tropical low. Part of the ITCZ.	682
?	Feb 1966	Cyclone Claude.	406

Seasons with flood events are shown in figure 3.7. The height of nine major floods recorded at Crooks Corner and Baobab Hill House (table 3.3) suggest that cyclones and the ITCZ have approximately equal roles in causing floods in the MCP. Unfortunately, the heights of the other floods were not recorded or did not reach the Wenela pump house to be recorded.

The Limpopo and Luvuvhu Rivers can flood independently, or they can flood simultaneously (RSIS,2016). There are three scenarios of flooding of the floodplains by the rivers, with the approximate relative historical frequencies given in parenthesis (extracted from Harries, 1999; Joubert, 2007; and other miscellaneous sources). A total of 35 recorded floods during the period 1943 to 2018 were analysed:

1. (55%) The Limpopo floods but the Luvuvhu does not flood. In this scenario the Limpopo floodplain is flooded, and the Limpopo is high enough to push back up the Luvuvhu and flood the lower reaches of the Luvuvhu floodplain (back flooding), flooding the areas around

Crooks Corner, Rietbokvlei and Nwambi pans. This scenario recently occurred in 2009 and 2017 when both floods reached Nwambi pan but did not flood the floodplain.

2. (42%) Both the Limpopo and Luvuvhu flood simultaneously. In this scenario both the Limpopo and Luvuvhu floodplains are flooded. The Luvuvhu floods the upper reaches of the Luvuvhu floodplain, and the Limpopo flood pushes back up the Luvuvhu and both rivers flood the lower reaches of the Luvuvhu floodplain (back flooding). This scenario recently occurred in 2000 and 2013 when Baobab Hill House (Maleteni) was surrounded by water and the Hutwini plains were flooded.
3. (3%) The Luvuvhu floods but the Limpopo does not flood. In this scenario only the Luvuvhu floodplain is flooded, the extent of flooding depending on the height of the flood. There is little back flooding by the Limpopo. This scenario has only occurred before 2000 when the river channel was narrow. The floods of 2000 and 2013 have widened and straightened the channel make this type of flooding in the upper reaches of the Luvuvhu floodplain less likely in the future.

Because of its small catchment, floods in the Luvuvhu have a short duration of a couple of days. A return to base flow conditions occurs within 3 weeks of flood peak (Botha, 2001, quoting KNP Pafuri Section Rangers) and occurred after the 2013 flood (pers obs).

In all cases flooding can occur due to rainfall in the catchment of the rivers while the MCP receives average rainfall. However, the regional weather systems that cause of floods usual result in above average rainfall in the MCP (table 3.3).

The frequency of flooding is very variable. Notwithstanding that flood data is incomplete between 1949/50 and 1963/64, the flood frequency between 1943/44 and 1979/80 is much greater than between 1979/80 and 2017/18 (fig 3.7) (averaging about 0,8 compared with 0,2 floods per annum). In the period 1943/44 to 1979/80 there was occasionally more than one flood per season (Harries, 1999). The floods recharge the ground water and fill the pans. Without flooding the floodplain pans can be dry for several months and some even for years (Turner and Riddell, 2020) indicating extremely dry floodplain conditions.

The high coefficient of variation of MCP annual rainfall would suggest frequent droughts. The first recorded year the Luvuvhu River stopped flowing was in 1963/64 (Louw,1994), and until 1970/71 the river ceased to flow occasionally (Joubert, 2007). There were 3 farther periods of drought; 1981/82 to 1983/84, 1991/92 (when the river stopped flowing for 14 months) (Joubert, 2007) and the current period 2017/18 to 2019/20. Figure 3.7 shows periods of several years of below average rainfall.

An additional factor affecting the floodplain hydrology was the damming and extraction of water for agriculture, human consumption, and industrial use. Prior to 1950 both the Limpopo and Luvuvhu Rivers were perennial. In the winter, the Limpopo is now dry on the surface with subterranean flow in an alluvial aquifer. The Albasini Dam (built in 1952) and Nandoni Dam (built in 2005) both on the Luvuvhu River affect flow in the MCP. A study by the DWA predicted the Nandoni Dam would decrease the base flow of the river by 40% (Louw, 1994). In recent years, an ecological reserve of water has been released from the Nandoni Dam to keep the Luvuvhu River flowing in the MCP (Riddell, E., Manager: Aquatic Biodiversity Management, KNP Conservation Services, pers comm).

The important climate period for the study was 1965/66 to 2019/20, which can be divided into three separate periods:

1. The first period was between 1965/66 and 1980/81 with above average rainfall and very frequent (almost annual) floods.
2. The second period was between 1981/82 and 1998/99 with below average rainfall and few floods.
3. The third period was between 1999/2000 and 2019/20 with average but variable rainfall and few floods (2 large and 1 minor floods), but within which the three most recent seasons 2017/18 to 2019/20 was a dry period of 72% of average rainfall and no floods (fig 3.7).

3.4. ELEPHANTS

Elephants are ecosystem engineers and play a major role in modifying the landscapes in which they exist. There has been an immense amount of research on elephants and their impact on woodlands and is well documented (O'Connor *et al*., 2007). They are probably the most researched animal in the KNP (Whyte et al., 2003).

There is little information about elephants in the area of the MCP prior to 1965 when the annual KNP census commenced. Anecdotal evidence suggests a very low elephant population.

"Based on the scarce occurrence of elephant in KNP San rock art sites it is postulated that in the San era there were very few elephants in what is now KNP. During the colonisation period the stories from the earliest explorers, hunters and settlers continue to paint a picture of low elephant numbers in the KNP" (quote in Whyte *et al*., 2003). "It seems likely that the few elephants that inhabited what is now Kruger were shot to extinction between 1880 and 1896" (quote in Whyte *et al*., 2003).

The Makuleke people arrived in about 1820 and there is no oral tradition of many elephants after that time. During the time when Cecil Barnard was based at Crooks Corner (1910 to 1929) and hunted in Zimbabwe and Mozambique there is no mention of elephants in the MCP (Bulpin, 1954). Elephants re-colonised the KNP in about 1905, entering the Letaba/Olifants junction area from Mozambique. They slowly dispersed and reached the north of Punda Maria in about 1945 (Whyte *et al.,* 2003). It is postulated that elephants only arrived in the MCP area after this date.

Recent data has been from two research programs.

Annual KNP elephant census (Conservation Services, Skukuza, KNP). Data was extracted from the KNP elephant census to determine the elephant population size and growth for the whole of KNP, the area north of 22. 45° S and the area north of 22.60° S for the period 1985 to 2017. No census was done in 2013, 2014, 2016, 2018, 2019 and 2020. The area north of 22. 45° S consists of the MCP (90%) and the floodplains on the southern bank of the Luvuvhu River (10%). Elephants in this area are called the "Makuleke population" for convenience. Due to possible elephant movements in and out of this area, the Makuleke population determined on a single day by the census can only be considered a best August (dry season) estimate and useful to show population trends. The elephant population north of 22.60° S was also determined and called the "Pafuri population" (which includes the Makuleke population north of 22.45° S).

Culling commenced in the KNP in 1967 and ceased in 1994. After 1994 the KNP elephant population increased and reached about 20000 in 2017, a growth rate of about 4,2% per annum (fig 3.11). The Pafuri and Makuleke populations from 1985 are shown in figure 3.12. Both these populations show growth from 1994 when the culling ceased with growth of about 5,2% per annum (linear) but with significant annual variability. Personal observations suggest a significant increase in the Makuleke

population in 2018, 2019 and 2020 when no censuses were conducted. It is postulated that the fluctuations in the Makuleke population was a consequence of elephant movements southwards (across 22. 45° S) out of the MCP following landscape scale spatio-temporal changes in resource distribution since there were no constraints to elephant movements within KNP. This is supported by research which showed significant north-south elephant movements across 22.45° S but minimal elephant movements into neighbouring Zimbabwe or Mozambique (Henley and Henley, 2012).

Until 1969 the Makuleke people lived in the MCP area and farmed sections of the floodplains. To protect the crops from animals they mounted a permanent guard during growing and harvesting season and any elephants were chased away (E V Tivani, pers comm). This would have created a landscape of fear which elephants would have avoided. The average Makuleke population recorded by the KNP census from 1985 to 1994 was 75 elephants at a density of 0,3 per km^2. The Makuleke population prior to 1985 is postulated to have increased from none in 1945 to about 75 elephants by 1985. The average Makuleke population for the period 2010 to 2017 was 410 elephants (range 225 to 536) at an overall density of 1,6 per km^2. The census spatial data showed a gradual temporal shift of the Makuleke population into the floodplain, presumably as the fear landscape abated. By 2010 to 2017 the density in the floodplains would have been significantly higher than 1,6 per km^2 due to the concentration of elephants in the floodplains (fig 3.13). As a comparison the KNP overall density in 2017 was about 1,0 per km^2.

Research by Henley and Henley, 2012. Twelve elephants in the MCP were fitted with GPS collars (six cows representing herds, and six bulls) to determine elephant movements and range use patterns over an approximate 3-year period 2009 to 2012. Spatio-temporal distributions of the Makuleke population within the MCP were extracted from this data (Henley, pers comm, 2016). In comparison to the KNP census conducted on a single day, the data from this research covered 24 hrs per day, 365 days per year on an 8-hour download frequency. It is postulated that the distribution and movements of the 12 elephants fitted with GPS collars was representative of movements of the Makuleke populations of bulls and herds.

The elephants of the Makuleke population were not all residents. The increasing population trend with significant annual variability suggests this. The 12 elephants fitted with GPS collars in the MCP, and elephants fitted with GPS collars in the APNR (Henley, 2012) showed that bulls and breeding herds were generally spatially separate, and both travelled large distances linked to breeding, food, water, and seasonal drivers. The drop in the Makuleke and Pafuri populations in 2015 and 2017 was balanced by a greater increase in the population south of 22.60° S, indicating nomadic movement south into KNP. Elephants concentrated in MCP in the dry season (Henley and Henley, 2012).

Figure 3.13 shows the peak wet season (December to February, 2009 to 2012) and peak dry season (August to October, 2009 to 2012) distributions of the elephants fitted with GPS collars (data from Henley, pers comm 2016). Each dot represents the position downloaded every 8 hours of one of the elephants fitted with GPS collars. The difference in the observable density of dots between bulls and cows is due to a few lost collars on bulls and bulls using a larger home range than cows, portion of which is outside the map area. The density of dots also shows seasonal movements. The elephants concentrated in the MCP in the dry season and the floodplains experienced the highest utilisation. Elephants moved south in the wet season. Elephants that remained in the MCP in the wet season dispersed a little but still utilised the floodplains. The utilisation of the floodplains applied over 24 hours (data from Henley, pers comm 2016). Bulls and cows occupied slightly different but overlapping areas in both seasons. The spatial distribution extracted from the annual censuses from 1985 showed that the elephants only started concentrating in the floodplains after about 2000. It is interesting to note that the elephants showed minimal movement across the unfenced Limpopo

River into a rural area of Zimbabwe, indicating human presence causing a landscape of fear which the elephants avoided.

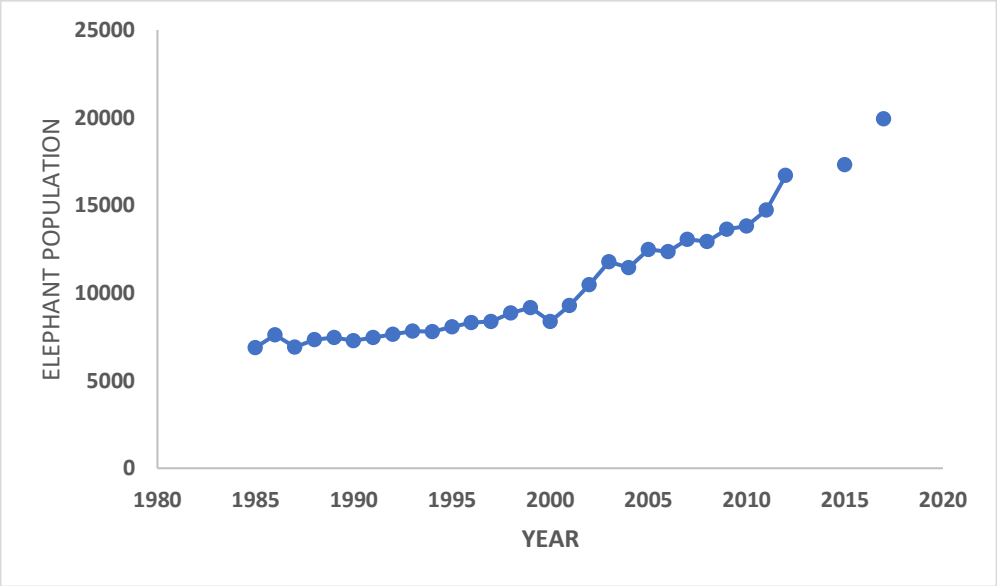


Figure 3.11: The KNP elephant population from 1985 to 2017 from KNP census data. Culling ceased in 1994 and the population shows a continuous increase since then.

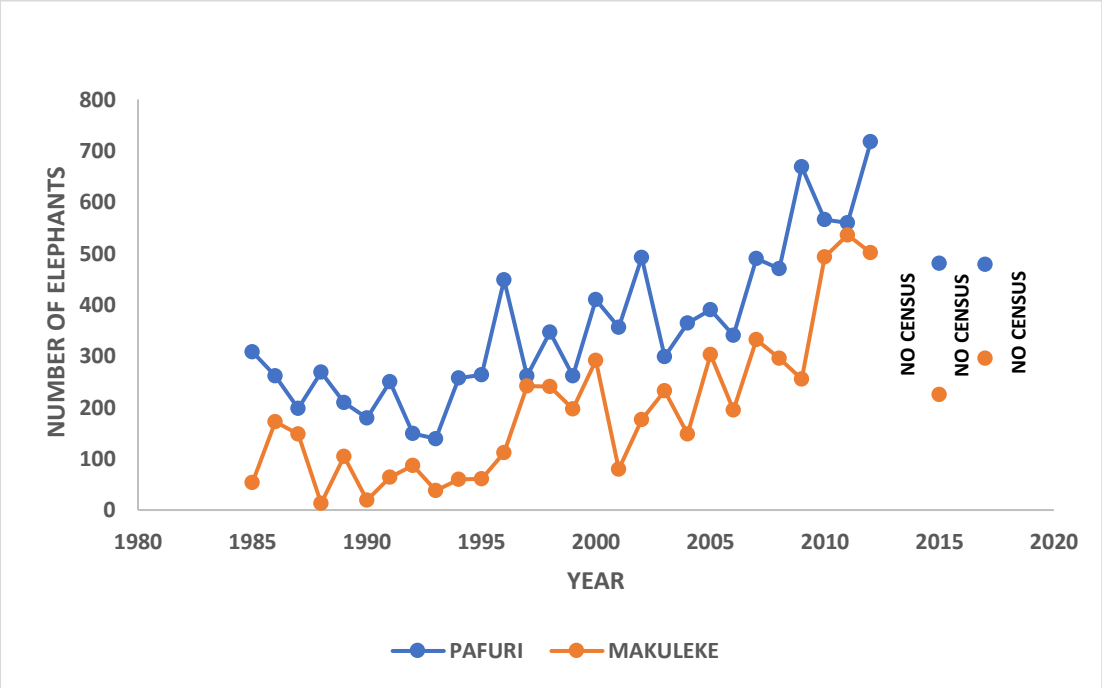


Figure 3.12: The Pafuri and Makuleke elephant populations from 1985 to 2017 from KNP census data. The Pafuri population is north of latitude 22.60° S and includes the Makuleke population north of 22.45°S. Culling ceased in 1994 and the Makuleke population shows growth with fluctuations due to movements south into the KNP. The decline in population in 2015 and 2017 was balanced by a greater increase in populations south of 22.60° S.

The Makuleke population showed five important dynamics:

1. The elephant density increased gradually from none in 1945 to about 0,3 per km^2 as a dry season best estimate in the period 1985-1994 (culling ceased in 1994).
2. From 1994 the elephant density continued to increase to about 1,6 per km^2 as a dry season best estimate in the period 2010 to 2017.
3. The dry season elephant density was much greater than in the wet season. In the wet season many of the elephants moved southwards across 22.45° S.
4. The floodplains were the preferred habitat in the MCP throughout the year which would have resulted in higher elephant floodplain densities than the average density over the whole MCP. The *V. xanthophloea* and *F. albida* woodlands were in the floodplain.
5. There is a degree of spatial separation of cows and bulls, although the floodplains were the preferred habitat of both.

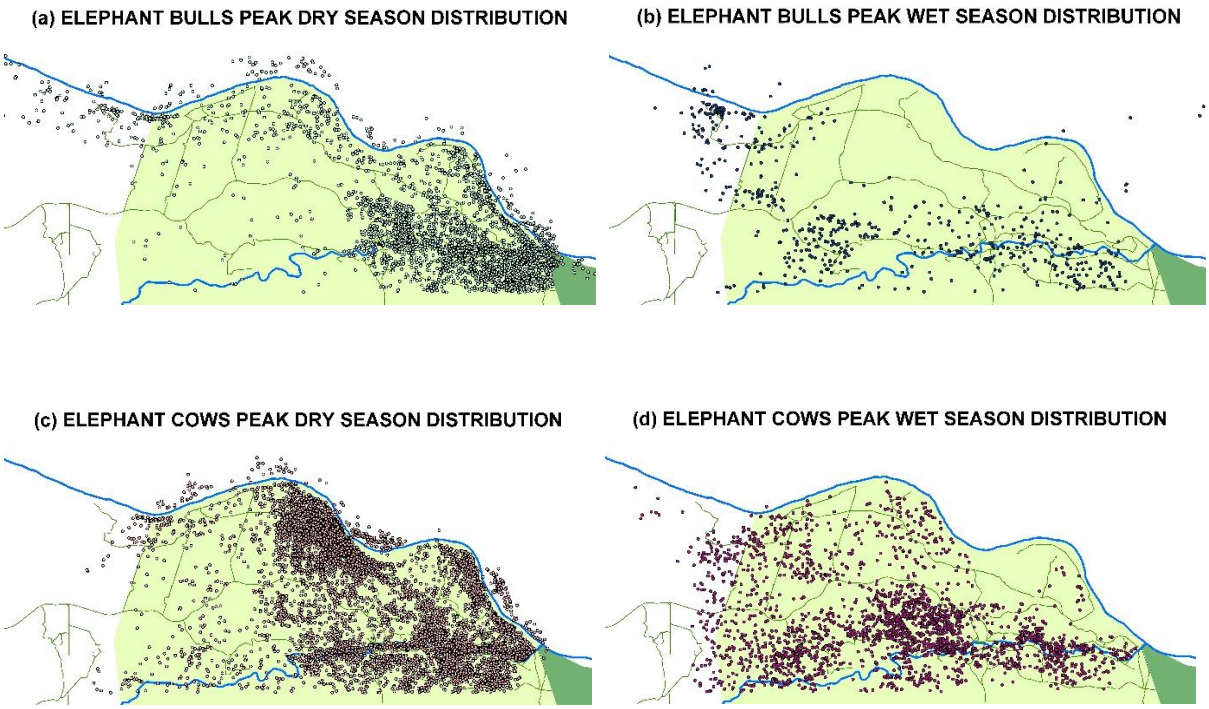


Figure 3.13: Distribution of elephant bulls in the MCP in the (a) peak dry season (August to October 2009-2012), (b) peak wet season (December to February 2009-2012) and elephant cows in the (c) peak dry season (August to October 2009-2012), (d) peak wet season (December to February 2009-2012). Each dot represents the position of one of six bull, or six cow elephants fitted with GPS collars downloading every eight hours. The difference in observable density of dots between bulls and cows was due to lost bull collars and bulls using a larger home range than cows, portion of which was outside the above map area. The difference in the density of dots between the dry and wet seasons for each sex indicates movement out of the MCP in the wet season. The floodplains have higher utilisation in the dry season, and elephants moved south in the wet season (unpublished data from Henley, M., 2016).

3.5. HUMAN HISTORY

Human influence on the African environment goes back about 2 million years to the evolution of early humans (*Homo* species.). A rock art site in the MCP attests to the historical presence of stone age San people. The first humans of the iron age arrived in Southern Africa about 2000 years ago. Evidence of these inhabitants in the Makuleke area is the Thulamela ruins just south of the Luvuvhu River and smaller ruins within the MCP, estimated to have been built about 700 years ago.

The Makuleke people arrived in the area in about 1820 and were forcibly removed in September 1969, and the Makuleke area was incorporated into the KNP.

It is postulated that any anthropogenic influence that is evident today originated in the last 100 years and can be divided into two periods of different human occupation.

1920 to 1969: This information is based on unpublished personal research and discussions with E V Tivani, a member of the Makuleke Royal Family who lived in the MCP area before the removal in 1969. The Makuleke people occupied the area. Based on the number of village sites at the time of removal in 1969 the estimated population was less than 2000 people in 240 family units. It is assumed that the population was not greater than this during the period 1920 to 1969.

The Makuleke lived adjacent to, but above the elevation of, the floodplains. Their lifestyle was based on hunting smaller animals, fishing in the pans and rivers, harvesting food from the naturally occurring plants and cultivating crops in the floodplains. Keeping cattle and goats was banned in 1939 by the authorities at the time to control the spread of foot-and-mouth disease from Zimbabwe. Donkeys continued to be used. Wild and domestic animal populations were low.

To cultivate the floodplains, trees in the farming areas were cut down and areas cleared by fire. The village sites and farming areas up to 1969 are shown on figure 3.14. Some farming areas close to Rietbokvlei were abandoned after the floods of cyclone Claude in 1966. Permanent guarding was undertaken to protect crops from animals during the growing season, 24 hour per day, 7days per week. This was to create a fear landscape for animals.

1970 to present: The area of the MCP was incorporated into the KNP in 1969, and KNP assumed responsibility for the conservation management. Until 2000 the only residents were a limited number of KNP employees and a military presence controlling the border with Zimbabwe (until 1994). The main KNP conservation activity was the culling of elephant and buffalo between 1970 and 1994. The military influence from 1970 to 1994 is unknown but gossip suggests some illegal hunting occurred. The land was returned to the Makuleke community in 2000 but they did not occupy it. Between 2000 and 2003 some commercial hunting occurred. From 2003 ecotourism operations started which followed policies of low and responsible environmental impact.

Up to 1969 the main anthropogenic influences were farming in the floodplains and small scale hunting which kept the wild animal population low. Since 1970 the area has been subject to the KNP management philosophy of minimal interference in nature and acceptance of the natural processes except where human induced pressures have led to deviations from natural processes (Joubert, 2007). Except for the temporary culling of elephant and buffalo, this was practiced. This allowed animals to gradually recover from low population levels. Any external anthropogenic influence has not been quantified but increased water extraction upstream on both the Limpopo and Luvuvhu Rivers would have affected the floodplain hydrology.

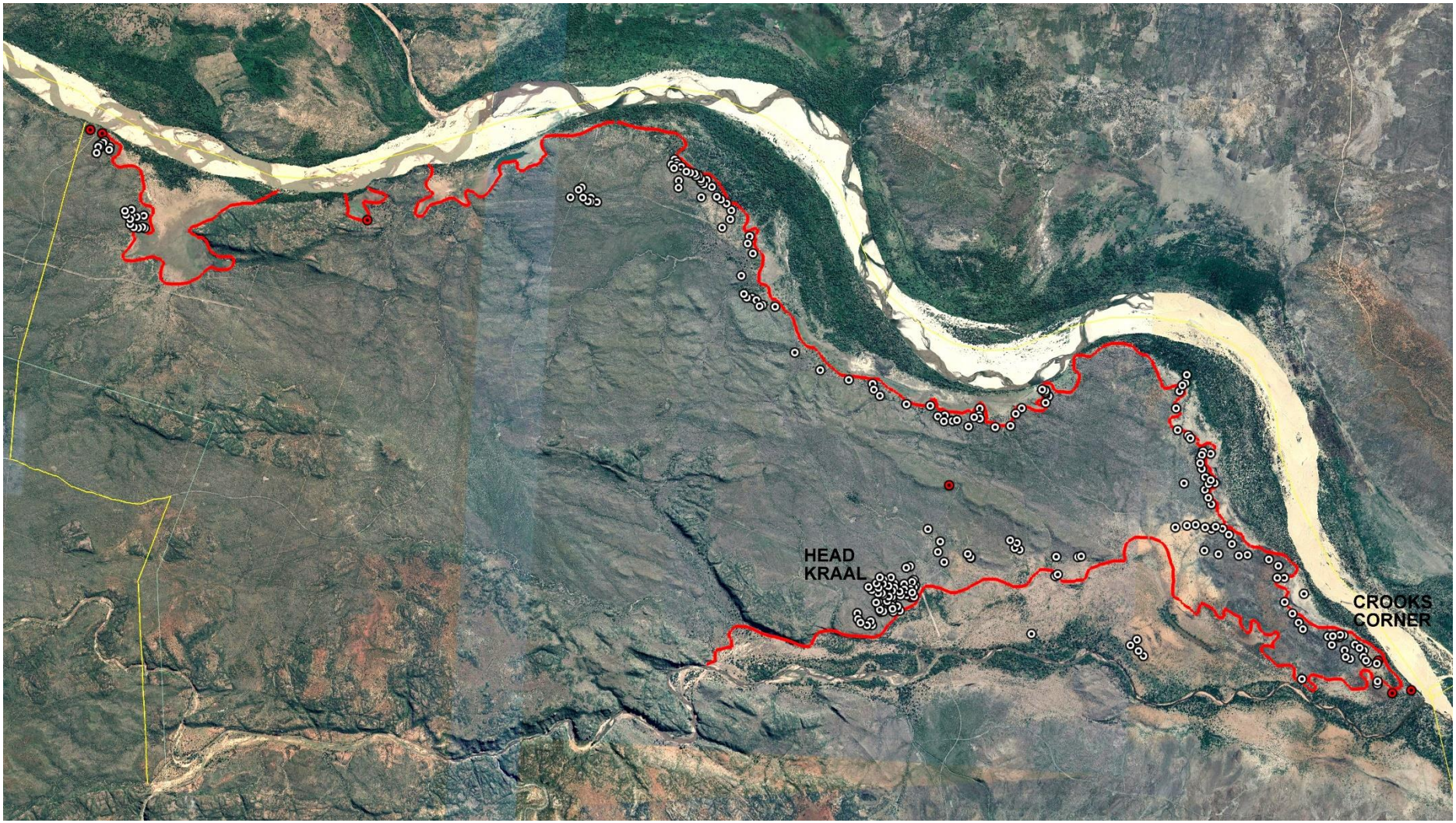


Figure 3.14: Makuleke village sites in 1969 (white dots) and the floodplain boundary (red line). Individual villages were situated on higher ground adjacent to the floodplain where crop farming occurred. (Personal research with E.V. Tivani).

4. THE MONOSPECIFIC *VACHELLIA XANTHOPHLOEA* WOODLANDS

4.1. LITERATURE SURVEY

Vachellia xanthophloea Benth. (Mimosaceae), commonly known as the fever tree, is native to southern and eastern Africa occurring from KwaZulu-Natal in South Africa to Somalia. It is semi-deciduous to deciduous growing up to 30 m in height in low lying, swampy areas in warm climates (Palgrave, 1991). The canopy is sparse with bipinnately compound leaves with small leaflets. In what could be a compensatory adaption the tree also photosynthesises through its yellow/green bark.

The tree grows in warmer climates but can tolerate the occasional mild frosts. It grows at altitudes from sea level to almost 2000 m asl. In Southern Africa monospecific woodlands occur in Mkuze Game Reserve and Pongola Game Reserve (altitude below 150 m asl) and the Limpopo River floodplain (altitudes of 500 m asl to below 220 m asl) in the MCP and adjacent Dumela area of Mozambique. In East Africa woodlands occur at a range of altitudes in Lake Nakuru National Park (altitude 1760 m asl), Lake Naivasha National Park (1880 m asl), Ngorongoro Crater (1700 m asl), Arusha National Park (1500 m asl), Amboselli National Park (1100 m asl), and Lake Manyara National Park (600 m asl). In its local landscape *V. xanthophloea* is found in low lying areas associated with water typically on the margins of rivers, lakes, and pans and in swampy locations. It often forms dominant stands in seasonally flooded areas (Palgrave, 1991., Schmidt *et al*., 2017). The tree is adapted to these wet conditions with a shallow root system (see fig 4.2) and functional pneumatophores on the surface roots (manifesting as knobbly growths) for respiration in waterlogged conditions (Moll, 2013).

Vachellia xanthophloea woodlands sometimes occur in arid bushveld areas where rainfall is low but water from other sources is available. Amboselli National Park and the Limpopo River floodplain all experience annual rainfall of 450 mm or less. Mkuze Game Reserve and Pongola Game Reserve receive annual rainfall of 680 to 720 mm. In East Africa, the Ngorongoro Crater, Lake Manyara National Park, Arusha National Park, Lake Nakuru National Park and Lake Naivasha National Park all experience annual rainfall in the range 600 to 1000 mm. A characteristic of all these woodlands is that they are in lower lying areas and receive additional water from higher elevation topography or flooding of rivers and lakes.

The East African woodlands are situated close to the equator with a warm tropical temperature and no frost, while in southern Africa the natural distribution at lower altitude on the eastern side of the continent coincides with warm temperatures and very occasional mild frosts. The distribution along the Limpopo River extends to Mapungubwe National Park at about 500 m asl.

Even height monospecific stands of *V. xanthophloea* woodlands are common and occur in all the above locations (Dharani *et al*, 2006; Belsky 1984; Ruess and Halter, 1990; Norton Griffiths 1979; Botha 2001) as well as south-eastern Zimbabwe and the Limpopo floodplain at Dumela, Mozambique (pers obs). Single *V. xanthophloea* trees occur in mixed species woodlands. This even height characteristic is attributed to a synchronisation of suitable conditions or episodic events that create the necessary conditions for establishment (Dharani *et al.,* 2006). Germination is reported not to occur under *V. xanthophloea* canopy (Dharani *et al.*, 2006)) and these monospecific woodlands do not exhibit the well-known reverse J-shaped size class distribution. It may occur at landscape level, which appears to be the case at Lake Nakuru and Arusha National Parks (Dharani *et al.*, 2006; Botha, 2001) and the Mozambique Limpopo floodplain (pers obs). Monospecific *V. xanthophloea* woodlands vary in spatial extent and tree density but the key characteristic is the absence of other tree species and a short understory.

Vachellia xanthophloea is a relatively fast growing species (Western and Maitumo, 2009; Dharani *et al.*, 2006). Its seed germinates very easily under the right conditions. This is illustrated by a germination success of >90% achieved by the Kruger National Park plant nursery (Michele Hofmeyr, Nursery Manager, Skukuza, KNP, pers comm). The nursery process is to soak the seed for five hours, plant it 10 mm deep and keep the soil moist in a warm sunny place. The seed germinates in ten days and after 6 to 12 months the sapling should be 1 m tall (KNP nursery brochure). Thereafter the plant is expected to grow at 1 to 1,5 m per annum under ideal conditions (World Agroforestry Centre, 2016). In a natural environment seed germination success is impossible to determine considering predation of seeds by disease and animals. Mass simultaneous germination appears to occur in episodic events when conditions are right and in more than sufficient seedling density to generate future woodlands, evidenced by the existence of even height stands of mature woodlands (Dharani *et al.*, 2006; Ruess and Halter, 1990).

The even aged structure of *V. xanthophloea* woodlands appears to play a role in the synchronous decline of these woodlands (Young and Lindsay, 1988). These tend to suffer environmental stress, senesce, and die at around the same time.

Research at Amboselli National Park (Western and Maitumo, 2009) and Lake Nakuru National Park (Dharani et al., 2008) examined the growth of *V. xanthophloea* saplings under conditions where small, medium, and large browsers were absent. Growth rates with full exclusion of browsers varied between 1053 mm per year (76-month growth period with a tree flowering and producing seed in 72 months in Amboseli National Park) and 1610 mm per year (28-month growth period in Lake Nakuru National Park). The growth rate with the exclusion of only elephants (other browsers present) was 673 mm per year (46-month growth period in Amboseli National Park). One tree in an environment of few elephants achieved a height of 15 m in 13 years or growth of 1150mm per year (156 month growth period in Arusha National Park). These studies confirm *V. xanthophloea* in the East African environment as a fast growing species.

The role of herbivory as a top down driver in savanna vegetation generally has been well studied. Browsing is expected to decrease growth rates. Feeding-height stratification has been studied in the KNP (du Toit, 2003) which suggests the height of browse impact is a function of the browsers that are present. A “browse trap” controlling woodland establishment has been suggested (Midgley and Bond, 2001; Sankaran *et al.,* 2013; Bond, 2008; Holdo, 2014; Staver and Bond, 2014).

Elephant. Elephant impact on adult savanna trees has been documented in eastern and southern Africa for over 30 years (Barnes, 2001). Decline in mature trees is ubiquitous wherever elephants occur covering a wide range of tree species (O’Connor *et al.,* 2007). In the KNP elephant impact on mature trees has been extensively studied (Whyte *et al*., 2003; Asner and Levick, 2012). The mortality of mature trees is primarily through ring barking and push over.

V. xanthophloea woodlands are well utilised by elephants. In the Tsavo-Amboseli ecosystem in Kenya, out of four woodland habitats *V. xanthophloea* woodlands supported the highest presence of elephants (Kioko *et al*., 2006). In Amboseli National Park the loss of large areas of *V. xanthophloea* woodlands was shown to be elephant induced mortality (Western, 2006; Western and Maitumo, 2009). The re-introduction of elephants into the Pongola Game Reserve showed that with a wide range of tree species available, *V. xanthophloea* comprised 20% of large trees killed by elephants (Duffy *et al*., 2002). Anecdotal evidence from Gorongosa National Park in Mozambique (Daskin *et al*., 2015) suggests that following the near elimination of elephants during the Mozambique civil war (1972 to 1977) dense *V. xanthophloea* forests emerged which in 2012 were being opened up by the now increasing re-introduced elephant population.

Elephant impact on savanna tree saplings has been less studied but there is evidence in the Savuti, Botswana, that elephants browsed saplings <1 m high (Barnes, 2001). Elephant induced sapling mortality was 36% over 2 years, and the mean height of the surviving saplings was reduced from >550 mm to <300 mm, effectively keeping the saplings in both the fire and browse trap zones. In the Sengwa Wildlife Research Area, Chirisa Game Reserve, Zimbabwe 82% of elephant mouthfuls were taken from below 2 m in height and 62% from below 1,2 m (Guy, 1976). In a study on *V. erioloba* (Barnes, 2001) two browsing methods by elephants on saplings <1,5 m in height and the sapling response were observed. When elephants broke the sapling off near ground level coppice growth was usually produced from the roots. Mortality occurred when elephants pulled the sapling and its root out of the ground.

In Amboselli National Park (Western and Maitumo, 2009) the death rate of *V. xanthophloea* seedlings removed by elephants was reported as high. Over a period of 7 years seedlings exposed to elephant and other browsing did not achieve any height growth while seedlings protected from elephants but exposed to all other large herbivores grew to maturity. In the Ngorongoro Crater elephants have been recorded to feed extensively on the *V. xanthophloea* saplings (Kabigumila, 1993).

Mesoherbivores, particularly the ubiquitous impala as the most abundant, are another well studied controller of seedling and sapling growth. The mean feeding height of impala is about 300 mm with a maximum of 1,5 m (du Toit, 1990). They browse on leaves and small shoots but are not capable of breaking shoots and sapling main stems >7 mm diameter (Barnes, 2001). In the Hluhluwe-iMfolosi Park sapling growth was considerably higher where browsers were excluded (Staver and Bond, 2014). This is supported in another Hluhluwe-iMfolosi study (O'Kane *et al.,* 2012) demonstrating a major reduction of seedlings in areas of high verses low impala density. In the Chobe National Park the significant reduction in survival of seedlings was attributed to impala browsing (Moe *et al.*, 2009). In the Serengeti (Belsky, 1984) browsers reduced the rate of growth of seedlings (but did not prevent growth). In Tanzania at multiple sites (van der Jeugd, 1993) bush encroachment and the establishment of even-aged stands are attributed to episodic releases from browsing pressure by significant reductions in the population of elephants (poaching), and smaller browsers (anthrax and rinderpest). Porcupine induced mortality of a range of species of mature trees through ring-barking or in combination with fire has been reported (Yeaton, 1998; Thompson, 1974).

Fire. Fire is one of the key determinants of savanna structure (Scholes and Walker, 2003) and described as a large generalist herbivore (Bond, 1997) exerting top down control. Plant height structure is important in how trees respond to fire. Fires are very variable and fire characteristics depend on rainfall, soil fertility, levels of herbivory, combustible biomass and conditions under which the fire burns (eg temperature and wind speed) in a complex inter-relationship. The role of fire and the concept of a "fire trap" in the savanna of Hluhluwe-iMfolosi Park has been well documented (Bond *et al.,* 2017). Studies in Lewa Wildlife Conservancy in Kenya, and the Eastern Cape and KNP in South Africa (Trollope and Trollope, 2010) showed that the percentage top kill through 0.5m saplings to 5m trees declined with height and was exacerbated by fire intensity. In the KNP top kill was dramatically influenced by the height of the bush with 92% top kill in the height range 0-0,5m, reducing to 48% in height range 1,51-2.0 m, and 8% in the height range 3,5-4,0 m. Additional studies in Hluhluwe-iMfolosi Park (Staver and Bond, 2014) confirm the role of fire in height reduction of saplings in the height range 1-1,5 m. The effects of fire and elephants in changing vegetation have been demonstrated in a KNP study (Trollope *et al*., 1998)

A study on *Vachellia erioloba* in the Savuti area of Chobe National Park (Barnes, 2001) showed fire caused 100% sapling top kill but saplings recovered with almost 100% coppice regrowth from the

base. Depending on fire frequency the saplings can be held within the fire trap and the browse height of smaller browsers for years. *Vachellia erioloba* adult trees are fire resistant but the saplings are not but respond by coppicing.

Savanna trees are normally fire adapted with fire resistant bark. Resprouting is one response to fire and mortality in adult trees often occurs when the flame height exceeds the canopy (Trollop and Tainton, 1986).

Fire impact on *V. xanthophloea* has not been well reported in the literature, probably due to the generally moist conditions where *V. xanthophloea* occur which are not conducive to fire. However, in the MCP the *V. xanthophloea* woodlands on the Limpopo floodplain often occur together with *S. consimilis* grasses. These tall grasses are unpalatable and not heavily grazed, so they are vulnerable to fire in the dry conditions which are characteristic of the MCP climate. This potentially exposes the *V. xanthophloea* woodlands to a fire hazard. Adult *V. xanthophloea* have a very thin bark and are not fire resistant (pers obs). It is not known whether saplings respond by coppicing or are killed. Farmers in the Limpopo floodplain in Dumela, Mozambique, clear adult *V. xanthophloea* trees using fire (pers obs). A small fire of small branches around the base of the trunk is sufficient to kill the tree. The bark does not burn but is scorched to a height of about 1 m and exudes copious gum before peeling away from the trunk. This is the extent of the fire necessary to cause the death of an adult tree. These farmers remove saplings by chopping the saplings at the base with a panga. The saplings coppice but are chopped repeatedly. Fire is not used to remove saplings.

The MCP is largely protected from invading fires by the Limpopo and Luvuvhu Rivers. The fire return period over 66 years (1941 to 2006) was between 12 and 67 years (van Wilgen *et al.,* 2014).

Water stress. Under natural conditions water stress will be climate induced. However, with increasing construction of dams and boreholes and abstraction of water the anthropogenic factor in combination with climate is playing a more important role.

In the Greefswald forest of Mapungubwe National Park a combination of drought, water abstraction (which lowered the water table) and creeper-induced stress caused significant mortality in a range of canopy trees between 1990 and 2007 (O'Connor, 2009). The four worst affected species were *V. xanthophloea* (56% mortality), *Vachellia tortilis* (50%), *Faidherbia albida* (37%) and *Senegalia nigrescens* (25%).

The 1991/92 drought in the KNP caused significant mortality in a wide range of savanna trees across different habitats (Viljoen, 1995). An average of 42% of >2 m high *V. xanthophloea* trees in sample sites along the Nwanetsi and Letaba Rivers died because of the drought.

In a comparison with similar sized *Vachellia tortilis* trees, *V. xanthophloea* showed double the water use under favourable soil water conditions and a much earlier response to water stress as the soil water content declined due to the shallower rooting depth (Otieno *et al.,* 2001).

Natural senescence in Mkuze was observed to occur at about 70 years (observations reported by Botha, 2001). In East Africa 70 year old *V. xanthophloea* woodlands have been reported (Vesey-FitzGerald, 1974) and senescence (called "dieback") commencing in trees aged 50 to 60 years (Young and Lindsay, 1988).

Grass competition. A study in the KNP (February *et al.,* 2013) suggested a very strong influence of competition from grasses which reduced the growth of saplings and juvenile trees in a mixed species savanna.

4.2. METHODS

Different methods were necessary for the different phases and are detailed separately. Observations formed an important part of the information gathered.

4.2.1. ESTABLISHMENT PHASE

The establishment of the monospecific *V. xanthophloea* woodlands was defined as the process which culminated with the existence of mature woodlands and before senescence and tree mortality commenced. This process was the achievement of stage 5 of the demographic bottleneck model (fig 2.1)

Vachellia xanthophloea occurred in the study site in two different population structures:

- as single trees or small groups of up to about 30 trees within mixed riverine woodland often along depressions in the mixed riverine woodland (MRW);
- as separate monospecific *V. xanthophloea* woodlands ranging in area from 5 ha to 150 ha.

Monospecific woodlands were defined as woodlands consisting exclusively of *V. xanthophloea* as large trees (greater than 15 m in height) and an understorey of bare soil, grass and/or forbs or shrubs.

Identification and selection of monospecific woodlands. Monospecific woodlands that existed in 2016 were identified through a combination of ground surveys and GE imagery for 2016. Ground surveys confirmed the monospecific character of the woodlands, and the woodlands were then identified on black and white aerial photographs from 1942, by using shade differences. The ground surveys in 2016 identified remnants of previous woodlands from remaining dead felled and/or standing trees. The historical existence of these woodlands was then identified on aerial photographs from 1942 and GE imagery from 2005.

A total of ten monospecific woodlands (ID as VW in table 3.2 and fig 3.3) were studied. They ranged in area from 5 ha to 150 ha and represented all monospecific woodlands greater than 5 ha identified by the combination of aerial photographs, Google Earth imagery and ground surveys. They appeared to be representative of the woodlands in the floodplains both inside and outside the study area.

Aerial photography and GE imagery. Aerial photographs and Google Earth imagery were used to follow the temporal changes from 1942 to determine when the woodlands established. Aerial photos were available for 1942, 1963, 1970, 1987, 1987, 1991, 1994, 1996, 1999, 2000 and 2004 (Surveyor General, Mowbray, Cape Town). The quality of resolution varied which affected which photos were used. GE imagery of acceptable resolution was available for 2005, 2006, 2007, 2010, 2012, 2013, 2017, 2018 and 2019. The period of establishment of each woodland was determined as the period between the date of one photograph showing the woodland location barren of trees and the next sequential photograph showing the woodland location with trees.

Woodland demographics. Specific demographic parameters measured were woodland area, tree density, heights, and diameters.

The heights of trees in the woodlands were determined by photographing a 2 m measuring stick and scaling the tree height on the photograph with an adjustment for photographic angle. It was difficult to isolate individual trees and woodland tree heights were determined from a few samples where the same height was given to several closely adjacent trees. Stem diameter at breast height (DBH) was determined by measuring the trunk circumference at 1,3 m above ground level and converting to diameter. A number of *V. xanthophloea* trees in the Limpopo mixed riverine woodland (MRW)

and a *V. xanthophloea* woodland in Dumela, Mozambique, were sampled for comparison. One -way ANOVA analyses (using the Excel single factor ANOVA program) were performed on combinations of woodlands VW1, VW2, VW3, VW5, VW6, VW8 and FW9 to compare stem diameters. The woodlands constituted the treatments and the stem diameters the responses. The null hypothesis tested was that the populations of each of the woodlands did not differ in stem diameter (measured as DBH).

The areas of the ten woodlands that existed in 2005 from GE imagery were determined using the area calculation function of GE. Woodland densities in 2005 could not be determined from aerial photography or GE imagery due to some overlapping of canopies and inadequate level of aerial photographic or GE imagery resolution. However, the density in 2005 of five of the woodlands (VW1, VW2, VW3, VW5, VW6) was estimated by counting all live and dead trees (standing and felled) in 2018. The density of two of the woodlands (VW8, VW9) was estimated by counting live and dead trees in 2016 in sample patches within the woodlands. The locations of sample patches were selected on a visual assessment that they were demographically representative of the whole woodlands. The density of 3 woodlands (VW4, VW7, VW10) could not be estimated as only a few isolated trees remained in 2016. The structure of the demographic sampling is given in table 4.1.

The elevation position of the woodlands in the floodplain was determined by observation with a simple classification into low or high lying. Soil forms of the individual woodlands were identified with the assistance of Dr G. Nortje.

4.2.2. DECLINE PHASE

In 2016 there were a substantial number of dead standing and felled trees in all the *V. xanthophloea* woodlands. The death of trees is an ongoing phenomenon. As woodland establishment progresses from seedling through sapling to adult, individual trees grow, and mortality (thinning) due to competition for light, water and nutrients is a necessity to reduce the high density at the seedling and sapling stages to lower densities at the adult stage. This does not constitute decline. Woodland decline is defined as a population level phenomenon of the death of trees leading to a reduction in woodland density and/or area caused by different ecological drivers.

The decline of the 10 monospecific woodlands VW1 to VW10 that established after 1970 was studied using aerial photographs and GE imagery to assess the change in the tree density, and after 2016 by counting numbers of trees.

Aerial photography and GE imagery. Aerial photographs and Google Earth imagery were used to follow the temporal changes from 1970 to determine when the woodland decline commenced and to track its progress. Aerial photos were available for 1970, 1987, 1987, 1991, 1994, 1996, 1999, 2000 and 2004 (Surveyor General, Mowbray, Cape Town). GE imagery was available for 2005, 2006, 2007, 2010, 2012, 2013, 2017, 2018 and 2019. The commencement of decline was determined as the date of an aerial photograph or GE image after which a visually recognisable reduction in woodland density could be seen in the subsequent aerial photograph or GE image. Woodland decline was confirmed by ground surveys which identified dead standing and felled adult trees.

Table 4.1: Structure of the sampling of the *V. xanthophloea* woodlands

WOODLAND NAME	ID	NUMBER OF TREES COUNTED IN 2016	WHOLE WOODLAND COUNTED	SAMPLE PATCHES IN WOODLAND COUNTED	ESTIMATED WOODLAND AREA IN 2005 HA	SAMPLE PATCHES AREA SQ M	NO OF SAMPLES FOR HEIGHT (NOTE 1)	NO OF TREES SAMPLED FOR DBH
NHLANGALUWE	VW1	99	YES		19,0		7	12
UKANGWA 1	VW2	162	YES		9,0		7	12
UKANGWA 2	VW3	19	YES		4,5		5	15
UKANGWA 3	VW4		NO COUNT		8,5			
LIMPOPO EAST	VW5	194	YES		6,5		10	23
LIMPOPO WEST	VW6	278	YES		9,5		4	16
MAPIMBI	VW7		NO COUNT		5,0			
GRAVEYARD	VW8	68	NO	YES	41,0	21480	8	15
RIETBOKVLEI TO NWAMBI	VW9	65	NO	YES	149,0	8130	6	25
NWAMBI NORTH WEST	VW10		NO COUNT		15,0			
TOTAL					267,0			

NOTE 1: EACH SAMPLE RECORDED THE SAME HEIGHT FOR MORE THAN ONE TREE WHERE TREES WERE CLOSE TOGETHER.
TEN WOODLANDS EXISTED IN 2005. BY 2016 WOODLANDS VW4, VW7 AND VW10 HAD DISAPPEARED AND NO COUNTS COULD BE DONE. ALL OTHER WOODLANDS HAD REDUCED IN AREA BY 2016, PARTICULARLY WOODLANDS VW8 AND VW9. SAMPLE PATCHES WERE PLACED IN THE CORE OF THE REMAINING WOODLAND.

Woodland demographics. For 5 woodlands (VW1, VW2, VW3, VW5, VW6) a count of all the live and dead (both standing and felled) trees was done in 2018. For woodland VW8 three patches were counted and for woodland VW9 two patches within the core of the woodland that remained were counted. The sampling is summarised in table 4.1. Tree trunks were marked with a felt tipped pen to ensure complete counts were done. The 3 remaining woodlands (VW4, VW7, VW10) consisted of only a few isolated trees and no counts were done.

A tree pushed over by an elephant in April 2016 was monitored until July 2020 (50 months). Based on its condition after 50 months it was judged that a tree that died in 2005 (from any cause) would still be recognisable in 2018 as a decaying log (after 156 months). On this assumption, the number of living trees in 2005 was calculated as the total of living and recognisable dead trees (standing and felled) in 2018. The counting of felled trees to determine the mortality was subject to certain errors. The felled trees were subject to different degrees of decay and sometimes difficult to find when there was understorey. The felled tree count may have underestimated the number of trees in 2005 and mortality to 2018. Nevertheless, the method was consistent between all woodlands and so provided mortality estimates on a relative basis. There were dead standing trees in all woodlands. There is no estimate of how long these dead trees remained upright.

Elephants. Observations suggested a significant number of trees were being pushed over by elephants. Elephant feeding behaviour on *V. xanthophloea* trees was studied using camera traps and personal observations. Elephants, both bulls and breeding herds, fed on the small branches and leaves in the canopy of the mature trees. To do this they pushed the tree over and immediately started feeding. If one elephant in a group of bulls pushed a tree over the others immediately joined it and fed together on the fallen tree. If a cow in a breeding herd pushed a tree over most of the herd immediately started feeding together on the fallen tree. The outer fringe of the fallen tree canopy was consumed within a couple of hours in one feeding session. Elephants fed on the small branches and leaves of the pushed over tree. The area immediately around the tree was also scattered with elephant dung. Trees that had been toppled by wind did not get browsed by

elephants. The browsed condition of the felled tree was used to determine whether the cause of its death was either by elephants or wind (fig 4.1).

The trunk and unbrowsed thicker branches of a pushed over tree undergo a colour transition from the green/yellow colour of living trees to a rust-brown colour of the dead tree after about four months (fig 4.2). In assessing elephant induced mortality, at any point in time the number of trees pushed over by elephants in the preceding four months was determined by the number of felled trees with the characteristic signs of elephant feeding and still showing colour between a green/yellow tinge or rust-brown colour ("the green/yellow colour test"). This was converted to an annualised rate by multiplying by three.

For woodland patches VW2 and VW6 a number of counts were done of living trees, recently pushed over trees (green/yellow colour test) and standing dead trees over a 50 month period between June 2016 and July 2020.

A survey was done on woodlands VW6 and VW9 to determine the extent of bark stripping by elephants. *Vachellia xanthophloea* bark structure does not "strip off" as happens with other *Senegalia* or *Vachellia* species. The bark flakes off only in the immediate area of attack by the elephant's tusk. The extent of bark stripping was determined as the percentage of the trunk circumference where bark had been removed (Botha *et al*., 2002).

Mesobrowsers. In three of the woodlands, porcupine impact was observed as bark removal at the base of the tree, identified by the characteristic rodent type teeth marks. A survey was done on all the trees of woodland VW6 to determine the extent of bark removal by porcupine by the same method as for elephants. Removal of bark by elephants and porcupines in the same woodland (VW6) was compared.

Wind. With a shallow root system (fig 4.2), *V. xanthophloea* trees are prone to uprooting by wind. Coincidentally, a windstorm flattened an area of trees in woodland VW1 in January 2016. The flattened trees were counted in June 2018 with a visual assessment of which had been living trees when flattened in 2016. This may have resulted in an overestimate of the wind damage.

Figure 4.1: *Vachellia xanthophloea* wind damage (left). The foliage was not browsed. The trunk had decayed making felling by wind easier. Elephant impact (right) 8 hours after being pushed over by elephants. The foliage and small branches had been extensively browsed. The incident was captured on a camera trap.

Figure 4.2: *Vachellia xanthophloea* with green/yellow bark (left) immediately after being pushed over and rust-brown bark (right) after 4 months. The shallow root system is clearly visible (left).

Fire. The potential effect of fire was observed when a fire occurred in the *S. consimilis* grasses of the Limpopo floodplain in 2016 just outside the study area. Fire induced mortality in a patch of 46 *V. xanthophloea* trees was counted. The fire was terminated by human intervention.

Soil. Soil and elevation in the floodplain potentially affected the spatial distribution of the woodlands were recorded.

4.2.3. REGENERATION PHASE

Seedlings were classified as 0-500 mm in height and saplings as 500 – 6000 mm but often subdivided into 500 – 1000 mm, 1000 – 2000 mm and 2000 – 6000 mm for convenience when a specific height range characterised a regeneration area. Trees were defined as greater than 6 m in height.

Regeneration was identified by the existence of seedlings or saplings in a monospecific patch greater than 0.25 ha at a density that visually was in excess of that required to develop into a woodland with a density of 100 trees per ha (the density of the core of woodland VW9). All regeneration patches easily met this criterion and no farther selection criteria were necessary. Extensive ground surveys were undertaken and identified 20 discrete regeneration patches each with well defined boundaries. These are designated VR1 to VR20 (fig 3.3 and table 3.2). Some of these patches in the Limpopo floodplain were not identified in 2016 but only later when the saplings reached a height above the surrounding *S. consimilis* grasses where the regeneration was occurring.

Regeneration patch areas were determined using the area function of a Garmin GPSMap 62S and walking the patch boundary. The regeneration progress was followed by observations, point photography and height measurements with a measuring stick. Browsing impact was observed and recorded with photographs.

Seedling density was measured by counting all seedlings in five separate 5 x 5 m patches in a few regeneration areas. Systematic seedling counts were not done because seedlings disappeared in these areas.

Sapling density showed variation within individual patches and between the different regeneration patches. It was not possible to enter most sapling patches due to the spikey nature of the saplings and not possible to determine an accurate sapling density by sampling. Accurate density measurements would have been extremely difficult to achieve and not considered necessary in the scope of the study. Sapling densities were classified visually as high, medium or low. Figure 4.3 shows the extremes of high and low sapling densities.

Camera traps. Camera traps were used to determine which animal species were impacting the regeneration. Camera traps were Bushnell Trophy CamHD (model 119598) with 24 hr photographic capability. The number of camera traps available was limited and camera traps were allocated to monitoring both *V. xanthophloea* and *F. albida* woodlands, which restricted their use. Positioning was governed by the availability of suitable camera trap mounting structures. Camera traps were removed by baboons, chewed by hyenas, waterlogged by rain, repositioned by elephants and rendered inoperable due to flat batteries, so that recording at different patches was not standardised. The range specification of the traps was 30 m with a recording trigger gap of ten seconds. Camera traps could not be installed in the Limpopo floodplain due to the absence of mounting structures. Camera traps were installed at different times at patches VR15, VR18, VR19 and VR20 in the Luvuvhu floodplain for a combined total of 363 days spread over about 2 years.

For the above reasons, no meaningful statistical analysis of camera trap recordings could be done. The value of the camera traps was in determining the relative frequency of the different browsers that visited the portions of the patches that were within the range of the camera traps. A statistic of animal species visits per day was calculated. An animal visit was defined as one or a group of the same species captured on the camera trap. For a period of ten minutes from the initial capture any farther capture of what appeared to be the same animal or group was considered the same visit. A new visit was assumed after ten minutes. The camera traps provided a rough guide to which species visited the regeneration patches where cameras were installed and whether browsing occurred. For the three most frequent browser species the visits per day were adjusted by the average number of that species per visit as recorded by the camera traps. This was used to determine a relative abundance of the browsers. Actual browsing activity was only occasionally captured.

Point photographs. Point photographs were used to monitor temporal changes in sapling height, density and the impact of browsers.

Observations. Observations formed an important part of the methods. Elephant feeding methods on seedlings was observed. Mesobrowser impact on seedlings was identified as shoots and stems up to 7 mm diameter browsed. Porcupine impact was identified by porcupine excavations and accompanying stem or root gnawed off at or below ground level at diameters up to 25 mm. Broken branches and main stem of anything greater than 7 mm diameter was attributed to elephants. Diameters were measured with a calliper.

Figure 4.3: *Vachellia xanthophloea* sapling density in 2018; high density patch VR1 (left) and low density patch VR20 (right). Medium density was in between. Density was determined visually. Patch VR1 is in the Limpopo floodplain on Arcadia soils surrounded by *S. consimilis* grasses. Patch VR20 is in the Luvuvhu floodplain on Duplex soils. The measuring stick height is 2 m.

4.3. RESULTS

4.3.1. ESTABLISHMENT PHASE

Ten woodlands were identified to have existed in 2005. Seven of these still existed during the period 2016 to 2018 (VW1, VW2, VW3, VW5, VW6, VW8 and VW9) but three woodlands (VW4, VW7 and VW10) had decline to the extent that they consisted of a few isolated trees only. These woodlands and their associated ecological parameters are shown in table 4.2.

Aerial photography and GE imagery. The series of aerial photographs and GE imagery from 1942 to 2018 show that all the woodland patches established after 1970. A series of photographs and GE imagery for woodlands VW5 and VW6 from 1942 to 2018 are used to illustrate the temporal changes (fig 4.4). Appendix 1 shows the same time series of photographs for woodlands VW1, VW8 and VW9 (VW8 and VW9 were the only woodlands with aerial photographs in 1996). All woodlands showed the same temporal changes with establishment occurring after 1970. The resolution of the aerial photography was only sufficient to allow an observational assessment of woodland changes but showed a decline in spatial extent and density of the woodlands commencing from about 2005 (fig 4.4). 2005 was postulated to be the point in time that the woodlands were fully established with establishment occurring between 1970 and 2005 but with woodland visible in 1987. Between 1970 and 2005 it was not possible to identify the sapling stage of the establishment of the woodlands. The establishment of woody vegetation on abandoned agricultural fields is a common phenomenon.

The Google Earth imagery of 2005 shows some interesting characteristics of the woodlands. The woodlands are well defined with clearly defined boundaries. The density of trees is higher in a central core and declines outwards from the core to the clearly defined boundary. The density in the core of each of the individual woodlands (where canopy closure often occurred) appears to be similar. However peripheral to the core some woodlands have trees that appear to be smaller in size.

Demographics. Tree height and DBH for each of the seven woodlands that existed between 2016 and 2018 (VW1, VW2, VW3, VW5, VW6, VW8 and VW9) were measured in 2018. Individual tree height determination was difficult and not always possible because of the difficulty of isolating individual trees to photograph. Usually, for each height determination it was the average height of several trees with overlapping canopies that was measured. Photographs taken of the woodlands from a distance illustrated an even height distribution (fig 4.5). The heights of the different woodlands are shown in figure 4.6.

Figure 4.6 shows the correlation between DBH and tree height for the seven woodlands existing in 2018. Also included for comparison are a monospecific woodland in Dumela, Mozambique and trees in the Limpopo mixed riverine woodland. In figure 4.6 woodland VW5 is separated from woodlands VW1, VW2, VW3, VW6, VW7 and VW8 (which are more closely grouped together by height and DBH). DBH was then used to compare the woodlands. A one-way ANOVA of the DBH of all seven woodlands showed that the null hypothesis that the population in each of the woodlands did not differ in stem diameter should be rejected ($F(6,114)=4,88$; $p=0,00018$) (Appendix 2). However, a one-way ANOVA of six of the seven woodlands (VW5 excluded) showed that the null hypothesis could not be rejected ($F(5,92)= 1,18$; $p=0,325$) (Appendix 2). Woodland VW5 was the anomaly. The unimodal DBH frequency distributions for VW5 and the other 6 woodlands combined are shown in figure 4.7. All woodlands established on Arcadia soils.

The aerial photographs of VW5 and VW6 showed that these two woodlands established at approximately the same time. The DBH anomaly of VW5, was likely to be the result of environmental

differences which were not examined. The combined evidence is used to conclude that the all the trees of the seven woodlands are same age cohorts.

Floods in 1988 and 1996 are recorded as initiating additional cohort sapling establishment (Botha, 2001) but the size, location and persistence of these saplings is unrecorded. They could have been the smaller trees on the periphery of some woodlands that disappeared after 2005.

Table 4.2: Parameters associated with the *V. xanthophloea* woodlands established by 2005

ID	WOODLAND NAME	ESTIMATED AREA IN 2005 HA	ESTIMATED DENSITY IN 2005 TREES PER HA	SOIL FORM	ELEVATION	POSITION
VW1	NHLANGALUWE	19,0	28	ARCADIA	LOW LYING	SPOROBOLUS PLAINS, LIMPOPO FLOODPLAIN
VW2	UKANGWA 1	9,0	34	ARCADIA	LOW LYING	SPOROBOLUS PLAINS, LIMPOPO FLOODPLAIN
VW3	UKANGWA 2	4,5	30	ARCADIA	LOW LYING	SPOROBOLUS PLAINS, LIMPOPO FLOODPLAIN
VW4	UKANGWA 3	8,5	ND	ARCADIA	LOW LYING	SPOROBOLUS PLAINS, LIMPOPO FLOODPLAIN
VW5	LIMPOPO EAST	6,5	60	ARCADIA	LOW LYING	SPOROBOLUS PLAINS, LIMPOPO FLOODPLAIN
VW6	LIMPOPO WEST	9,5	48	ARCADIA	LOW LYING	SPOROBOLUS PLAINS, LIMPOPO FLOODPLAIN
VW7	MAPIMBI	5,0	ND	ARCADIA	LOW LYING	SPOROBOLUS PLAINS, LIMPOPO FLOODPLAIN
VW8	GRAVEYARD	41,0	86	ARCADIA	LOW LYING	LUVUVHU FLOODPLAIN
VW9	RIETBOKVLEI	149,0	100	ARCADIA	LOW LYING	LUVUVHU FLOODPLAIN
	TO NWAMBI			and DUPLEX	HIGH LYING	LUVUVHU FLOODPLAIN
VW10	NWAMBI NORTH WEST	15,0	ND	DUPLEX	HIGH LYING	LUVUVHU FLOODPLAIN
	TOTAL	267,0				

TEN WOODLANDS EXISTED IN 2005. BY 2016 THREE OF THESE WOODLANDS HAD DISSAPPEARED (VW4, VW7 AND VW10)

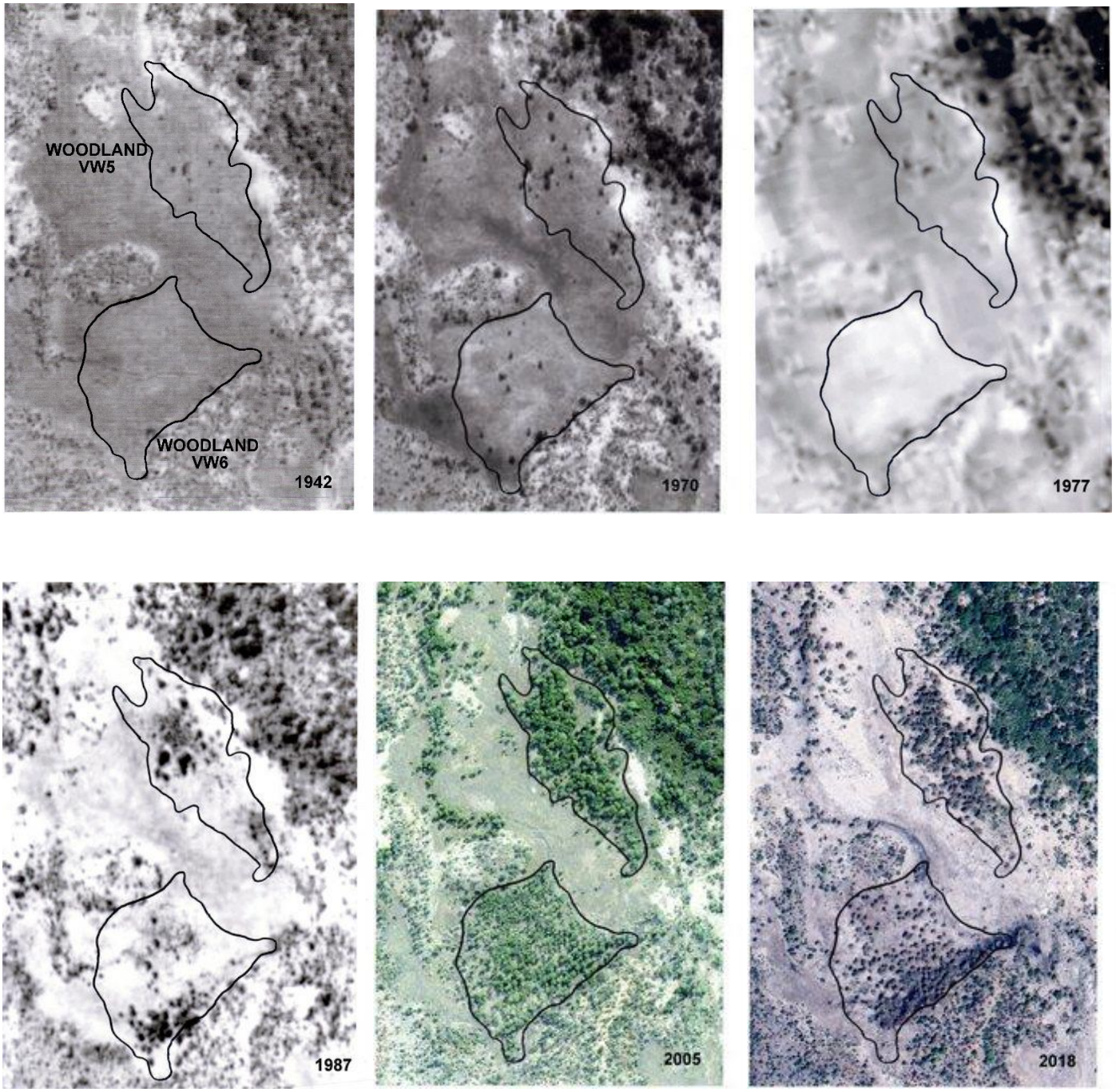


Figure 4.4: A series of aerial photographs and GE imagery for *V. xanthophloea* woodlands VW5 (upper marked area) and VW6 (lower marked area) from 1942 to 2018 show the establishment of the woodlands to a peak density in 2005 and subsequent decline to 2018. The Makuleke people farmed these floodplains until their removal in September 1969. The aerial photographs of 1942 and 1970 show no woodland existed between these dates. The resolution of aerial photographs of 1977 and 1987 is not sufficient to show smaller trees but the establishment of the woodlands after 1970 can be seen. The open areas in the GE imagery of 2005 and 2018 was *S. consimilis* grassland in 2018.

Figure 4.5: Photographs of *V. xanthophloea* woodlands VW9 (left) (average height 19,4 m) and VW8 (right) (average height 20,6 m) illustrating the even heights characteristic.

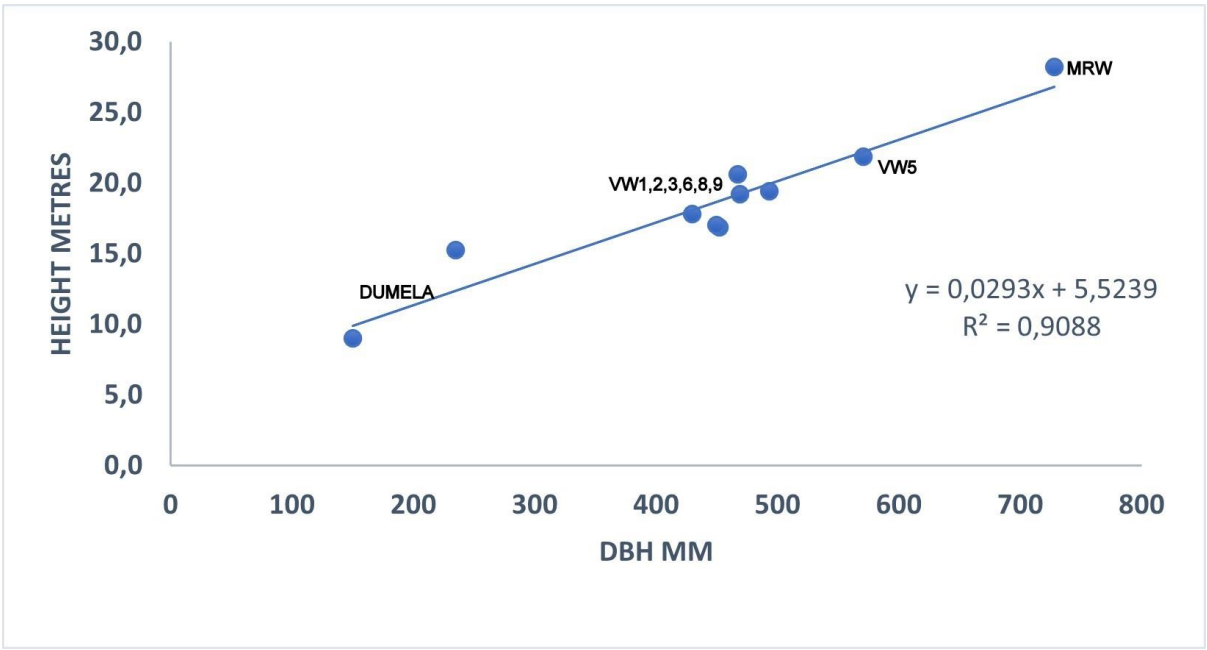


Figure 4.6: The relationship between average height and DBH for *V. xanthophloea* woodlands occurring in the Limpopo River valley. Woodlands VW1,2,3,5,6,8,9 (showing similar height and DBH characteristics) and VW5 are in the MCP floodplain. Sample sizes are given in table 4.1. Other data points are from miscellaneous trees or woodlands in Dumela, Mozambique (sample sizes of height and DBH expressed as height/DBH of 4/15 and 4/4) and the MRW in the MCP (sample size height/DBH of 6/6). Each height sample used to determine the woodland average was the visual average of several closely spaced trees.

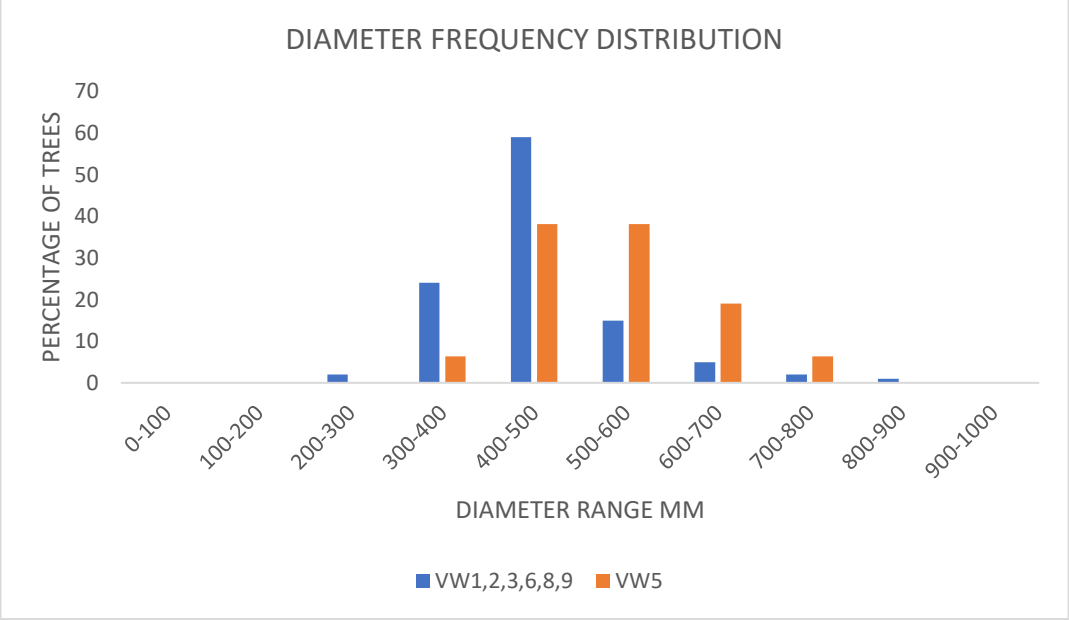


Figure 4.7: Diameter frequency distribution comparing woodlands VW1, VW2, VW3, VW6, VW8 and VW9 (combined) with woodland VW5. A one-way ANOVA on all seven woodlands rejected the null hypothesis that the woodlands are populations with the same mean. The null hypothesis could not be rejected for a one-way ANOVA on six woodlands VW1, VW2, VW3, VW6, VW8 and VW9. Sample sizes are given in table 4.1.

4.3.2. DECLINE PHASE

In 2016 the woodlands were in a phase of decline illustrated by the high number of dead trees (standing and felled) (pers obs) and the steady reduction in spatial extent and density seen in GE imagery.

Visual assessment of the aerial photographs and GE imagery from 1970 to 2020 showed the woodlands were fully established by about 2005 and subsequently started to decline (fig 4.4 and Appendix 1), although it is not possible to establish exact dates. From 2005 a reduction in area and tree density is observable on Google Earth imagery for all woodlands. The decline from 2005 is split into 3 periods which are considered in the following order:

1. the full period from 2005 to 2020.
2. the later part of the full period from 2016 to 2018/20 (depending on actual sampling period).
3. the earlier part of the full period from 2005 to 2016.

Decline 2005 to 2020 (full period). The GE resolution is not adequate to determine exact number of trees, but sufficient to make clear observations. A temporal reduction in spatial extent and tree density was observed in all the woodlands. This is illustrated in figure 4.4 (woodlands VW5 and VW6), figure 4.8 (woodland VW2), figure 4.22 (woodland VW1) and Appendix 1 (woodlands VW8 and VW9). A characteristic of the decline was that it occurred from the outside inwards towards the core of the woodland patch with the core being the highest density and least affected. Any peripheral trees and those trees that appeared to be smaller in 2005 disappeared by 2018/19, and the remaining trees appeared to be larger. The woodlands in 2018/19 were the remaining core of

those that existed in 2005, a factor which could have contributed to the even size and even age structure.

Woodland mortalities for the period 2005 to 2018, as determined by the number of live and dead (standing and felled) trees, are show in figure 4.9. The mortality levels for six woodlands (VW1, VW2, VW3, VW5, VW6, VW8) range from 77% to 22%. The core (two patches) of woodlands VW9 (and not the whole woodland) were sampled. The mortality level of the core was 27%. The overall woodland mortality would have been significantly higher.

Three woodlands (VW4, VW7, VW10) had almost completely disappeared. By 2018 only a few trees remained, and the density was insufficient to classify them as woodlands. The mortality was close to 100%.

The initial woodlands densities in 2005 of woodlands VW1, VW2, VW3, VW5, VW6 and VW8 ranged from 28 to 62 trees per hectare and for the core patches in VW8 and VW9 from 86 to 100 trees per hectare (fig 4.9). Woodlands with a lower initial density (as estimated for 2005) had a higher mortality as shown in figure 4.10. No reason is suggested.

Decline 2016 to 2020 (later part of full period). Two woodlands (VW2 and VW6) were monitored on a regular basis from June 2016 to July 2020 (fig 4.11). These woodlands had similar areas but different densities (see table 4.2). Over this period woodland VW2 lost 54% (or 83 trees) and woodland VW6 lost 60% (or 110 trees) of the living trees. This is equivalent to a mortality rate of about 20 and 26 trees per annum for woodlands VW2 and VW6 respectively. The decline in both woodlands is linear indicating that tree mortality is not a function of the woodland tree population.

Decline 2005 to 2016 (earlier part of full period). Results for two woodlands (VW2 and VW6) for the period June 2016 to July 2020 were subtracted from the period 2005 to 2020 to obtain results for the period 2005 to 2016. For both woodlands the mortality rate for the earlier part (2005 to 2016) was lower that the later part (2016 to 2020) of the full period (fig 4.12). Woodland VW2 mortalities increased from 13 to 20 trees per annum and woodland VW6 from nine to 26 trees per annum.

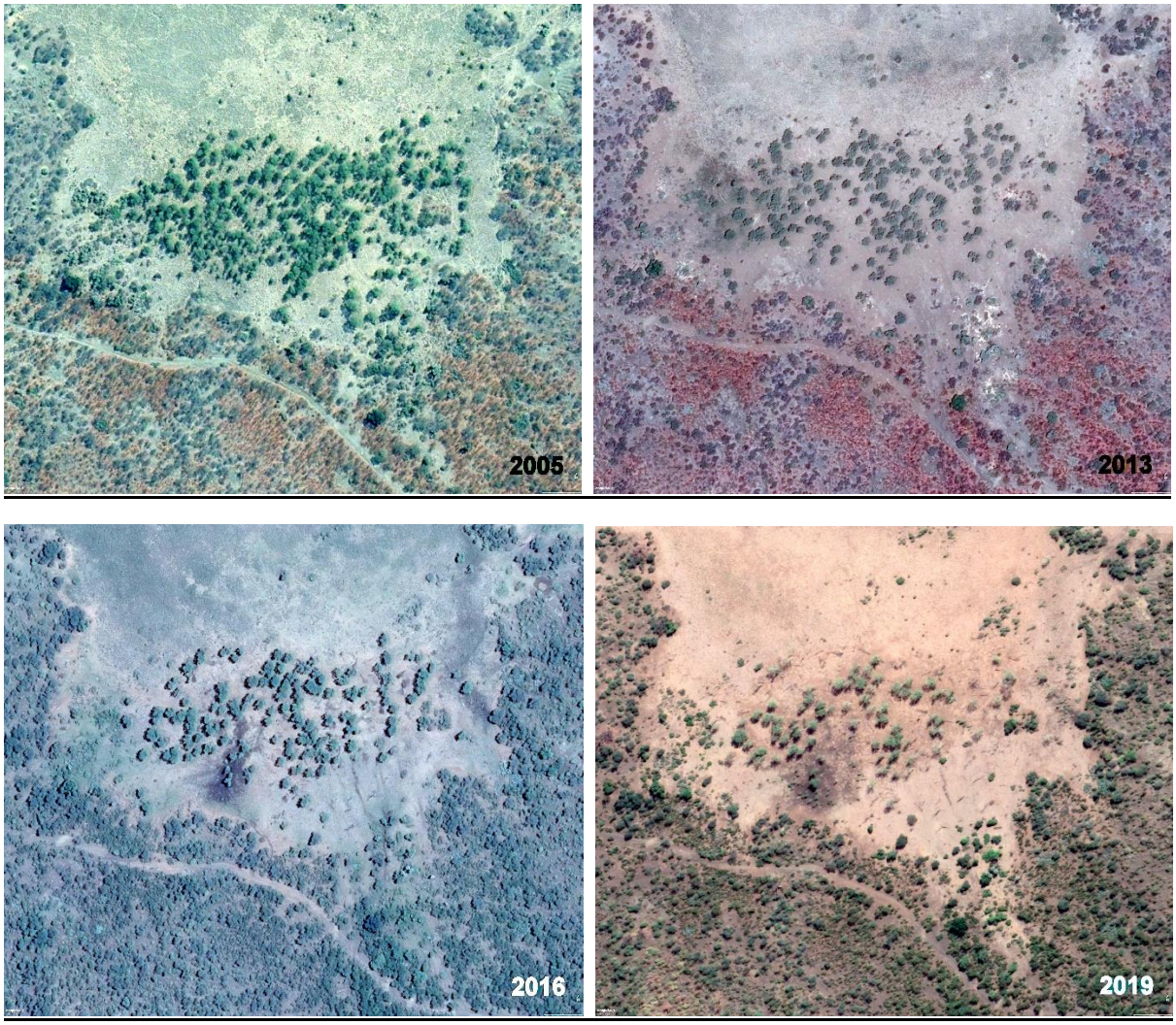


Figure 4.8: The progressive decline in *V. xanthophloea* woodland VW2 from 2005 to 2019 (top left to right, bottom left to right). Individual tree counts from 2016 to 2020 are shown in figure 4.11.

Figure 4.9: The estimated woodland density in 2005 and mortality from 2005 to 2018. In woodlands VW1, VW2, VW3, VW5, and VW6 the whole woodland was counted, in VW8 three patches were counted, and in VW9 two patches in the remaining central core were counted (where mortality is expected to be lower and density higher). Sample sizes are given in table 4.1. Woodlands VW4, VW7 and VW10 had disappeared by 2016.

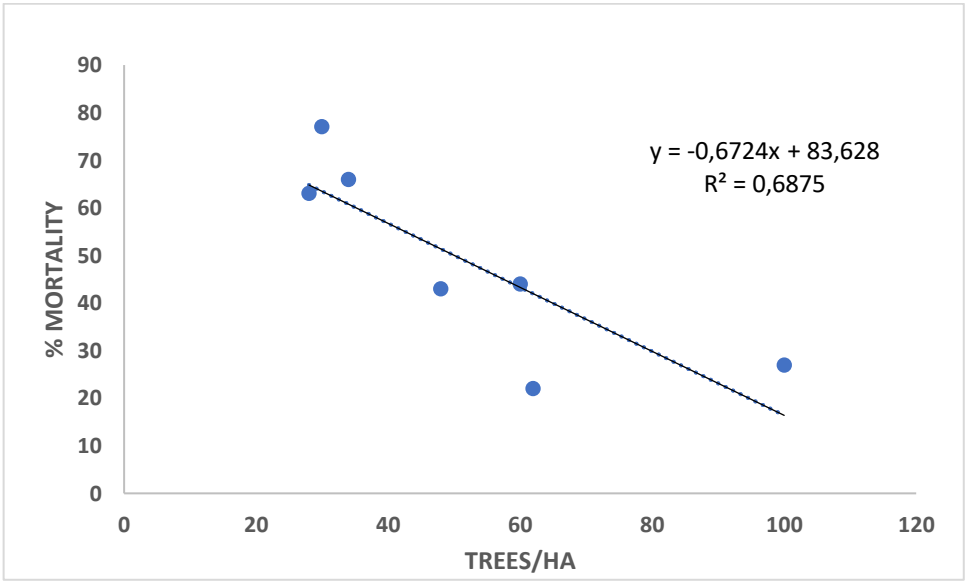


Figure 4.10: Woodland percentage mortality for woodlands VW1, VW2, VW3, VW5, VW6, VW8 and VW9 in 2018 as a function of initial woodland density (calculated for 2005) as extracted from figure 4.9. The higher mortality at lower densities may indicate a generally poorer environment for woodland establishment and subsequent higher early senescence.

Figure 4.11: Linear declining trend in the number of live trees in woodlands VW2 and VW6 between 2016 and 2020. The primary causes of mortality were elephant push over and death following premature senescence, with porcupine ring barking as a minor cause. These woodlands had similar areas of 9,0 ha and 9,5 ha respectively.

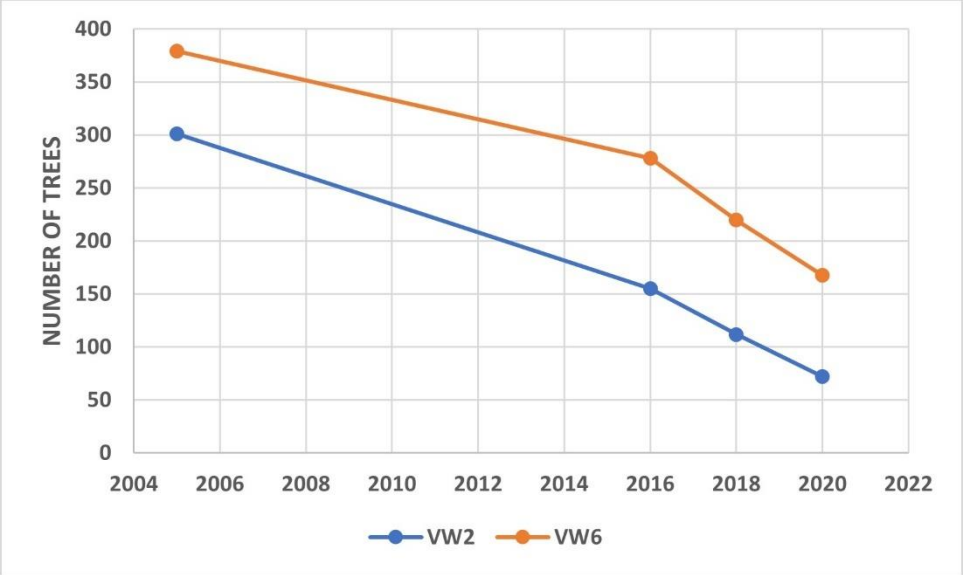
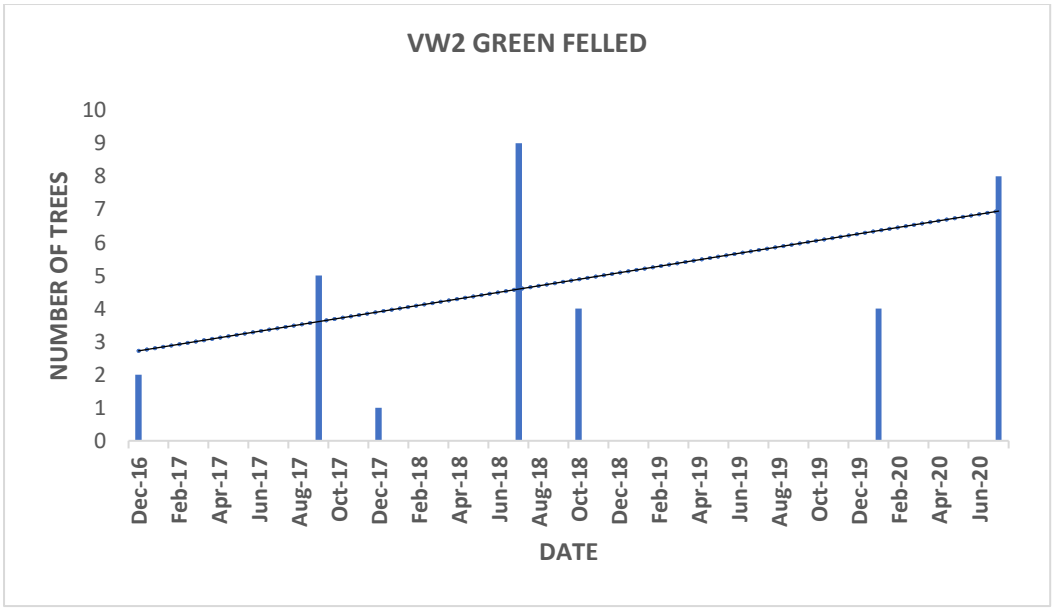


Figure 4.12: The decline of woodlands VW2 and VW6 from 2005 to 2020. The number of live trees in 2005 was assumed to be the same as the number of live and felled trees counted in 2016. Counts were done for 2016 and 2020. The rate of decline increased after 2016. These woodlands had similar areas of 9,0 ha and 9,5 ha respectively.

Elephant induced mortality. The number of trees pushed over by elephants in woodlands VW2 and VW6 was determined using the green/yellow colour test together with the characteristic elephant browsing sign of browsed canopy leaves and branches.

Elephant induced mortality by tree pushover was measured 16 times in the woodlands between June 2016 and July 2020. The pushover rate was highly variable but showed no relationship to the number of trees (fig 4.13) typical of consumer driven demand. The average push over rate was 1,2 trees/month (14 trees/annum) and 1,4 trees/month (16,8 trees/annum) for woodlands VW2 and VW6 respectively. These averages were used to estimate that the percentage of mortality caused by elephants was 71% and 63% respectively of the total mortality between June 2016 and July 2020 (fig 4.14).

Elephants also removed patches of bark which became entry points for activity such as wood borers and fungi (pers obs). These potentially lead to a weakening of the trunk which made it easier for trees to be subsequently felled by elephant or wind. Some of the trees snapped by elephant had broken at this weakened point. Bark stripping was examined on woodland patches VW6 and VW9 (fig 4.15). About 90% of trees had less than 25% bark stripping and no complete ring barking was observed.



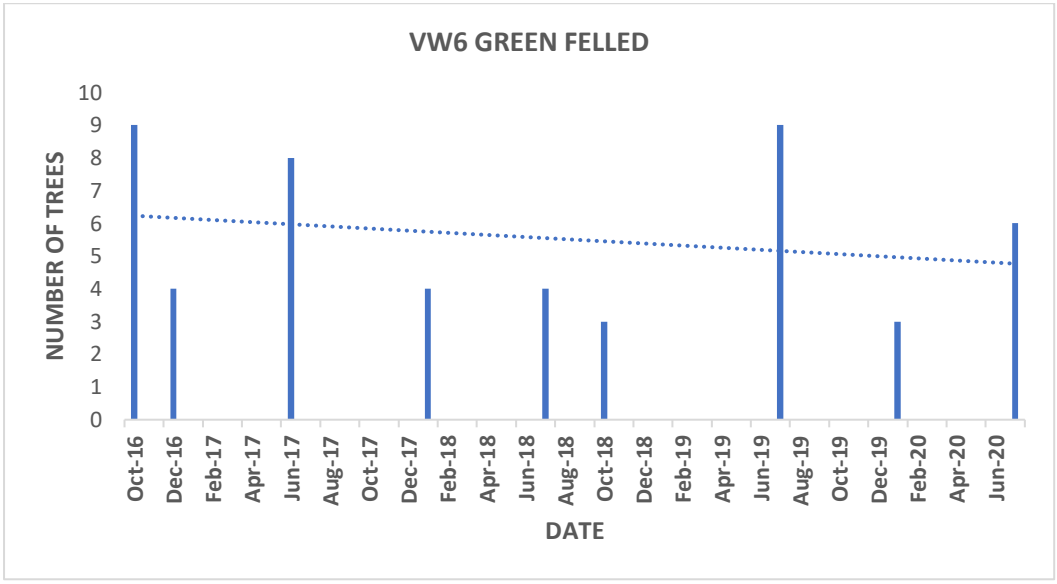


Figure 4.13: Number of trees pushed over by elephant in the four months prior to the date of sampling for woodlands VW2 (top) and VW6 (bottom) as determined by the green/yellow colour test. (Referred to as "green felled"). No trends exist. The average for each woodland was 4,7 trees pushed over in four months (14,1 trees per annum) for VW2 and 5,6 trees pushed over in four months (16,8 trees per annum) for VW6. These woodlands had similar areas of 9,0 ha and 9,5 ha respectively.

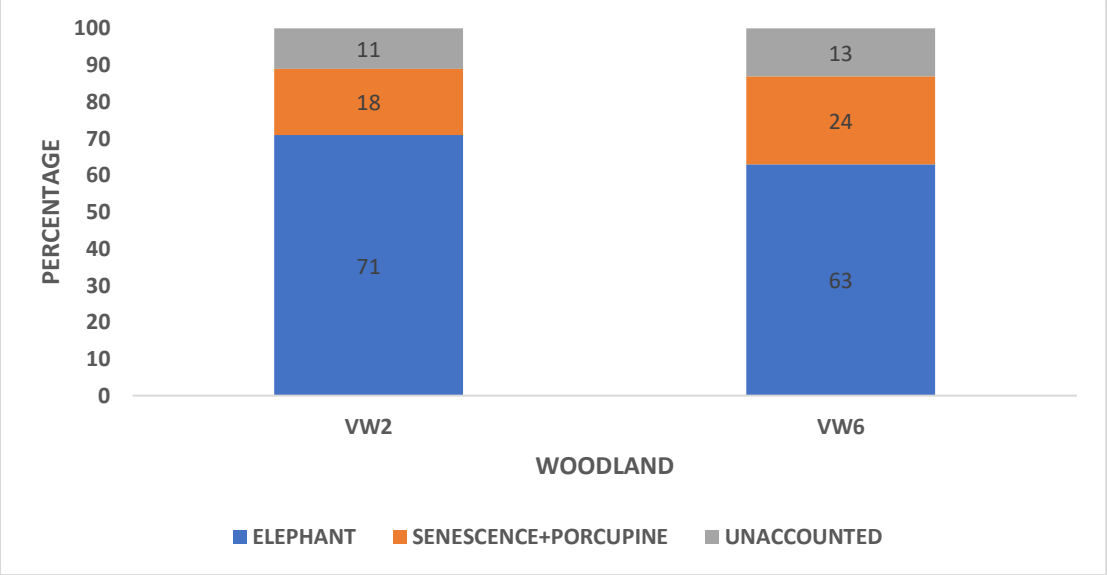


Figure 4.14: Estimated causes of woodland decline in woodlands VW2 and VW6 between June 2016 and July 2020 using data from the yellow/green colour test to determine elephant push over rates (see fig 4.13), and dead standing trees to determine senescence and porcupine mortality (see fig 4.16). The unaccounted portion is probably due to the inherent inaccuracy of this test. These woodlands had similar areas of 9,0 ha and 9,5 ha respectively.

Porcupine induced mortality. Removal of bark by porcupines was seen in three of the woodlands. This was identified by the rodent teeth marks at the base of the *V. xanthophloea* trees and the occasional porcupine droppings. The extent of bark removal was determined for woodland VW6 (fig 4.15). 90% of trees had less than 25% bark removal, 9% of trees had more than 50% bark removal) and about 1% of trees were completely ring barked. Porcupines remove bark at a lower level than elephants.

Figure 4.15: Comparison of elephant (left) and porcupine (right) bark stripping on woodland VW6. The extent of bark stripping by elephants and porcupine is similar. In 88% to 90% of the trees the percentage of the circumference of the trunk that was bark stripped trees less than 25%. In less than 1% of the trees the percentage of the circumference of the trunk was bark stripped was 100% (full ring barking). The whole woodland of 278 trees was sampled.

Dead standing trees and senescence. In 7 woodlands surveyed in 2016, standing dead trees varied between 3% and 49% of the total dead standing and live trees. In woodlands VW2 and VW6 from June 2016 to July 2020 dead standing trees (not pushed over by elephants) increased from 13 to 28 trees and 11 to 29 trees respectively (fig 4.16). Included are dead standing trees which are known to have toppled after June 2016 so dead standing refers to trees that died standing. It is assumed that porcupines would only have caused a small number of dead standing trees because of their low impact on living trees (fig 4.15) but this was not quantified. Most dead standing trees were the result of premature senescence. The estimated combined percentage of mortality caused by senescence and porcupine was 18% and 24% for woodlands VW2 and VW6 respectively (fig 4.14).

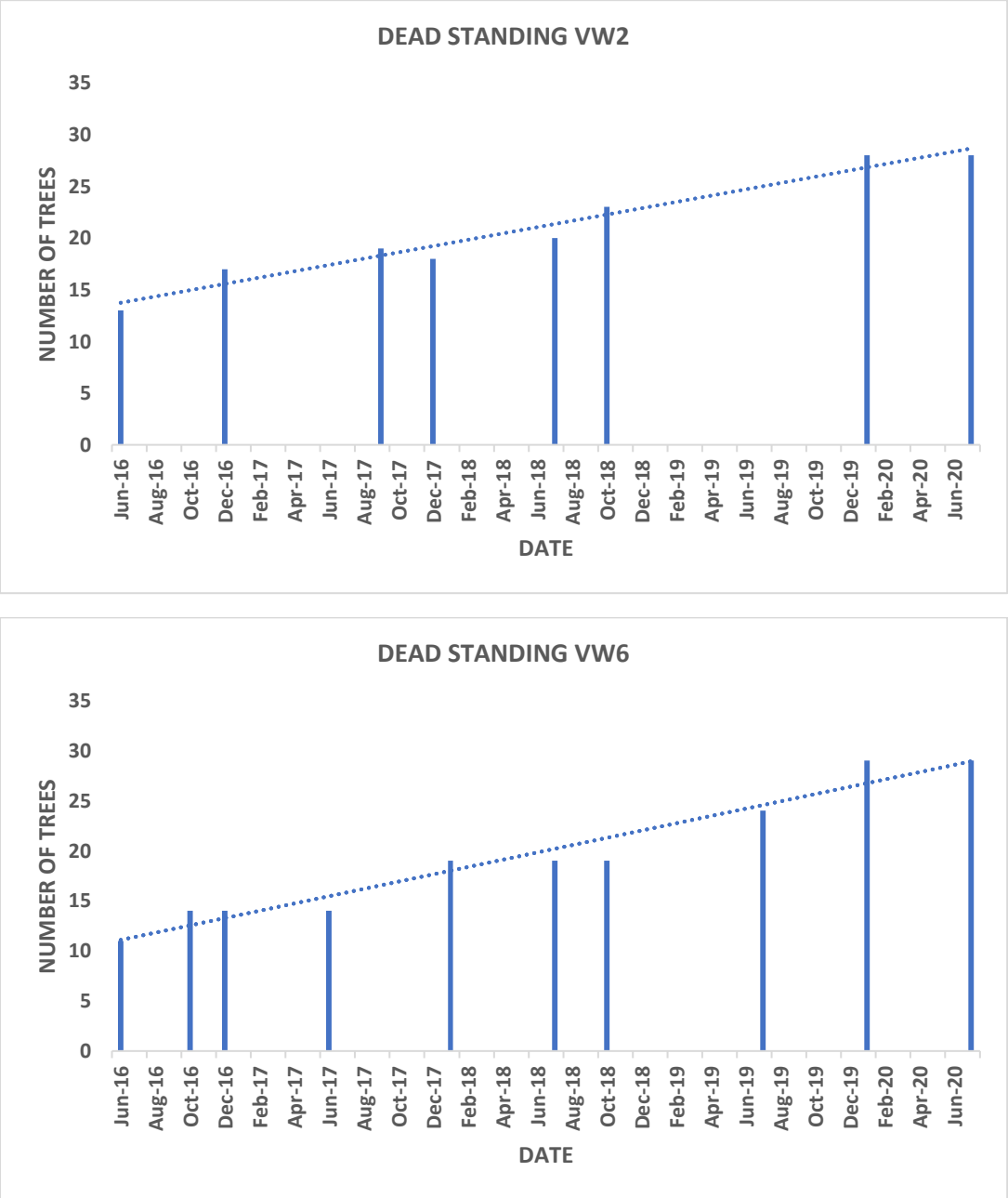


Figure 4.16: Dead standing trees for woodlands VW2 (top) and VW6 (bottom). These were trees not pushed over by elephants but dead and standing. An adjustment has been made to include any initial dead standing trees that toppled after June 2016.

Wind induced mortality. Isolated individual trees were uprooted by wind. The uprooting of 30 trees in woodland VW1 by a windstorm in 2016 was the major observed wind induced mortality. The windstorm also left a trademark of felled trees in the nearby mixed riverine woodland. Between 2005 and 2018 woodland VW1 experienced the loss of 167 trees (63% mortality) of which 30 trees (11% mortality) was caused by the episodic windstorm event. Counting the wind felled trees in 2018 and assessing which were alive in 2016 may have resulted in an overestimate of wind induced mortality.

Fire. In the Limpopo floodplain the understory of the woodlands was often dominated by *Sporobolus consimilis* grasses. *Sporobolus consimilis* is a tough unpalatable grass which is only grazed by buffalo, carries a large biomass into the dry season and burns easily. In October 2018, a fire which occurred in a small *V. xanthophloea* woodland of 46 trees one kilometre outside the study area (Lala Palm windmill area) caused the death of 43% of the mature trees. By 2020 no coppicing had occurred. This fire demonstrated that fire could have been an historical factor in the decline of the fever tree woodlands in the Limpopo floodplain. The previous record of a fire in the *S. consimilis* grasses of the floodplain was in 2005 but also outside the study area. Both fires were ignited by humans.

Soils. Woodlands VW4, VW5 (on Arcadia soils), VW10 (on Duplex soils) and a large portion of VW9 (on Duplex soils) disappeared before 2016. The Duplex soils coincided with areas of higher elevation on the floodplain and visually drier soil conditions than the remaining woodlands which were on Arcadia soils.

4.3.3. REGENERATION PHASE

Regeneration of the monospecific *V. xanthophloea* woodlands is defined as the process of germination of seedlings and subsequent recruitment of seedlings to the adult phase creating new woodlands to wholly or partially replace the *V. xanthophloea* woodlands that had disappeared. This process involves progressing through the five stages of the demographic bottleneck model (fig 2.1)

In September 2013, eight months after the floods, I observed the first evidence of large-scale areas of *V. xanthophloea* seedlings in the Luvuvhu floodplain near Rietbokvlei. Since my arrival in 2006, I had covered much of the MCP on foot and had not previously seen *V. xanthophloea* seedlings on this scale. The assumption was that the regeneration had been initiated by the floods of January 2013. By 2016 the regeneration was in stages 2 and 3 of the demographic bottleneck model.

The regeneration patches were patchily and widely distributed in the open areas of the floodplains (see fig 3.3) and not in the mixed riverine woodland or under the canopy of *V. xanthophloea* woodlands (pers obs), so the regeneration patches and mature woodlands were spatially separate but in close proximity. Regeneration patches occurred on two different soil forms and different elevations within the floodplain. A few of the regeneration patches were in areas where the original *V. xanthophloea* woodlands had disappeared.

The regeneration study was split into two periods.

Regeneration period January 2013 to April 2016. The period from January 2013 (flood date) to April 2016 was a period of general observation prior to commencing the more structured study between April 2016 and October 2018:

1. The first evidence of regeneration of *V. xanthophloea* seedlings was in the Luvuvhu floodplain near Rietbokvlei in September 2013, eight months after the floods. A superficial inspection confirmed the existence of seedlings was widespread. The seedling densities,

varied between 12000 and 1200 per ha in 5 x 5 m patches (fig 4.17 shows typical examples of regeneration patches at seedling and sapling stages).

2. The regeneration was only in the Limpopo and Luvuvhu floodplains and within the boundaries of the 2013 floods, which flooded the whole floodplain. The mature *V. xanthophloea* woodlands already existed in the same floodplain area.
3. The regeneration was in open areas not under existing woodland canopy. The woodland and regeneration areas were separate, but in close proximity.

Figure 4.17: *V. xanthophloea* regeneration patches; (left) VR19 seedlings less than 500 mm high in December 2013 (11 months after the floods) on Duplex soils and (right) VR16 saplings more than 1000 mm high in April 2014 (15 months after the floods) on Arcadia soils.

Annual rainfall during this period was average with characteristic variability between 682 mm and 350 mm. By April 2014, a mix of patches of seedlings, and saplings existed (fig 4.17). The seedlings in regeneration patch VR19 were below 500 mm while the saplings in regeneration patch VR16 exceeded a height of 1000 mm. Browsing was evident on regeneration still at seedling height and may have been the cause of maintaining the seedling stage in some patches (eg patch VR19).

By March 2015 the seedlings and saplings were still visually healthy, and the effect of browsing was noticeable. By February 2016, some seedling patches had disappeared, and the area of regeneration considerably reduced but the spatial extent of reduction was not determined. Patches of seedlings, small saplings and large saplings still existed and evidence of browsing on all sizes was common. Patches of seedlings were being maintained at seedling height by browsing of the seedling stems.

Regeneration period April 2016 to October 2018. Table 4.3 lists the 20 regeneration patches that existed in April 2016 and October 2018 and various of their parameters. An unknown number and area of seedling patches had disappeared before April 2016 and therefore could not be included. In April 2016 the area of regeneration was about 22 ha.

The status of the regeneration patches in April 2016 and October 2018 is shown in table 4.3. The impact of impalas (browse signs were broken off stems or twigs to 7 mm diameter) was only observed at the seedling stage and by October 2018 all remaining regeneration patches were at sapling stage. By October 2018 four regeneration patches had disappeared and the remaining

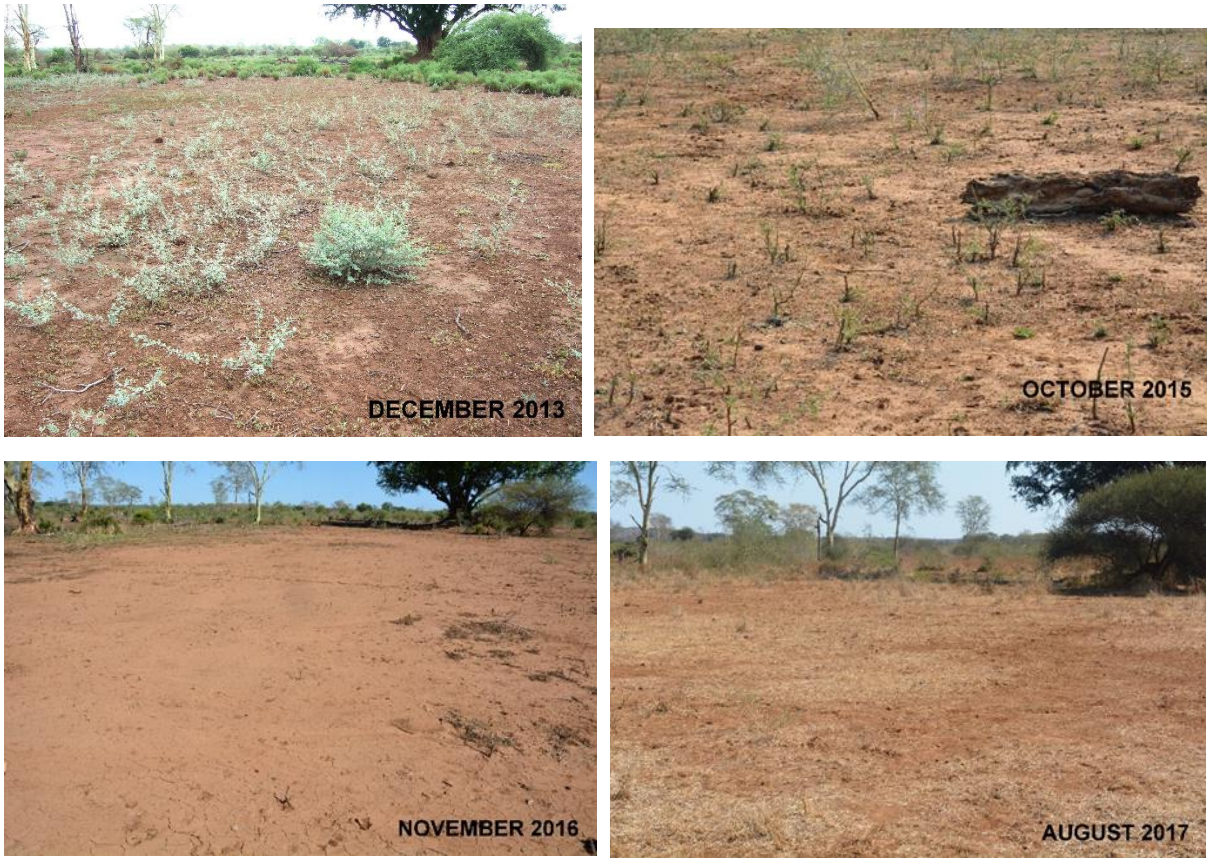


Figure 4.18: *Vachellia xanthophloea* regeneration patch VR19 on higher floodplain elevation and Duplex soils showing the decline from December 2013 (11 months after the flood) to August 2017 (44 months after the flood). The browsing impact by impala can be seen in the photograph of October 2015. Camera traps captured impala as the dominant browser.

regeneration area had reduced in area to about 18 ha. As an example, VR19 was monitored by point photography from December 2013 and had disappeared by November 2016 (fig 4.18).

The surviving regeneration reached heights of between 2,5 m and 5 m, which is in line with growth rates recorded in East Africa. Most areas had been impacted by elephants. Recovery from the impact of elephants (broken off sapling branches and main stems greater than seven mm were considered elephant browsing) occurred to different extents, illustrated by regeneration patch VR9 which was heavily impacted in Nov 2016 and recovered by October 2017, (although at a reduced sapling density), and then heavily impacted again by July 2020 (fig 4.19).

VR1, VR2 and VR9 were the only regeneration patches with no elephant impact (fig 4.20). By July 2020, these patches were up to 7,5 m in height. Table 4.4 summarises the different levels of browser impact.

Table 4.2: *Vachellia xanthophloea* regeneration patches in June 2016 and October 2018. Colours highlight the different soil forms

ID	REGENERATION PATCH NAME	SOIL FORM	REGEN AREA M2 2016	REGEN AREA M2 2018	AVERAGE SAPLING HEIGHT M 2018	IMPALA IMPACT	ELEPHANT IMPACT	SAPLING DENSITY 2018	POSITION IN FLOODPLAIN	OTHER VEGETATION
LIMPOPO FLOODPLAIN										
VR1	NHLANGALUWE 1	Arcadia	9000	9000	5	none	none	high	Lower floodplain elevation	*S. consimilis* grasses
VR2	NHLANGALUWE 2	Arcadia	1616	1616	5	none	none	high	Lower floodplain elevation	*S. consimilis* grasses
VR3	UKANGWA 1	Arcadia	10700	10700	4,4	none	medium	low	Lower floodplain elevation	*S. consimilis* grasses
VR4	UKANGWA 2	Arcadia	3100	3100	4,4	none	high	low	Lower floodplain elevation	*S. consimilis* grasses
VR5	UKANGWA 3	Arcadia	13500	13500	4,4	none	medium	low	Lower floodplain elevation	*S. consimilis* grasses
VR6	LIMPOPO EAST	Arcadia	8700	8700	2,5	none	low	medium	Lower floodplain elevation	*S. consimilis* grasses
VR7	LIMPOPO WEST	Arcadia	8300	8300	4	none	medium	medium	Lower floodplain elevation	
VR8	LIMPOPO CENTER	Arcadia	11300	11300	5	none	medium	high	Lower floodplain elevation	
VR9	LIMPOPO BVEKENYA	Arcadia	51000	51000	4,4	none	high	medium	Lower floodplain elevation	*S. consimilis* grasses
VR10	MAPIMBI WEST	Arcadia	8389	2866	3		high	low	Lower floodplain elevation	*S. consimilis* grasses
VR11	GRAVEYARD	Arcadia	5000	0			unknown		Lower floodplain elevation	Datura infestation
			130605	120082						
LUVUVHU FLOODPLAIN										
VR12	RIETBOK HIGH GROUND 1	ND	4600	4600	3	low	high	low	Higher floodplain elevation	
VR13	RIETBOK HIGH GROUND 2	ND	2000	2000	3	low	high	low	Higher floodplain elevation	
VR14	RIETBOK HIGH GROUND 3	ND	2000	0		low	unknown		Higher floodplain elevation	
VR15	RIETBOK CENTRAL	Arcadia	12621	0		high	unknown		Lower floodplain elevation	
VR16	RIETBOK CROTON CORNER	Arcadia	13100	13100	4,4		medium	medium	Lower floodplain elevation	
VR17	RIETBOK-NWAMBI	Duplex	8000	8000	3,5		medium	low	Higher floodplain elevation	
VR18	NWAMBI CENTRAL	Duplex	13300	13300	3,5		medium	medium	Higher floodplain elevation	
VR19	NWAMBI NORTH	Duplex	14000	0		high	unknown		Higher floodplain elevation	
VR20	NWAMBI NORTH WEST	Duplex	20000	20000	3,5		high	medium	Higher floodplain elevation	
			89621	61000						
	TOTAL		220226	181082						
			22 ha	18 ha						
				0	PATCH DISAPPEARED					
	ARCADIA SOILS, LOWER FLOODPLAIN ELEVATION									
	DUNDEE SOILS, HIGHER FLOODPLAIN ELEVATION									
	SOILS NOT DETERMINED, HIGHER FLOODPLAIN ELEVATION									

Table 4.3: Examples of 3 different levels of browser impact

IMPACT LEVEL	EXAMPLE	FIGURE	COMMENT
SEVERE (MESOBROWSERS)	VR19	Fig 4.18	Regeneration never escaped the seedling stage and disappeared. Camera trap recordings suggest that impalas were the dominant browser.
SEVERE TO INTERMEDIATE (ELEPHANTS)	VR9	Fig 4.19	Regeneration patches reached about 4,4 m in height, but each patch was impacted by elephants on at least one occasion and by July 2020 patches consisted of broken saplings of below 3 m in height and reduced density. Some regeneration disappeared.
MINIMAL OR NONE	VR1	Fig 4.20	Regeneration experienced no elephant impact and by July 2020 consisted of a dense patch of saplings of about 7,5 m in height.

Camera traps. The productive use of camera traps was restricted to VR19. Fig 4.21 shows the relative abundance of the four most important browser species (frequency of visits adjusted for group size). The two important browsers were impala and elephant. Only impalas were captured browsing the seedlings. VR19 never grew to sapling height and disappeared by November 2016.

Elephants. A group of three bull elephants were observed feeding on seedlings in patch VR15. One elephant was feeding at a rate of four saplings per minute for 15 minutes (until disturbed). The elephant wrapped its trunk around the seedling, kicked the ground with one of its front feet and extracted the sapling stem and root.

For saplings up to about 6 m in height elephants broke the main stem and branches. The signs of elephant feeding were obvious (patch VR9 in fig 4.19). The impact varied in severity from main stem breakage to minor branch breakage.

The extent of browsing in a patch depended on the number of elephants and the frequency of visits. Patches were left untouched for periods of more than a year and then subject to an episodic browsing event. When a herd of elephants browsed in a patch in this irregular fashion, most of the saplings were impacted. The elephant impact and recovery of patch VR9 was typical. Patch VR10 was reduced in size from 8389 m^2 to 2866 m^2 by severe elephant browsing.

Mesobrowsers. Impala were the main browser of patch VR19 seedlings (see figs 4.18 and 4.21). No negative mesobrowser impact on saplings in any regeneration patches was observed. Porcupine impact was not observed although they removed some bark on adult trees.

Soils. On the Limpopo floodplain the regeneration patches occurred on Arcadia soils and lower floodplain elevations. On the Luvuvhu floodplain regeneration patches occurred on Arcadia soils on lower floodplain elevations and on Duplex soils on higher floodplain elevations (table 4.3). By 2018 the taller and denser regeneration was on Arcadia soils and lower floodplain elevation. Four patches which disappeared at seedling stage occurred on both soil forms.

From observations, the Arcadia soils on lower floodplain elevations had higher soil moisture, demonstrated by the fact that they were the last areas to dry out as the dry season progressed. These lower floodplain elevations temporarily swampy in a normal wet season even if there was no flooding from the rivers. The higher floodplain elevations with Duplex soils did not become swampy during a normal wet season and did not get flooded as frequently as the lower floodplain elevations.

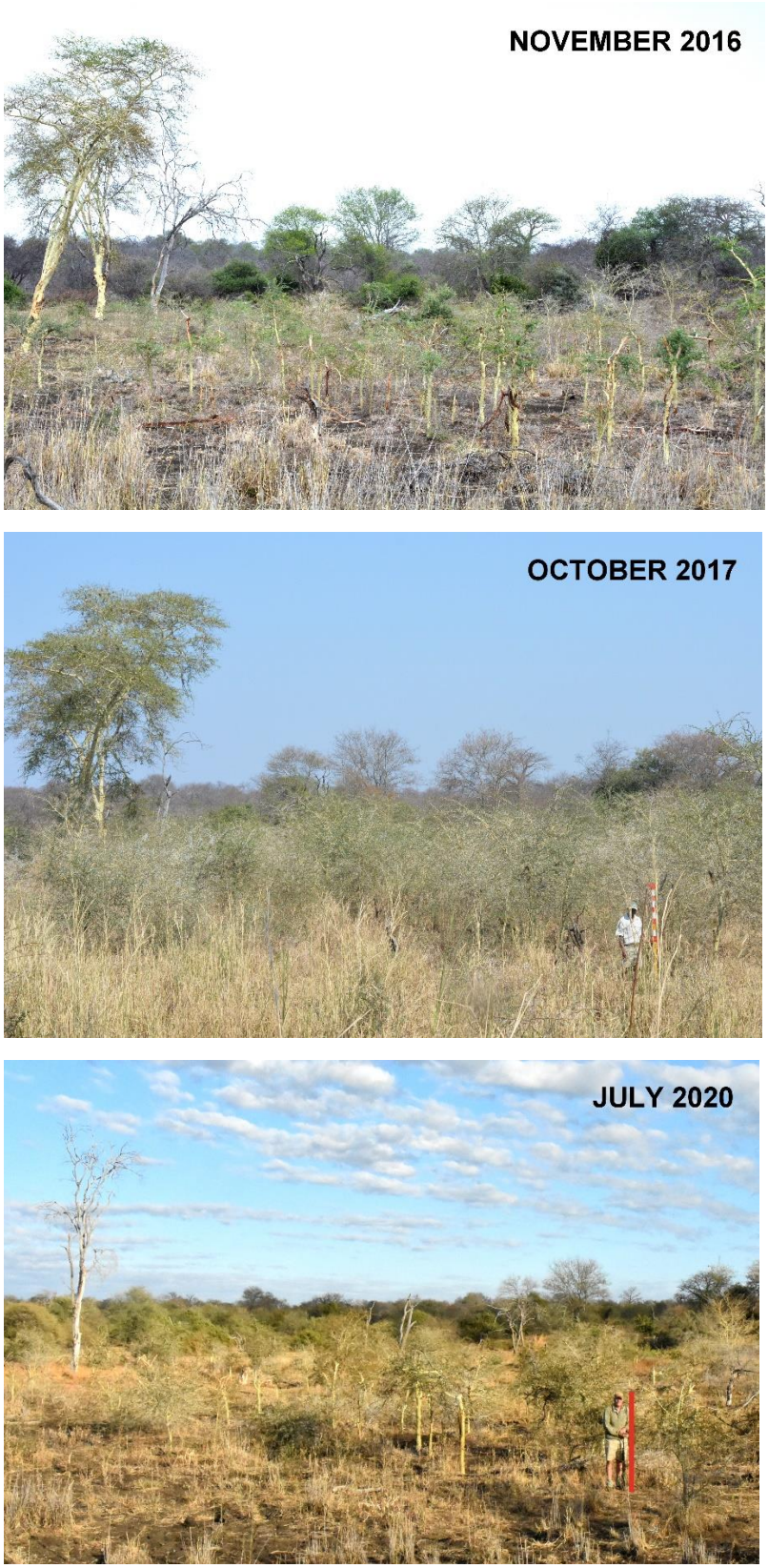


Figure 4.19: *Vachellia xanthophloea* regeneration patch VR9 in the Limpopo floodplain on Arcadia soils showing elephant impact in November 2016 (top), a year later after coppice recovery in October 2017 (middle) and 2 years 9 months later in July 2020 after additional elephant impact. Grasses are *S. consimilis.* The measuring stick height is 2 m.

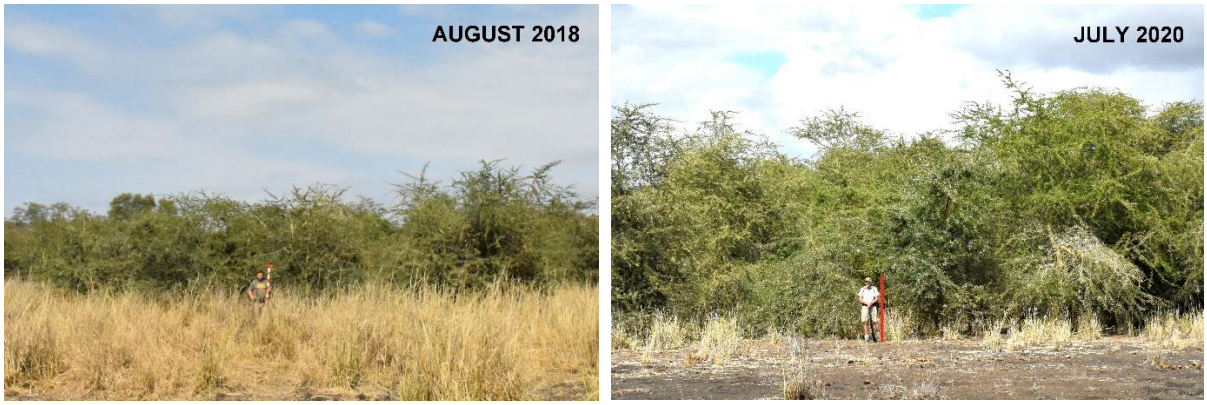


Figure 4.20: *Vachellia xanthophloea* regeneration patch VR1 in the Limpopo floodplain on Arcadia soils in August 2018 and July 2020. The patch experienced little elephant impact and was 7,5 m high by July 2020. Grasses are *S. consimilis.* The measuring stick height is 2 m.

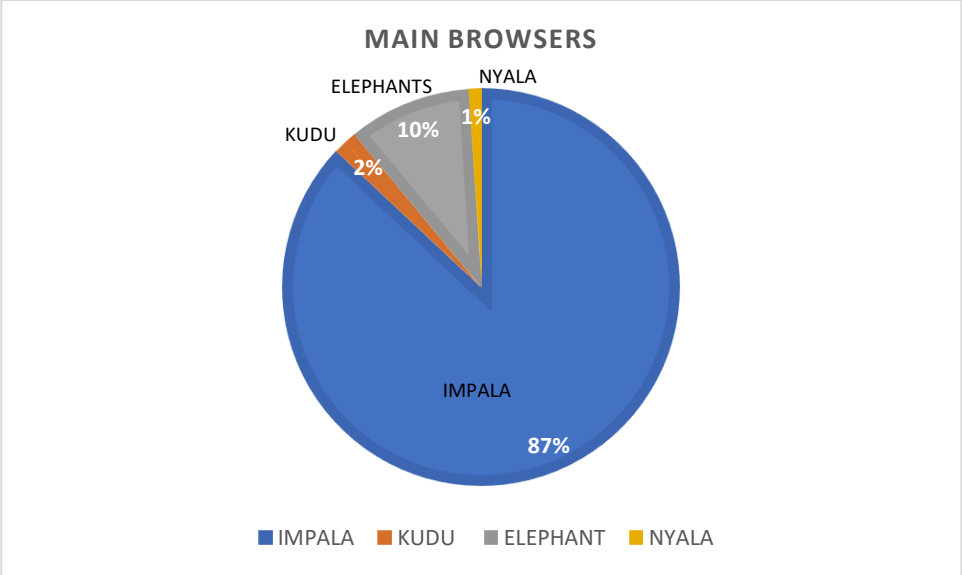


Figure 4.21: Main browsers visiting regeneration patch VR19 captured on a camera trap. Only impalas were recorded browsing. Based on a total of 172 recorded animal visits

This combination of Duplex soils and higher elevation resulted in an observably drier soil environment. Floodwaters only reach the Duplex soils on the higher floodplain elevations in the largest floods, as occurred in 2013 but not subsequently. These observations led to classifying the Arcadia soils as optimal and Duplex soils as suboptimal.

Competition. Potentially competitive species occurring in the floodplain were *Azima tetracantha, Litogyne gariepina, Panicum maximum, Urochloa mosambicensis, Sporobolus consimilis* and *Datura* species. Datura infestation was particularly severe in and around woodlands VW8 and VW9 (near regeneration areas VR11 and VR15) and was visible on GE imagery for October 2013 and March 2016. It created complete canopy closure at a height of between 500 mm and 1000 mm. This would have covered seedlings and small saplings. Regeneration started but never progressed in patch VR11 and this regenerating patch disappeared. *Datura* species were a serious invader in both the Limpopo and Luvuvhu floodplains and could have impacted regeneration where it occurred. Regeneration

patch VR6, which had the lowest sapling height of all patches in 2018 (with low elephant impact) was in the *S. consimilis* grasslands where competition could have been a cause.

Fire. No fires occurred during the study period, although regeneration in the *S. consimilis* grasslands of the Limpopo floodplain could be exposed to fire.

Spatial distribution of woodlands and regeneration patches. The temporal and spatial dynamics of regeneration are illustrated in the GE imagery of figure 4.22 for woodland VW1 and regeneration patches VR1 and VR2 in the Limpopo floodplain. Woodland VW1 declined progressively in area and density from 2005. Regeneration was initiated by the floods of 2013 but in patches where there was no or minimal woodland in 2005 and no woodland in 2012 just before the 2013 floods. After the floods, the woodland decline continued while the regeneration prospered.

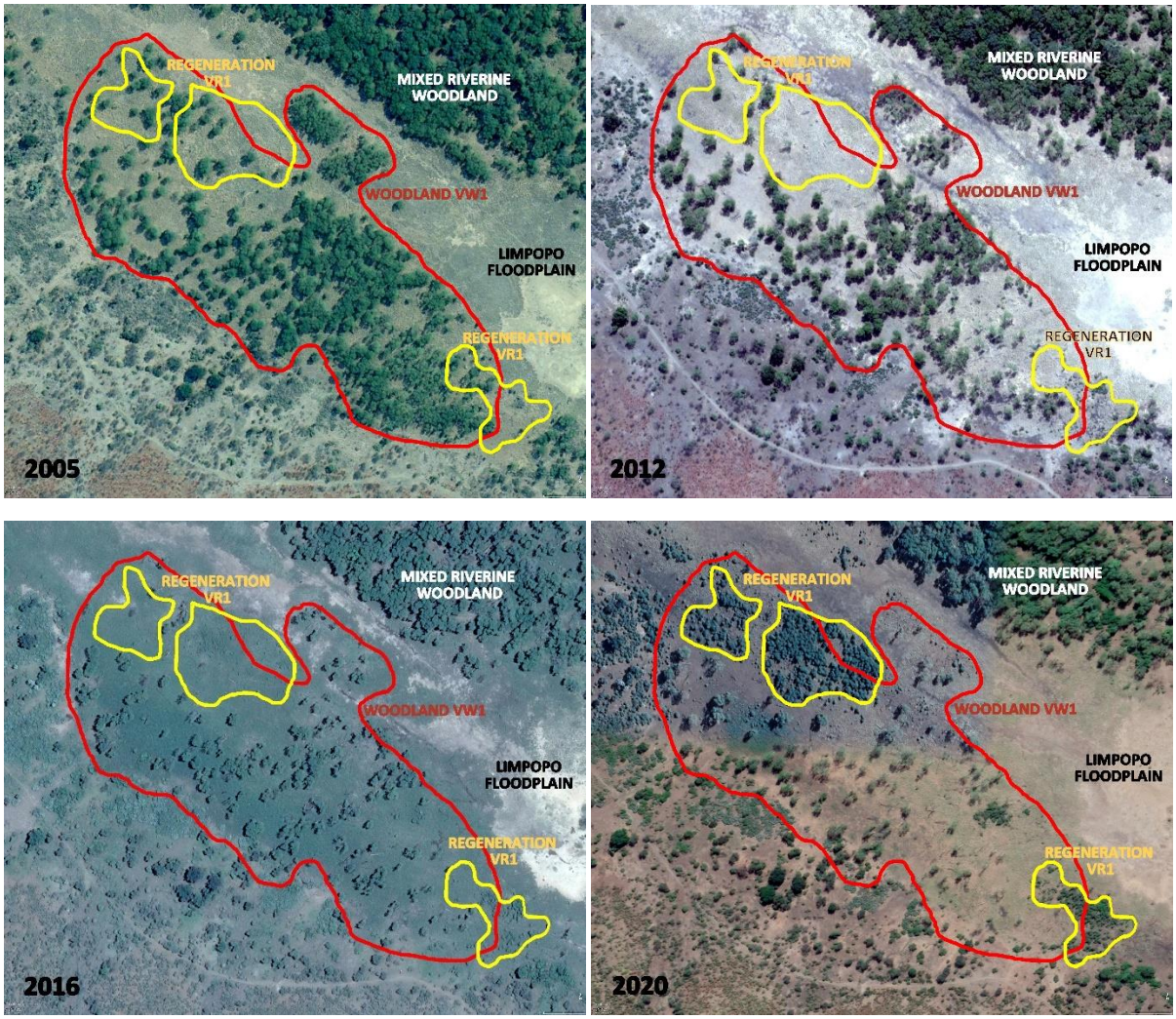


Figure 4.22: GE imagery for 2005, 2012, 2016 and 2020 (top left to right, bottom left to right) showing the decline of woodland VW1 (red boundary) and appearance of regeneration patches VR1 and VR2 (yellow boundaries) where no woodland or regeneration existed in 2012 (before the 2013 flood).

4.4. DISCUSSION

The dynamics of the woodlands concerned the temporal and spatial changes to these woodlands and the ecological drivers that caused these changes. The impact of the different ecological drivers varied across the different woodland phases and was also affected by changing river morphology between 1970 and 2020.

4.4.1. ESTABLISHMENT PHASE

From the sequence of aerial photographs, the establishment of the monospecific woodlands occurred after 1970. They exhibited even heights and unimodal DBH distributions which suggested that each woodland consisted of even aged cohorts. The anomaly of woodland VW5 with a different DBH distribution from the rest of the woodlands was likely to be the result of environmental differences, which were not examined.

The conclusion from the combined evidence of aerial photographs and woodland demographics was that the woodlands established in the floodplains approximately at the same time. Even aged cohorts are a characteristic that is common with *V. xanthophloea* woodlands elsewhere (Dharani *et al.*, 2006; Ruess and Halter, 1990). Establishment coincided with four episodic events, each of which contributed favourable conditions.

Anthropogenic factors. Suitable land for woodland establishment became available when the Makuleke people were removed from the area in 1969. The Makuleke lived on higher ground adjacent to the floodplains and farmed sections of the floodplains where the woodlands subsequently established. The Makuleke people relied on regular flooding to irrigate their crops and kept the area clear of *V. xanthophloea* trees. This is a farming practice that can still be seen in the *V. xanthophloea* woodlands in the Limpopo floodplain at Dumela in Mozambique (pers obs).

Portion of the farming area where woodland VW9 established was abandoned after the flood of cyclone Claude 1966 and the areas where the other woodlands established were farmed up to 1969. At the end of 1969 the MCP area was incorporated into the KNP, and no farther farming activity occurred. The vegetation was then free to respond to nature's agents.

Climate and hydrology. The seasons between 1965/66 and 1980/81 were above average rainfall and with frequent floods. This was also a time when the Luvuvhu River channel was narrow (before the floods of 2000 and 2013 widened the channel) (see Chapter 5) which would have promoted flooding of the Luvuvhu floodplain. Both the rainfall and floods would have kept the water table high.

Elephants. The elephant population was very low during the period 1970 to 1994. The population was controlled by culling and the few elephants in the MCP area were unlikely to have had any effect on a large area (267 ha) of establishing *V. xanthophloea* woodlands. The elephants in the MCP did not concentrate in the floodplains until after 2000, probably due the floodplains continuing to exist as a landscape feared and avoided by elephants. In a 20 year study in Amboseli National Park, Kenya, elephants were shown to be the only factor preventing the recovery of *V. xanthophloea* woodlands (Western and Maitumo, 2009). The elephant population in the MCP has grew dramatically after 1994, but the woodlands were well established by 1994.

Mesobrowsers. All evidence indicates a low mesobrowser population existed while the woodlands were establishing. This applies particularly to impala as the current ubiquitous browser in the area (pers obs). A low mesobrowser population would have had minimal browsing impact on a large area (267 ha) of establishing *V. xanthophloea* woodlands at the time when the establishment was at seedling stage. Numerous studies have shown the ability of mesobrowsers to prevent woodland establishment by creating a browse trap at the seedling stage (Belsky,1984; O'Kane *et al*., 2012; Moe

et al., 2009). In some East African national parks even-aged stands of *Acacia tortilis* (*Vachellia tortilis*) have been linked to herbivore population crashes caused by rinderpest and anthrax (Prins and van der Jeugd, 1993). In the current study impala had their greatest impact on seedlings and little impact at the sapling stage.

Soils. Optimal *V. xanthophloea* habitat has been described as low lying seasonally flooded swampy areas in warm climates. In the MCP the monospecific woodlands established on Arcadia soils as delineated by the soils map of the CDF (fig 3.6). These soils were in the lower lying areas of the floodplain. Soils and associated floodplain elevation affected woodland spatial distribution. In situ inspections in 2020 showed that some of these soils (Arcadia soils in the CDF) in the Luvuvhu floodplain were modified by the floods of 2000 and 2013 to a Duplex soil form consisting of a silt A horizon overlying an Arcadia type B horizon. This modification occurred after the woodlands had established and had no effect. The MCP Arcadia soils are alkaline and always occur in the lower lying areas of floodplains, local depressions, or drainage lines.

Since all ecological drivers were common for all the woodlands, the greater height and DBH of woodland VW5 could be attributed to chemistry differences in the Arcadia soils of this woodland, which were not examined. The mixed riverine woodlands on both Dundee and Oakleaf soils contain individual *V. xanthophloea* trees which were taller with greater DBH than the monospecific woodlands (but of unknown age), indicating ideal conditions but with competition from other tree species preventing the establishment of monospecific *V. xanthophloea* woodlands.

4.4.2. DECLINE PHASE

The woodlands have declined significantly since about 2005. Three woodlands disappeared by 2016 and the remaining seven woodlands declined in density by between 22% and 77% between 2005 and 2018. The total woodland area also reduced substantially.

Aerial photographs and GE imagery indicate the decline of the woodlands occurred from about 2005 although with the continuous nature of woodland decline there was no specific starting date or episodic triggering event. An exact date was neither determinable nor important. Decline is different to woodland thinning, a process that occurs while a woodland is establishing due to competition between individual trees for light, water and nutrients. Woodland decline is the reduction in the number of mature trees due to different ecological drivers. The decline was observable with trees newly felled by elephant and additional standing dead trees regularly seen.

Elephants. Elephants were the main ecological driver causing decline through tree felling. The woodlands were within the area of highest elephant densities in the MCP where food, water and shelter resources were excellent. The rate of decline for the two woodlands studied in detail (VW2 and VW6) increased in the period 2016 to 2020 compared to the period between 2005 and 2016. Between 2016 and 2020 elephants accounted for 71% and 63% of the mortality in these two woodlands respectively through tree push over and trunk snapping, and observations suggested elephants had a similar impact on the other *V. xanthophloea* woodlands. The extent of elephant induced woodland mortality prior to 2016 could not be quantified but it is likely to have been directly related to the elephant population which in 2005 was approximately half of the population between 2016 and 2018. Elephant impact through bark stripping did not play a significant role.

The linear decline of woodlands VW2and VW6 are indications of elephant feeding behaviour. It is postulated that elephants feeding in a woodland would push over and feed on a number of trees dependent on the size of the herd or bull group and not a function of the area or density of the

woodland. With a randomness of herd size and frequency of visits, the push over rate would have been expected to fluctuate (fig 4.13). Elephant induced mortality in the MCP was consistent with mortality seen in other areas, particularly in East Africa (Ruess and Halter, 1990; Western, 2006).

There was no evidence that elephants preferentially selected for *V. xanthophloea* trees above other nearby tree species (pers obs). A study in the Pongola Game Reseve, South Africa (where *V. xanthophloea* is a common tree) showed that many factors affect which tree species are selected for and killed by elephants (Duffy *et al*., 2002). In the MCP *Colophospermum mopane* woodlands close to the *V. xanthophloea* woodlands were very heavily browsed and pollarded. When *C. mopane* trees were browsed, they usually coppiced at browsed height. *Colophospermum mopane* trees were consequentially not removed from the community and became entrenched as C*. mopane* woodland 2 to 4 m in height. This was not the case with adult *V. xanthophloea* trees which were pushed over, or trunks snapped, and did not coppice but died. Elephant impact on the adjacent mixed riverine woodlands was also high and observations and elephant distributions show they were extensively utilised.

Climate and floodplain hydrology. There is no evidence that any floods prior to 2000, the floods of 2000 or the floods of 2013 had any negative impact, either through direct flood water impact or excessive, lengthy periods of flooding. The woodlands were in areas of the floodplain where the flood had spread out and the flood energy dissipated. The MCP floods normally had a rapid recession time so any consequences of lengthy periods of flooding did not exist. The recession time of the 2013 floods was less than one week (pers obs).

The woodland decline occurred during a period of variable but average rainfall and less than historical flooding frequency. However, there was an eight year dry period from 2004/05 to 2011/12 when rainfall was 90% of average and no floods occurred. This coincided with the commencement of the woodland decline. Drought induced mortality of *V. xanthophloea* was recorded in Mapungubwe National Park following an extended drought coupled with water extraction (O'Connor, 2010) and in the KNP at sites along the Nwanetzi and Letaba Rivers following the severe 1991/92 drought (Viljoen, 1995). In the MCP with its low rainfall (average 437 mm per annum), the absence of floods would be considered a significant disturbance to the floodplain hydrology.

Soils. Woodlands VW9 and VW10 in the Luvuvhu floodplain, which accounted for most of the area of woodlands that disappeared before 2016, were established in an area which in 2020 was Duplex soils (silt A horizon overlying an Arcadia type B horizon) on a higher elevation of the floodplain. Two smaller woodlands, VW4 and VW7 in the Limpopo floodplain on Arcadia soils also disappeared, but all remaining woodlands in 2016 were on Arcadia soils and lower floodplain elevation, confirming this as optimal habitat.

Senescence. Dead standing trees were a consequence of premature senescence, with a possible minor contribution by porcupine ring barking. Environmental factors which introduce stress can accelerate senescence and lead to death of trees (Ciesla and Donaubauer, 1994). Fluctuating floodplain water table depths due low and variable of rainfall could have been a cause of stress on the woodlands. In a woodland of cohorts, Young and Lindsay (1988) attributed decline to synchronous cohort senescence.

In East Africa 70 year old *V. xanthophloea* woodlands have been reported (Versey-FitzGerald, 1974) and senescence (called "dieback") commenced in trees aged 50 to 60 years (Young and Lindsay, 1988). In the MCP premature senescence appears to have started in about 2005 in trees of about 35 years of age at a time when the elephant population and impact was low. The disappearance of

woodlands VW10 and part of VW9 appears to be due to premature stress induced senescence imposed by a combination of Duplex soils, higher floodplain elevation and the reduction in frequency of floods. The current woodlands were not more than 48 years old with evidence of continued senescence. The observation of high and increasing numbers of dead standing trees in the period 2016 to 2020 (woodlands VW2 and VW6) coincided with seasons 2017/18 to 2019/2020 when rainfall averaged 313 mm (72% of normal) with no floods. In the high temperature and evaporation environment of the MCP this could have provided the necessary stress for premature senescence.

4.4.3. REGENERATION PHASE

The floods of January 2013 initiated the current regeneration. *Vachellia xanthophloea* regeneration following floods has been reported elsewhere. After the floods of cyclone Demoina in 1984, several large stands of *V. xanthophloea* established on the Mkuze floodplain while none appeared in the adjacent *V. xanthophloea* mature woodlands of Mkuze Game Reserve, KZN (Botha, 2001). However, the most appropriate examples are in the Limpopo River valley. The *V. xanthophloea* woodlands in the MCP which established after 1970 after a succession of floods and a section of the *V. xanthophloea* woodlands in Dumela, Mozambique which established after the Limpopo flood in 2000 (pers obs and discussions with Dumela farmers). While the floods initiated regeneration, other drivers affected the subsequent regeneration progress.

In the years with no floods, *V. xanthophloea* seedlings have been observed to occur in the MCP at very low densities in small areas with a suitable microhabitat, but these seedlings did not survive (pers obs). The 2013 floods initiated landscape scale regeneration with the germination of *V. xanthophloea* seedings in high densities in large areas the floodplain close to, but not within, the existing *V. xanthophloea* woodlands. The area of regeneration declined during the period 2013 to 2016 before detailed monitoring commenced (pers obs), and the extent and reasons are unknown. Surviving regeneration in 2016 consisted of 22 ha as a patchwork of a few seedling patches and numerous sapling patches still at high density. If the template for the establishment of the original woodlands after 1970 had been repeated after 2013, then regeneration on a similar spatial scale to the establishment phase would have proceeded. However, these conditions did not occur and regeneration after 2013 was not on the scale as occurred after 1970.

Climate and floodplain hydrology. Woodland establishment after 1970 was during a period of above average rainfall and frequent floods. The first four seasons after the 2013 floods (2013/14 to 2016/17) were above average rainfall (553 mm or 127% of normal) and a Limpopo flood in 2017. The next three seasons (2017/18 to 2019/2020) were below average rainfall (313 mm or 72% of normal) with no floods. The widening of the Luvuvhu River channel by the 2000 and 2013 floods and the retention and controlled release of water from Nandoni dam (built in 2005) may have affected the Luvuvhu flood regime and could have been a contributing factor affecting lack of floods in the Luvuvhu floodplain in the period after 2013.

The impact of climate, however, may have been trumped by other ecological drivers (eg browsers) and difficult to assess. The fact that regeneration patches VR1 and VR2 achieved 7,5 m in height by 2020 indicates that when other drivers were favourable, the impact of climate may not have been controlling.

Soils. After 1970 all optimal habitat was available for the woodlands to establish. As the woodlands declined from 2005 potential areas for regeneration became available. However, regeneration after

2013 did not occur within existing woodlands, a phenomenon also reported on the Mkuze floodplain (Botha, 2001) and in East Africa (Dharani *et al*., 2006). Consequently, a significantly smaller area was available for regeneration after 2013 than after 1970. Regeneration after 2013 occurred on lower floodplain elevation on Arcadia soils (considered optimal) and a smaller area on higher floodplain elevation on Duplex soils (considered suboptimal). By 2018 the regeneration on lower floodplain elevation on Arcadia soils was taller and denser than regeneration on Duplex soils. The taller regeneration growth indicated that Arcadia soils were optimal. Regeneration that disappeared (VR11, VR14, VR15, VR19) occurred at seedling stage on both soil forms and except for regeneration patch VR19 (impacted by heavy impala browsing) the causes were not clear.

Mesobrowsers. Impala browsing was the main driver in the failure of one regeneration patch (VR19). It could have been a factor in two other regeneration patches which disappeared at the seedling stage and the reductions that occurred before 2016 in seedling regenerating area. The seedling height in the failed patches never exceeded 500 mm and the density declined until there were no seedlings remaining. The rest of the regeneration patches escaped the mesobrowser browser trap and reached a sapling height of 2,5 to 5,0 m (large saplings) by 2018 probably because the impala population was not sufficient to prevent all the initial seedlings escape the impala browse trap.

Elephants. Elephant extraction of whole seedlings (stem and root) was observed. This method of feeding was recorded in the MCP on *F. albida* seedlings (pers obs) and in Amboseli National Park where it was considered the main cause preventing recruitment of *V. xanthophloea* seedlings to saplings (Western and Maitumo, 2009).

Elephant browsing was the main driver impacting regeneration which had reached sapling height. Elephant browsing impacted most sapling patches causing broken saplings and reductions in area, height and density. Where the main sapling stem had been broken, coppice regrowth occurred. This characteristic was also observed in the farming areas at Dumela (per sobs) where saplings stems were chopped with a panga and coppice regrowth occurred. Studies in the Ngorongoro Crater, Tanzania (Kabigumila, 1993) showed elephant selected for <1 m high *V. xanthophloea* saplings when a height range of up to 15 m was available. The elephant browsing in the Ngorongoro Crater was considerably greater in the dry than wet season and the impacted saplings coppiced in the wet season. Observations suggested this also happened in the MCP.

By 2020 (7 year regeneration growth) only VR1, VR2 and VR8 appeared to be escaping the elephant browse trap. Growth rates of about 1 m per annum in these three patches were in line with or slightly below browser free growth rates in East Africa and Dumela.

After 1970 the elephant and impala populations were low, and the area of seedlings and saplings was large (at least 267 ha) so browse pressure would have been minimal. After 2013 the elephant and impala populations were much higher and the area of seedlings and saplings small (22 ha by 2016) so browse pressure would have been much greater. This constitutes a major difference between the two periods.

Competition. Competition from other plants was a potential ecological driver that could not be quantified. Regeneration patch VR6 in the *S. consimilis* grasslands showed the lowest sapling height in 2018 with little observed browsing by elephant and could have been affected by *S. consimilis* competition. Regeneration patches VR11 and VR15, which disappeared, could have been affected by *Datura* species competition.

In the complete regeneration process seedlings initially measured at 12000 to 4000 seedlings per ha develop into mature woodlands at about 100 trees per ha. At these mature woodland densities,

mortality of more than 97,5% of the initial seedlings and saplings must occur while the regeneration progresses. Without elephants and mesobrowsers this would be a natural self-regulated process of thinning. Elephants and mesobrowsers accelerate this thinning process.

4.5. SUMMARY

4.5.1. ESTABLISHMENT PHASE

The woodlands established over about 35 years after 1970 to what appears to be their peak in about 2005. Five main ecological drivers played a role, as summarised in table 4.5. It is difficult to rank the roles of the main ecological drivers. However, without the removal of the Makuleke people farming would have continued and woodland establishment would not have occurred.

Table 4.4: Ecological drivers that affected the establishment of the monospecific *V. xanthophloea* woodlands

Anthropogenic	Land suitable for the woodland establishment became available after the Makuleke people were removed in September 1969 and farming activity ceased.
Climate	The period from 1969/70 to 1980/81 was above average rainfall and frequent floods which created ideal conditions for woodland establishment.
Elephants	There were very few elephants during the period of woodland establishment and did not negatively impact the establishment.
Mesobrowsers	There were few mesobrowers during the seedling and sapling stage of woodland establishment and did not negatively impact the establishment.
Soils	Soils and associated elevation in the floodplain determined the spatial distribution of the woodlands. Woodlands established on Arcadia soils.
Timeline	With all ecological drivers being favourable, the woodlands would have been expected to reach a mature tree height of at least 10 m by 1980/81.

4.5.2. DECLINE PHASE

The woodlands decline started in about 2005. In the period between 2005 and 2020 mortality of the different woodlands was between 100% and 56% and in the central core of the largest woodland the decline was 22%. The woodland areas reduced. Five main ecological drivers played a role, as summarised in table 4.6. Other observed ecological drivers such wind, fire and insects played a minor role.

Table 4.5 Ecological drivers that affected the decline of the monospecific *V. xanthophloea* woodlands

Anthropogenic	No effect.
Climate	The floods had no detrimental effect. Reduced flood frequency during a period of average but variable rainfall could have contributed to moisture stress induced premature senescence.
Elephants	Elephants were the major ecological driver of woodland decline as the elephant population increased. In 2 woodlands monitored from 2016 to 2020 elephants caused 71% and 63% of the mortality, which is likely to be indicative of all woodlands. Elephant impact prior to 2016 could not be measured.
Mesobrowsers	Porcupine ring barking occurred but was not significant.
Senescence	Moisture stress induced premature senescence occurred, particularly on the Duplex soils on higher floodplain elevation.
Soils	Woodlands on Duplex soils on higher floodplain elevation showed the greatest decline, probably because of moisture stress.
Timeline	The decline commenced in about 2005 and the rate of decline accelerated after 2016.

4.5.3. REGENERATION PHASE

Monospecific regeneration occurred in isolated patches which were separate from the monospecific woodlands. Although some regeneration patches had failed, most had not yet escaped the elephant browse trap and three appeared to be progressing unimpacted (VR1, VR2 and VR8). The main ecological drivers are summarised in table 4.7 together with a comparison of the main ecological drivers that enabled the establishment of the monospecific woodlands after 1970.

Table 4.6: Ecological drivers that affected the regeneration of the monospecific *V. xanthophloea* woodlands and comparison with the conditions after 1970 when the monospecific woodlands established

	AFTER 1970: INITIAL ESTABLISHMENT	AFTER 2013: CURRENT REGENERATION
Anthropogenic	Farming the floodplains prevented establishment before 1970.	No influence.
Climate	Above average rainfall and regular floods for 10 years created ideal conditions for seedling and sapling growth.	The 2013 floods initiated the regeneration. Up to the 2019/2020 season the rainfall conditions were adequate, but no follow up floods occurred to initiate additional regeneration.
Elephants	Elephant population was very low and establishing area large. No browse trap occurred.	Elephant population was high and impacted seedlings and sapling growth through a browse trap.
Mesobrowsers	Mesobrowser population was very low and establishing area large. No browse trap occurred.	Mesobrowser population was high and impacted seedlings. A browse trap on seedlings occurred which some regeneration escaped.
Soils	Large area of optimal Arcadia soils was available, on which the woodlands established.	Only a small area of optimal Arcadia soils was available. Most of the suitable Arcadia soils were occupied by mature woodland.
Area	About 267 ha of woodland established.	The area of regenerating patches in 2018 was 18 ha, although some regeneration patches had already disappeared.
Timeline	Establishment commenced after 1970. After 10 years of ideal conditions trees would have been adult size.	Regeneration commenced after the 2013 floods and by 2020 was about seven years old. Maximum height was 7,5 m, but most saplings were <4 m.
Replacement of declining woodlands		Even if all the regenerating patches progress to mature woodlands, the area would be less than 10% of the area of woodlands that had declined.

5. THE MONOSPECIFIC *FAIDHERBIA ALBIDA* WOODLANDS

5.1. LITERATURE SURVEY

Faidherbia albida (Del.) A. Chev (Mimosaceae), commonly known as the Ana-tree, has been well documented in a monograph and annotated bibliography (Barnes and Fagg, 2003). *Faidherbia albida* occurs as far north as the Negev desert in Israel and is widely distributed in Africa. It occurs right across the Sahelian zone from West to East, up into Sudan, Ethiopia, and Egypt, southwards east of the Rift valley and then across the whole of southern Africa from Mozambique to Angola southwards to Botswana, Namibia and South Africa to a latitude of about 27^{o} S in northern KZN (fig 5.1).

Faidherbia albida's preferred natural habitat is deep alluvial soils and it has a tap root that can penetrate as deep as 40 m to access the ground water. Most characteristically, it colonizes deep sandy clay soils, particularly alluvial deposits along the flood plains of rivers and typically the sand and silt beds on the inside of river bends. It will, however, grow on a wide range of other soils (sand, gravel, clay and fissured laterites) where the soil is free draining to groundwater that the roots can access (Barnes and Fagg, 2003).

Faidherbia albida occurs naturally from 270 m below sea level in Israel to 1860 m asl in Ethiopia (associated with human cultivation) (Barnes and Fagg, 2003) under a very wide range of meteorological conditions. In Namibia it can thrive under desert conditions where the mean annual rainfall (MAR) is only 20 mm and the mean annual daily temperature (MAT) 16.8°C whereas in West Africa it thrives in humid tropical conditions with MAR of 1800 mm and a MAT of 28°C within an absolute range of 0-42°C. Where rainfall is low, the tree is only able to establish and survive if there are episodic events bringing water. Its occurrence is therefore generally limited to watercourses where groundwater is present or to wadis and floodplains where there is residual water in the alluvium following flooding. In the Hoanib and Kuiseb in Namibia the tree grows where the annual rainfall varies between 75 and 20 mm and relies on the groundwater and frequent floods for germination, recruitment and survival (Jacobson, 1997; Ward and Breen, 1983). It grows along the Shashi River between Botswana and Zimbabwe where the annual rainfall is 300 mm. These locations compare with the MCP at 210 m asl and an MAR of 437 mm.

Although *F. albida* grows as a single tree, episodic events can result in a cohort of the same age developing as a monospecific grove. The largest monospecific woodland is in the Jabel Marra drainage system in Sudan where it occurs in belts up to 1,6 kms wide (Barnes and Fagg, 2003).

Faidherbia albida is a fodder for domestic livestock and as such is cultivated in many parts of Africa which has led to improved knowledge of its biology. It is unusual in that it exhibits reverse phenology, shedding its leaves at the start of the rainy season and in full leaf during the dry season (Dunham, 1991). The flowers, leaves and pods are highly palatable and nutritious with approximate median values of crude protein of 190 grammes/kg, 170 grammes /kg and 140 grammes /kg respectively (reported in Barnes and Fagg, 2003) and eaten by a wide range of domestic and wild animals. *Faidherbia albida* trees produce huge quantities of pods starting from about the twelfth year. A single mature tree may yield over 1000 kg of pods in a single season (Palmer and Pitman, 1972). In the Zambesi valley an average of 290 kgs per year per tree was measured in a study of two trees over eight years, after removal of an unquantified amount by baboons (Dunham, 1990).

The reverse phenology plays in important ecological role. In Southern Africa peak flowering occurs in June and July and peak fruiting in October and November. The pods ripen and fall off, or are wind blown off the trees in the late dry season. At this stage it is also in leaf, so the tree is an important source of forage for browsers, when other foliage during the dry season is limited (Dunham, 1990;

Wickens, 1969)). In Sengwa Wildlife Research area, Zimbabwe, the pods are a large portion of the diet of elephants, waterbuck, buffalo, eland, kudu impala and baboons (Guy, 1976), even though waterbuck and buffalo are predominantly considered grazers. Hippos consume the floating pods in the Luvuvhu River, MCP (pers obs). Elephant showed a strong positive selection for *F. albida* in a mixed (*Vachellia tortilis*/*Grewia* species dominated) riparian woodland (Guy, 1976). The reverse phenology also exposes young trees to potentially heavy browsing during the late dry season.

Barnes and Fagg (2003) listed conditions required for the initial stages of a successful regeneration:

1. *Scarification of the hard seed coat*. This is provided by the many animals that consume the pods.
2. *Dissemination of the seed to a suitable environmental niche*. Elephant and buffalo (where they occur) are the main vectors providing this service. The pods float for a few days and dispersal by rivers before consumption by herbivores occurs (pers obs). *Faidherbia albida* is considered a pioneer species and does not regenerate under its own canopy (Barnes and Fagg, 2003).
3. *Sufficient moisture* to allow water to be imbibed by the seed and a temperature over 30^{o}C for germination.
4. *Extension of the roots after germination to a permanent source of moisture in the soil*. The seed germinates within a couple of days if desiccation does not happen. Root growth far outstrips aerial growth. The tap root is reputed to be able to grow at 1 cm a day at seedling stage and up to 5 m in a year (Vandenbeldt, 1991). In comparison height growth of the aerial parts can be up to 5,5 m in three years (Wickens, 1969).
5. *Lack of early competition*, particularly from grasses.
6. *Protection from excess browsing*. Because the leaves are very nutritious, the density of browsing herbivores is an important factor. Once the root system has developed, which can take one to three years if there has been no grass competition, the seedlings and saplings can withstand a considerable amount of browsing and are able to coppice repeatedly and grow fast until they escape for a long enough interval for a shoot to get above the browse line. In Chobe National Park, Botswana, the survival of *F. albida* seedlings in designated plots was negatively related to impala densities and unrelated to densities of other browsers such as elephants and kudu (Moe *et al*., 2009).

Once established the root can penetrate to 40 m and the tree can grow up to 15m in height and 73 cm diameter at breast height in 14 years and 30 m as a fully mature plant (reported in Barnes and Fagg, 2003.)

In the middle Zambesi floodplain (Mana Pools, Zimbabwe) prior to the Kariba Dam, regeneration of *F. albida* was episodic following the creation of bare habitats of alluvial deposits after large floods. Trees could establish on new alluvial deposits where there was reduced competition (reported in Barnes and Fagg, 2003). Construction of Kariba Dam significantly reduced the flooding causing a lack of regeneration of *F. albida* woodlands on the floodplain and old islands in the Zambezi River (Ncube *et al.*, 2012). The unimodal size distribution of established woodlands linked these woodlands to flood periods prior to the building of the dam. *Faidherbia albida* regeneration switched to new river islands created by an altered river morphology and a new lower flood height regime (Gope *et al.,* 2014).

In dry climates episodic events are necessary to provide the moisture required by the seedlings' taproot to reach groundwater and to recharge the alluvial aquifer. Dry season growth relies on

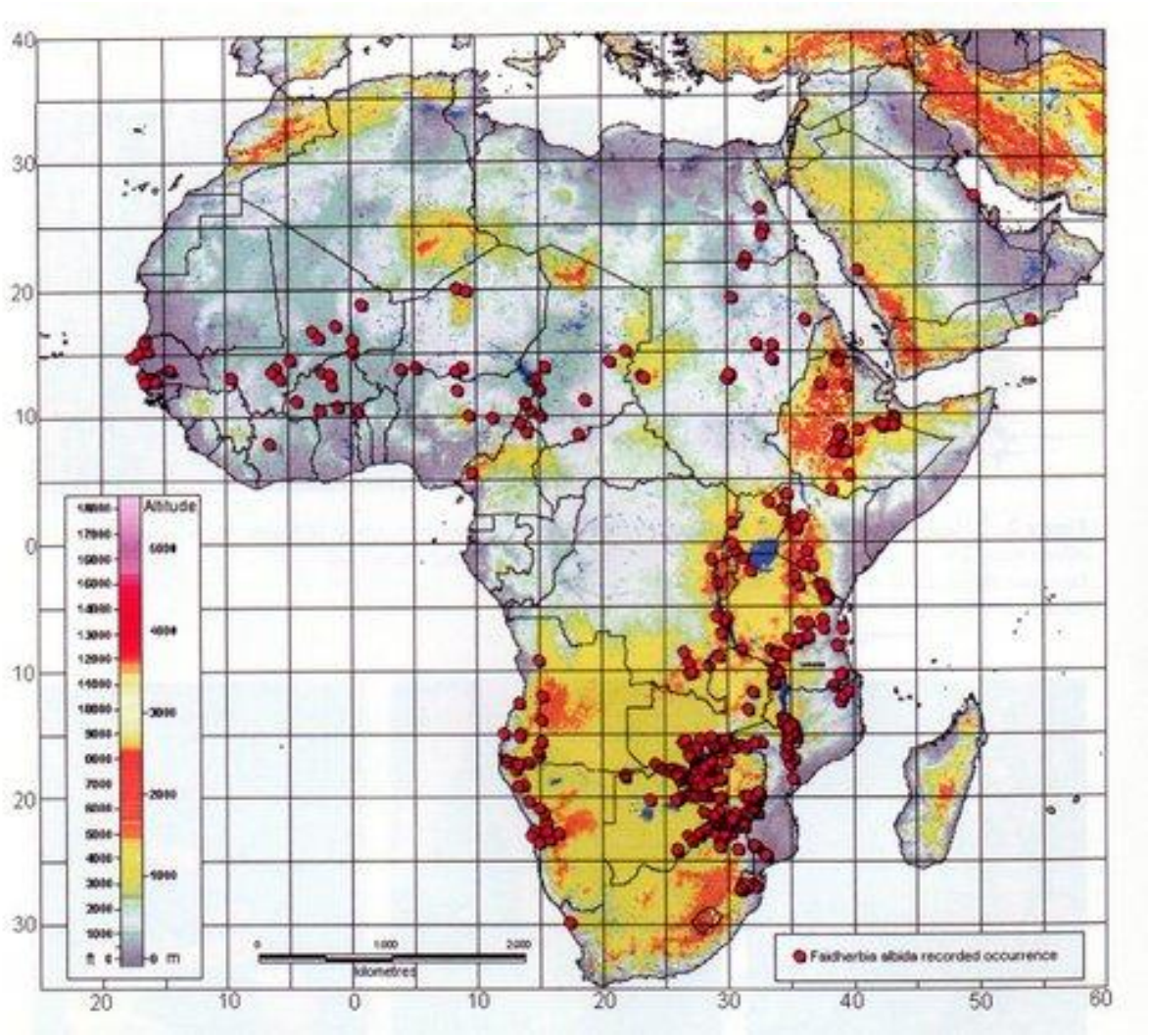


Figure 5.1: Distribution of *F. albida* based on collected herbarium specimens (Barnes and Fagg, 2003).

uptake of water from deep soil layers, making the tree a facultative phreatophyte (Roupsard *et al*., 1999). The tree is reported to reach senescence at about 80–100 years and at diameters of about 200 cm (reported in Barnes and Fagg, 2003). Two trees in the middle Zambezi floodplain were estimated through ring counts at 103 and 84 years old both with a diameter of 52 cm (Gope *et al.*, 2014). The mean diameter of middle Zambezi floodplain trees was 100 cm (range 50 - 120 cm), so it would appear that many trees grow older than 100 years. There are other reports of *F. albida* trees in Zambia over 150 years (Wood, 1989) and of a tree that was noted in Libya by Oundey in 1822, which was still alive in the late 1960s about 150 years later (Wickens, 1969).

Faidherbia albida trees are generally very resistant to attack by fungi, nematodes and termites. Defoliation by caterpillars occurs but the trees recover (reported in Barnes and Fagg, 2003).

There are three major causes of the decline of *F. albida* riparian woodlands reported in the literature (Barnes and Fagg, 2003):

1. *Natural mortality*. Mortality is usually less than 1% per annum in mature woodlands. In Mana Pools National Park in the middle Zambezi floodplain, after the construction of Kariba Dam the loss of canopy trees occurred at a mean rate of 0.9% per year (Dunham, 1989). The deep root system allowed the trees to access groundwater notwithstanding the

reduced, erratic, and out of season artificial flood regime imposed on the floodplain by Kariba hydro-power production schedules.

2. *Browser damage*. For mature trees this is due to elephants by stem snapping and ring barking. Pushover is not a factor. Along the Hoanib River, Namibia, Jacobson (1997) reported no pushover and Dunham (1989) recorded that elephant could not push over healthy *F. albida* in the Zambezi Valley, Zimbabwe. Guy (1976) reported a single *F. albida* tree pushed over out of a total of 74 trees pushed over in a mixed species woodland.
   Stem snapping does occur. Along the Hoanib River, Namibia, elephants caused 30% mortality of *F. albida* by snapping trees up to 400 mm diameter (average 210 mm) (Jacobson, 1997) while Fennessy (2004) recorded 14,8% mortality.
   Generally, once established, *F. albida* exhibits remarkable powers of recovery after browse damage by herbivores. It rapidly produces new foliage after browsing and it responds to de-barking by producing a ridged bole with intact bark in the crevices that an elephant cannot remove with its tusks and which saves the tree from death by complete ring-barking (Barnes and Fagg, 2012). Jacobson (1997) also reported this unusual protection against ring barking. Dunham (1989) recorded occasional trees killed by ring barking. However, in Ruaha National Park in Tanzania in the early 1980's, 40% of the *F. albida* woodland had been killed by elephants (Barnes 1983, 1985) and O'Conner *et al* (2007) reported this from ring barking.

3. *Extreme disturbances*. Examples would be wind, fire, floods and extreme droughts. The reverse phenology, mature tree size, floodplain habitat and low understory in the fire season would suggest fire is unlikely to be a major factor. With its fast growing and deep root system, F. albida is adapted to survive normal flood perturbations. However, extreme flood events, particularly when exacerbated by anthropogenic factors, can inflict significant negative impact. In the 1995 flood of the Hoanib River (Jacobson, 1997), 2,8% of 638 *F. albida* trees ranging from 30 mm to 1900 mm in diameter, were removed by lateral channel erosion and associated removal of riverbanks.

The ability of *F. albida* to grow in areas of very low rainfall and not be affected by drought is due to its deep root system that keeps in touch with permanent moisture zones in the soil rather than to any physiological attribute that might enable it to regulate water use under stress. It is also likely to be one of the survivors in an extended drought. In the drought of 1991/92 in South Africa (the worst on record in the MCP to that date) the Luvuvhu River in the MCP stopped flowing for 14 months (Joubert, 2007). Nevertheless, unpublished data collected by van Coller in 1994 (reported by Botha, 2001) revealed that only 0,5 *F. albida* trees died per km along the riverine zone of the Luvuvhu River compared with 20,8 dead trees per km for *Ficus sycomorus*. However, extreme droughts can take their toll. In the anthropogenically induced drought conditions when the ephemeral Swartkops River in Namibia was dammed, 51% mortality of *F. albida* in the downstream riparian zone occurred (Douglas *et al*., 2016). In the early 1980's four years without flow in the lower ephemeral Kuiseb River (following at least 17 years of annual flows) triggered a considerable number of deaths in large *F. albida* trees (Ward and Breen, 1983). In the Greefswald forest of Mapungubwe National Park 37% of *F. albida* trees (as well as other canopy trees) died between 1990 and 2007 through a combination of drought, water abstraction (which lowered the water table) and creeper induced stress (O'Connor, 2010).

5.2. METHODS

Different methods were necessary for the different phases and are detailed separately. Observations formed an important part of the information gathered.

5.2.1. ESTABLISHMENT PHASE

The establishment of the monospecific *F. albida* woodlands is defined as the process which culminates with the existence of mature woodlands and before senescence and tree mortality commence. This process was the achievement of stage 5 of the demographic bottleneck model (fig 2.1).

Faidherbia albida occurred in the study site in three different population structures:

- on the Luvuvhu River floodplain as single trees or clumps of up to 5 trees within mixed riverine woodland;
- on the Luvuvhu River floodplain as separate monospecific *F. albida* woodlands;
- on the Limpopo River floodplain as single trees or clumps of up to 5 trees within mixed riverine woodland, but not as separate monospecific *F. albida* woodlands.

Monospecific woodlands were defined as woodlands consisting exclusively of *F. albida* as large trees (the majority greater than 10 m in height) and an understorey of bare soil, grass and/or shrubs or trees (of other species) of less than one third of the height of the *F. albida* trees.

Identification and selection of monospecific woodlands. Monospecific woodlands that existed in 2016 were identified through a combination of ground surveys and GE imagery for 2016. Ground surveys confirmed the monospecific character of the woodlands, and the same woodlands were then identified on GE imagery and aerial photographs going as far back as 1942 (by using shade differences). Woodlands in the floodplain on both sides of the Luvuvhu River were included. Ground surveys of woodlands south of the Luvuvhu River (in KNP) were conducted remotely from the northern bank using Swarovski 10x42 binoculars. One monospecific woodland was south of the Luvuvhu River (in KNP) before 2000 but was removed by the 2000 flood. Its existence before 2000 was confirmed by the Section Ranger (Scott Ronaldson, pers comm). This woodland was identified on aerial photographs.

Nine monospecific woodlands were identified (table 5.1 and fig 3.4). They ranged in area from 2,5 ha to 35 ha and represented all woodlands greater than 2,5 ha. Woodlands FW1, FW4 (in the period before 2000) and FW8 were in KNP on the south side of the Luvuvhu River. Woodlands FW2, FW4 (in the period after 2000) FW5, FW6, FW7, FW9 and FW10 were on the north side of the Luvuvhu River in the MCP. (There was no woodland FW3).

Aerial photography and GE imagery. Aerial photographs and GE imagery were used to follow the temporal changes from 1942. Aerial photographs were available for 1942, 1963, 1970, 1987, 1987, 1991, 1994, 1996, 1999, 2000 and 2004 (Surveyor General, Mowbray, Cape Town). The quality of resolution varied which affected which photographs were used. GE imagery of acceptable resolution was available for 2005, 2006, 2007, 2010, 2012, 2013, 2017, 2018 and 2019. The commencement of establishment of each woodland was determined as during the period between the date of one photograph showing the woodland location unvegetated and the next photograph showing the woodland location vegetated.

Woodland demographics. Specific demographic parameters measured were woodland area, tree density, heights and diameters. Demographic data in 2016 was obtained for whole woodlands or sample patches within the woodlands. Table 5.1 summarises the structure of the sampling. The

location of sample patches within woodlands FW5 and FW6 were selected on a visual assessment that they were demographically representative of the whole woodlands. Woodlands in KNP south of the Luvuvhu River were not sampled.

The heights of individual trees in the woodlands were determined by photographing a 2 m measuring stick against a tree and scaling the tree height on the photograph with an adjustment for photographic angle. It was difficult to isolate individual trees and woodland tree heights were determined from a few samples where the same height was given to several closely adjacent trees. This difficulty can be appreciated by looking at fig 5.8. Stem diameter at breast height (DBH) was determined by measuring the trunk circumference at 1,3 m above ground level and converting to diameter. Several *F. albida* trees in the mixed riverine woodland (MRW) between the bridge and Crooks Corner were measured for comparison as these MRW trees were probably the oldest *F. albida* trees in the MCP. A one -way ANOVA analysis (using the Excel single factor ANOVA program) was performed on the diameters of woodlands FW5, FW6 and FW7. The woodlands constituted the treatments and the stem diameters the responses. The null hypothesis was that the populations of each of the woodlands did not differ in stem diameter (measured as DBH).

The areas of established woodlands were determined using the area calculation function of GE or of a Garmin GPSMap 62s by walking the boundary of the woodland. Woodland densities could not be determined from aerial photography or GE imagery due to some overlapping of canopies and inadequate level of aerial photographic or GE imagery resolution. Woodland density determinations were made from a physical count of all the trees in a woodland or woodland patch. Densities were not determined for woodlands FW2 (due to major flood damage) or FW7 (due to an airstrip constructed in 1970 through the woodland). The density of woodland FW10 was affected by the floods of 2000 and 2013 which removed a few trees. Soil forms of the individual woodlands were identified with the assistance of Dr G. Nortje.

DECLINE PHASE

Woodland decline is defined as a population phenomenon of the death of adult trees leading to a reduction in density and/or area. This is a reduction in the number of trees is stage 5 of the demographic bottleneck model (fig 2.1).

A series of aerial photographs from 1942 to 1999 (Surveyor General, Mowbray, Cape Town) and GE imagery from 2005 to 2018 were used to identify temporal changes, particularly the removal of portions of the monospecific *F. albida* woodlands by the floods. These photographs and imagery were used to define five periods which included two flood events:

1. The period 1942 to 1999.
2. The period 1999 to 2000 (before and after February 2000, the date of the largest recorded flood).
3. The period 2000 to 2012 (between the floods of 2000 and 2013).
4. The period 2012 to 2013 (before and after January 2013, the date of a large flood, particularly the Luvuvhu River).
5. The period 2013 to 2018.

The aerial photographs and GE imagery were used to produce comparative maps of the Luvuvhu River from Mangala to Crooks Corner for 1942, 1999, 2000 (individual photographs were digitally stitched together by Roussel, 2016), 2012, 2013 and 2018. Areas of mixed riverine woodland and monospecific *F. albida* woodland removed by the floods were determined by using the area

calculation function of GE or of a Garmin GPS 62s by walking the boundary. Changes in the width of the Luvuvhu River channel were determined from aerial photographs and GE imagery using the bridge as a fixed length reference.

Tree mortality caused by elephants was identified as trees pushed over or trees snapped off at about 1 m above ground level. Although not commonly reported in the literature, an elephant's ability to push over trees was confirmed by a personal observation of a 500 mm diameter *F. albida* tree being pushed over. The ability of elephants to snap *F. albida* trees up to 640 mm in diameter was reported along the Hoanib River, Namibia (Jacobson, 1997).

Elephant bark stripping was surveyed by measuring the percentage of the trunk circumference where bark had been removed (Botha *et al*., 2002) of trees within a patch of woodland FW6.

Table 5.1: Structure of the sampling of the *F. albida* woodlands

ID	WOODLAND NAME	NUMBER OF TREES COUNTED IN 2016	WHOLE WOODLAND COUNTED	SAMPLE PATCH IN WOODLAND COUNTED	WOODLAND AREA SQ M	SAMPLE PATCH AREA SQ M	NO OF TREES SAMPLED FOR HEIGHT	NO OF TREES SAMPLED FOR DBH	COMMENT
FW1	MANGALA SOUTH	NO COUNT					NIL	NIL	IN KNP. NOT COUNTED OR SAMPLED.
FW2	MANGALA	NO COUNT					16	20	MAJOR DAMAGE CAUSED BY BY 2000 AND 2013 FLOODS.
FW4	ISLAND	108	YES		28000		108	99	
FW5	MAIN	50	NO	YES	220000	8036	6	29	
FW6	MALETENI	65	NO	YES	140000	9970	10	56	
FW7	AIRSTRIP	NO COUNT					10	19	MAJOR DAMAGE CAUSED BY CONSTRUCTION OF AIRSTRIP.
FW8	TRAILS CAMP SOUTH	NO COUNT					NIL	NIL	IN KNP. NOT COUNTED OR SAMPLED.
FW9	GWALALA	68	YES		30000		10	18	
FW10	LUVUVHU CAMP	74	YES		23500		14	12	SOME TREES REMOVED BY 2000 AND 2013 FLOODS.
MRW	MIXED RIVERINE						5	27	INDIVIDUAL TREES IN MIXED RIVERINE WOODLAND.

TREES SAMPLED FOR HEIGHT AND DIAMETER WERE SELECTED RANDOMLY FROM WITHIN THE WOODLAND OR WOODLAND PATCH.

5.2.2. REGENERATION PHASE

Seedlings were classified as 0-500 mm in height and saplings as 500-6000 mm but subdivided into 500-1000 mm, 1000-2000 mm and 2000-6000 mm for convenience when a specific height range characterised a regeneration area. Trees were defined as >6 m height.

Regeneration was identified by the existence of *F. albida* seedlings or saplings in a monospecific stand at a density that when mature tree heights are reached (above 15 m) would create a monospecific woodland with a density of at least 60 trees per ha (the density of woodland FW5).

Regenerating areas with *F. albida* seedlings and saplings were observed in the section between Mangala and the bridge near woodlands FW2, FW4, FW5 and FW8 (fig 3.4). Where seedlings and saplings occurred, they generally exceeded the density criterion, and no farther selection process was necessary (fig 5.14 as typical). Individual seedlings and saplings also occurred at very low density on the verges of the flood widened river channel and were excluded from the study.

Ground surveys identified five separate regenerating areas, with sampling design shown in table 5.2. Areas were designated FR and the numbering correlates with the numbering of the closest monospecific woodland (as shown in table 5.1 and fig 3.4) and is not sequentially continuous. Areas were allocated to two groups as explained below:

1. Two Groups: Group 1 consisted of four areas (FR3, FR4, FR5, FR8) within 1 km of each other (fig 3.4).
   Group 2 consisted of 1 area (FR2) located at Mangala 3 kms from group 1 (fig 3.4). This group/area met the density criterion if other regenerating species were included. It was the largest area of monospecific woodland removed by floods and available for regeneration.
2. Five Areas: Five larger areas within the two groups with defined boundaries within which seedlings and saplings existed. These were areas FR2, FR3, FR4, FR5 and FR8.
3. Six Patches: A patch was a smaller sampling section within an area. Patch size depended on local factors and could not be standardised. They were designated as sub-areas FR2A, FR3A, FR4A, FR4C, FR5A and FR8A (fig 5.2 and 5.3).
4. Two Transects: A transect was a smaller (2 m wide) sampling section within an area. Transect length depended on local factors and could not be standardised. They were designated as sub-areas FR3B and FR4B (fig 5.2).

The areas, patches and transects are shown for group 1 (fig 5.2) and group 2 (fig 5.3). They cover a range of conditions under which regeneration was taking place. Parameters of size, soil form, elevation above river level, distance from the river and degree of openness relevant to adjacent mature woodlands were recorded. Shapes and sizes of the sampling patches and transects were determined by local spatial configurations and not standardised.

Regeneration was studied by counting all seedlings and/or saplings in the patches and transects. For each group 1 sample patch every seedling or sapling was tagged with conventional garden plant labels in 2016, to identify temporal changes or any new (post tagging) regeneration. However, many of these labels disappeared for miscellaneous reasons which reduced the value of this technique. Thereafter all seedlings and saplings were counted, tagged or not, and seedlings and saplings with tags were counted separately to extract data where possible. For the Oxbow patch (FR3A) tags on several of the larger saplings survived and allowed tracking of these saplings.

The extent of browsing of individual seedlings and saplings was estimated from nil to 100% by visual assessment of the number of shoots browsed. 100% browsed was recorded if all shoots were browsed (as often happened with small seedlings) or the main stem was snapped or browsed off. Diameters of the browsed stems were measured with a calliper. Mesobrowser impact on seedlings was identified as shoots and stems up to 7 mm diameter browsed. Porcupine impact was identified by porcupine excavations and accompanying stem or root gnawed off at or below ground level at diameters up to 25 mm. Broken branches and main stem and any breakages greater than 7mm diameter was attributed to elephants.

Camera traps: Camera traps were used to determine which animal species were impacting the regeneration. Camera traps were Bushnell Trophy CamHD (model 119598) with 24 hr photographic capability. The number of camera traps available was limited and camera traps were allocated to monitoring both *V. xanthophloea* and *F. albida* woodlands, restricting the use in each woodland species. Positioning was governed by the availability of suitable camera trap mounting structures. Camera traps were removed by baboons, chewed by hyenas, waterlogged by rain, repositioned by elephants, and rendered inoperable due to flat batteries, so that recording at all patches was not simultaneous or for the same length of time. The range specification of the camera traps was 30 m with a recording trigger gap of ten seconds. A total of 797 days of camera trap recordings were spread across patches FR3A, FR4A, FR4C, FR5A and FR8A and covered all seasons.

For the above reasons, no meaningful statistical analysis of camera trap recordings could be done. The value of the camera traps was in determining the relative frequency of the different browsers that visited the areas that were within the range of the camera traps, which was assumed to be representative of the whole regeneration patch where the camera trap was positioned. A statistic of animal species visits per day was calculated. An animal visit was defined as one or a group of the same species captured on the camera trap. For a period of ten minutes from the initial capture any farther capture of what appeared to be the same animal or group was considered the same visit. A new visit was assumed after ten minutes. The camera traps provided an estimate as to which species visited the regeneration patches where cameras were installed and whether browsing occurred. For the three most frequent browser species the visits per day were adjusted by the average number of that species per visit as recorded by the camera traps. This was used to determine a relative abundance of the different browsers. Actual browsing activity was only occasionally captured, but impala and elephant feeding methods on seedlings and saplings were observed.

Point photographs. Point photographs were used to monitor temporal changes.

Table 5.2: Luvuvhu floodplain *F. albida* regeneration areas, patches and transects in June 2016

AREA ID	AREA NAME	AREA AVAILABLE FOR REGEN Sq meters	PATCH, TRANSECT ID	PATCH SAMPLED	TRANSECT SAMPLED	CAMERA TRAP	PATCH SIZE Sq meters	INITIAL DENSITY per ha	SOIL FORM	ELEVATION ABOVE RIVER meters	DISTANCE FROM RIVER meters	POSITION
GROUP 1												
FR3	OXBOW	30000										
			FR3A	YES		YES	2986	476	Dundee	2 to 3	200	Sample patch in the middle of Oxbow area. Old river channel.
			FR3B		YES		2104	727	Dundee	2 to 3	0-200	Two transects along the length of Oxbow area. Old river channel.
FR4	FR4	35000										
			FR4A	YES		YES	495	3636	Oakleaf	4	50	Sample patch in the middle of FW4 in an open section.
			FR4B		YES		314	2293	Oakleaf	4	50	Transect in the middle of FW4 in an open section.
			FR4C	YES		YES	735	122	Oakleaf	4	100	Sample patch in the middle of FW4 in a semi-open section.
FR5	MAIN	1000										
			FR5A	YES		YES	517	1567	Oakleaf	4	200	Small open area in the middle of FW5 area woodland.
FR8	TRAILS	15000										
			FR8A	YES		YES	1325	1064	Dundee	2 to 3	100	Sample patch near FW8 area, on the inner bend, north bank of the river.
GROUP 2												
FR2	MANGALA	155000										
			FR2A	YES			41 433	33	Oakleaf	2 to 4	0-250	Sample patch in the middle of FW2 area. Topsoil removed by flood.
	TOTAL	236000 (23,6 ha)										
	NOTE:	AREA AVAILABLE FOR REGEN REFERS TO THE APPROXIMATE AREA OF F. ALBIDA WOODLAND REMOVED BY THE FLOODS AND WHERE REGENERATION WAS OCCURRING.										

Figure 5.2: Group 1 sample patches FR3A, FR4A, FR4C, FR5A, FR8A and transects FR3B and FR4B. Google Earth image 2018.

Figure 5.3: Group 2 sample patch FR2A. Google Earth image 2013.

5.3. RESULTS

5.3.1. ESTABLISHMENT PHASE

The aerial photographs and Google Earth imagery show that there were four separate periods when the monospecific *F. albida* woodlands established in the Luvuvhu floodplain. These woodlands covered about 125 ha. Table 5.3 shows the existence of established woodlands at specific dates from which woodland establishment periods were inferred.

Table 5.3: The existence of established *F. albida* woodlands from aerial photography and GE imagery on different dates

WOODLAND	WOODLAND NUMBER	AREA HA	1942	1970	1977	1987	1999	2000	2013	2018	
MANGALA SOUTH	FW1	25	YES	YES	YES	YES	YES	PARTIAL	PARTIAL	PARTIAL	
MANGALA	FW2	35	YES	YES	YES	YES	YES	PARTIAL	PARTIAL	PARTIAL	
ISLAND	FW4	7	YES	YES	YES	YES	YES	NO	YES	YES	NOTE 1
MAIN	FW5	22	NO	NO	?	YES	YES	YES	YES	YES	
MALETENI	FW6	14	NO	NO	?	YES	YES	YES	YES	YES	
AIRSTRIP	FW7	5	NO	NO	?	YES	YES	YES	YES	YES	
TRAILS CAMP	FW8	12	YES	YES	YES	YES	YES	PARTIAL	PARTIAL	PARTIAL	
GWALALA	FW9	3	YES	YES	YES	YES	YES	YES	YES	YES	
LUVUVHU CAMP	FW10	2,5	NO	NO	NO	YES	YES	PARTIAL	PARTIAL	PARTIAL	
		125,5									
LARGE FLOODS								FEB 2000	JAN 2013		

NO	WOODLAND DID NOT EXIST ON THIS DATE.
YES	MATURE WOODLAND EXISTED ON THIS DATE.
PARTIAL	ONLY PART OF THE ORIGINAL WOODLAND REMAINED ON THIS DATE. PORTON WAS REMOVED BY THE FLOODS OF 2000 AND 2013.
?	AERIAL PHOTOGRAPHS RESOLUTION NOT ADEQUATE
NOTE 1	WOODLAND FW4 WAS REMOVED BY THE FLOOD IN 2000 AND SUBSEQUENTLY A SMALLER WOODLAND RE-ESTABLISHED.

Establishment before 1942. Five mature woodlands existed in 1942 (FW1, FW2, FW4, FW8 and FW9) (fig 5.4). The total area was about 82 ha. These woodlands are in the floodplain close to the river. Three of these woodlands (FW1, FW4 and FW8) were in KNP south of the Luvuvhu River and two (FW2 and FW9) were north of the Luvuvhu River.

Establishment after 1970. Three woodlands established after 1970 (FW5, FW6, and FW7). The total area was about 41 ha. The series of aerial photos over the period 1942 to 2017 (fig 5.5) shows the establishment of woodlands FW5, FW6 and FW7 in the period between 1970 and 1987. They were dense woodlands in 1999 and thinned by 2004. These woodlands are in the Hutwini/Maleteni section of the floodplain up to 1 km from the river.

Establishment after 1977. Woodland FW10 established after 1977. The area was about 2,5 ha. The series of aerial photos over the period 1942 to 2004 (fig 5.6) show a change in the course of the river created a barren riverbank by 1977 where woodland FW10 subsequently established between 1977 and 1987 and was dense by 1999.

Establishment after 2000. Woodland FW4 (originally 7 ha) was a mature woodland in 1942 on the south side of the Luvuvhu River. The sequence of aerial photographs from 1942 to 2017 (fig 5.7) show woodland FW4 was removed by the flood of 2000 when the position of the river channel changed. A smaller woodland (2,8 ha) re-established after 2000 on portion of the area of the original woodland, which was now on the north side of the Luvuvhu River (in the MCP). A small portion of this re-established woodland was removed by the 2013 floods, but establishment continued. No evidence existed that any other *F. albida* woodlands established after 2000. If this occurred, the woodlands were removed by the 2013 floods.

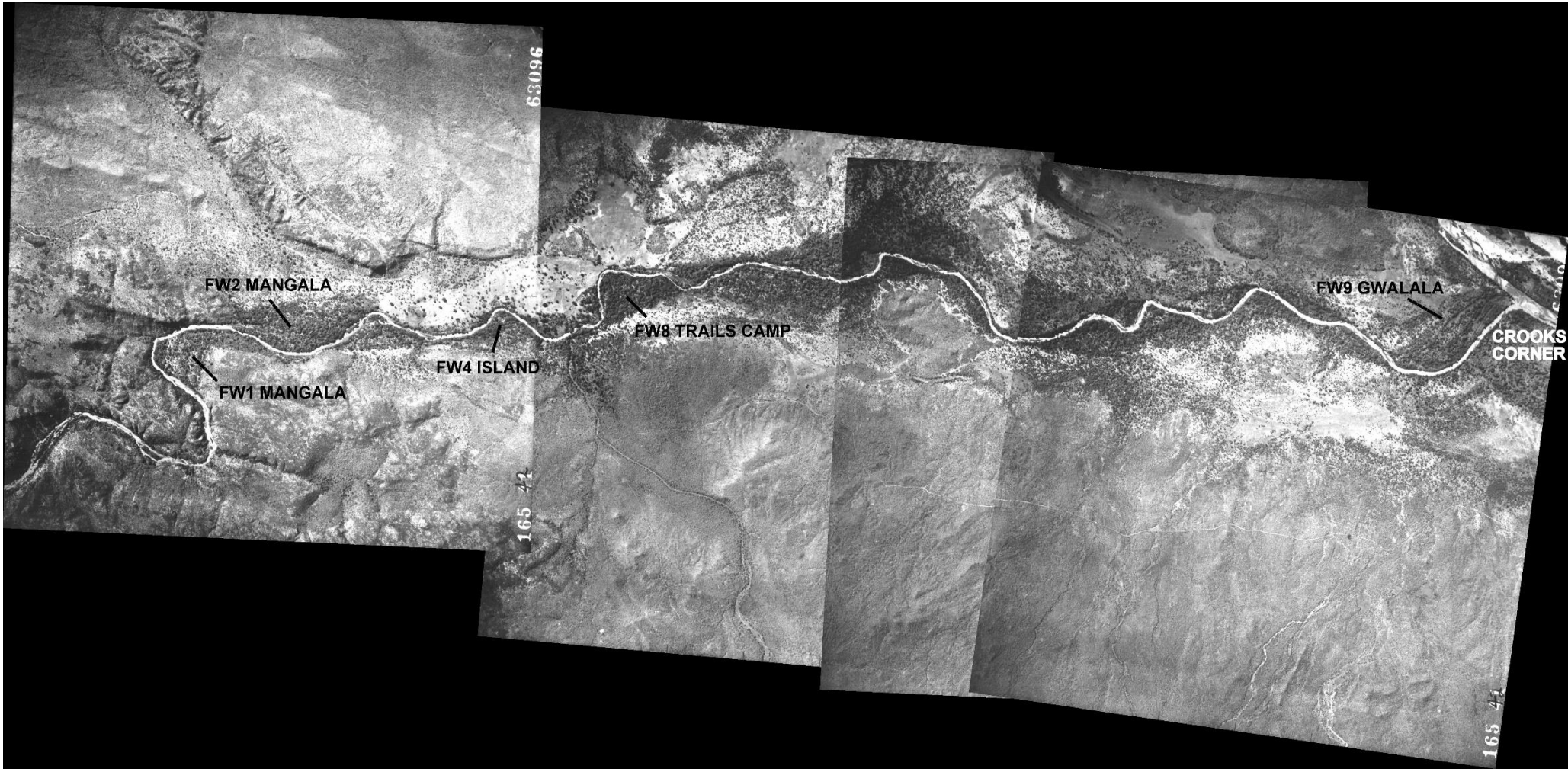


Figure 5.4: The position of *F.albida* woodlands FW1, FW2, FW4, FW8 and FW9 shown on the 1942 aerial photograph. Woodlands FW1, FW4 and FW8 are on the south bank of the Luvuvhu River. Woodlands FW2 and FW9 are on the north bank of the Luvuvhu River.

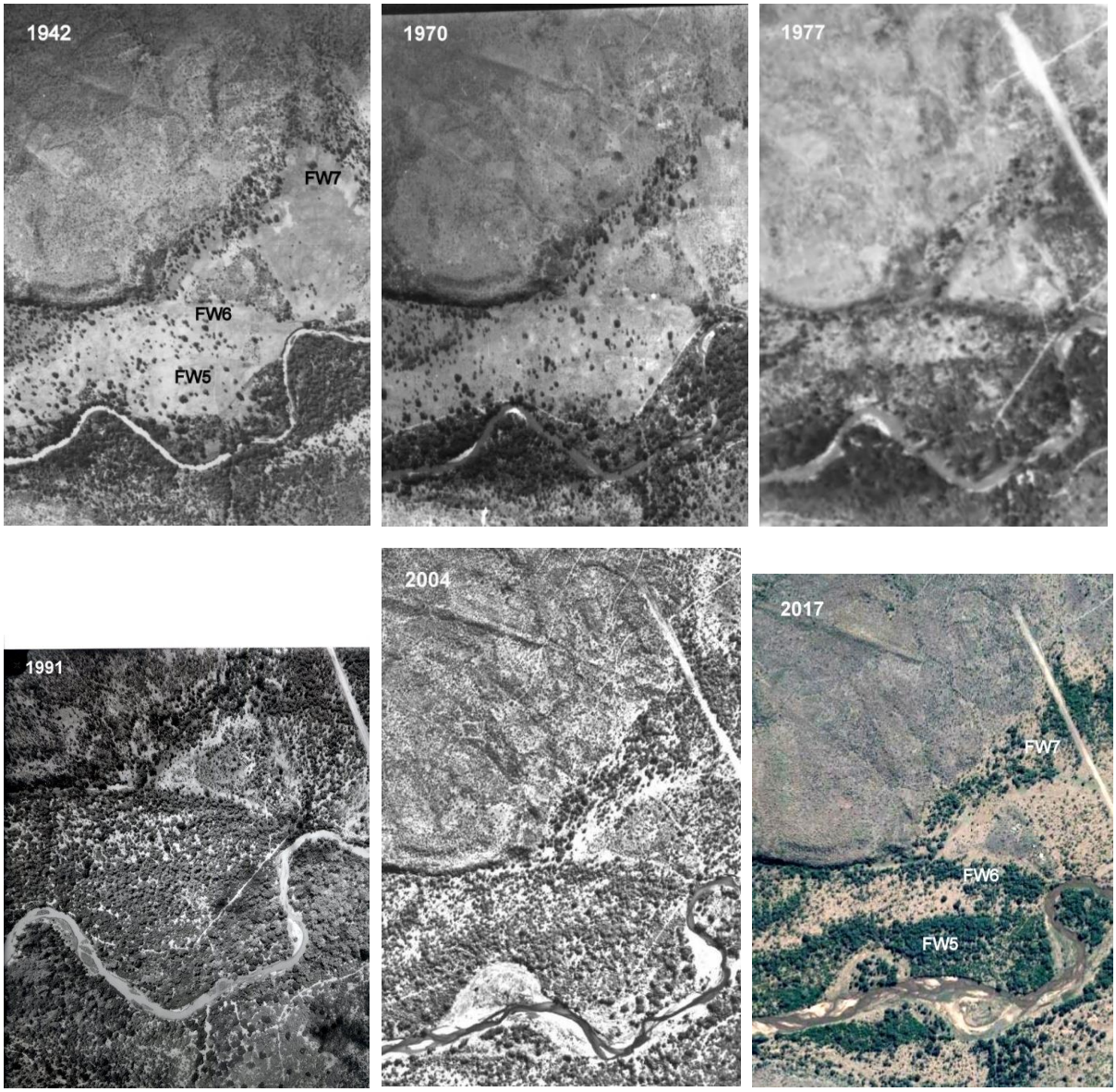


Figure 5.5: The establishment of *F. albida* woodlands FW5, FW6 and FW7 in the Hutwini/Maleteni section of the Luvuvhu floodplain shown on aerial photographs from 1942 to 2017 (top left to right, bottom left to right). No woodlands existed in the aerial photographs of 1942 and 1970 because the area was farmed by the Makuleke people until their removal in September 1969. Woodlands established after 1970 in these farmed areas. A few large trees in the farmed areas were not removed, at least one of which existed in 2020. The *F. albida* woodlands are clearly visible in the GE imagery of 2017.

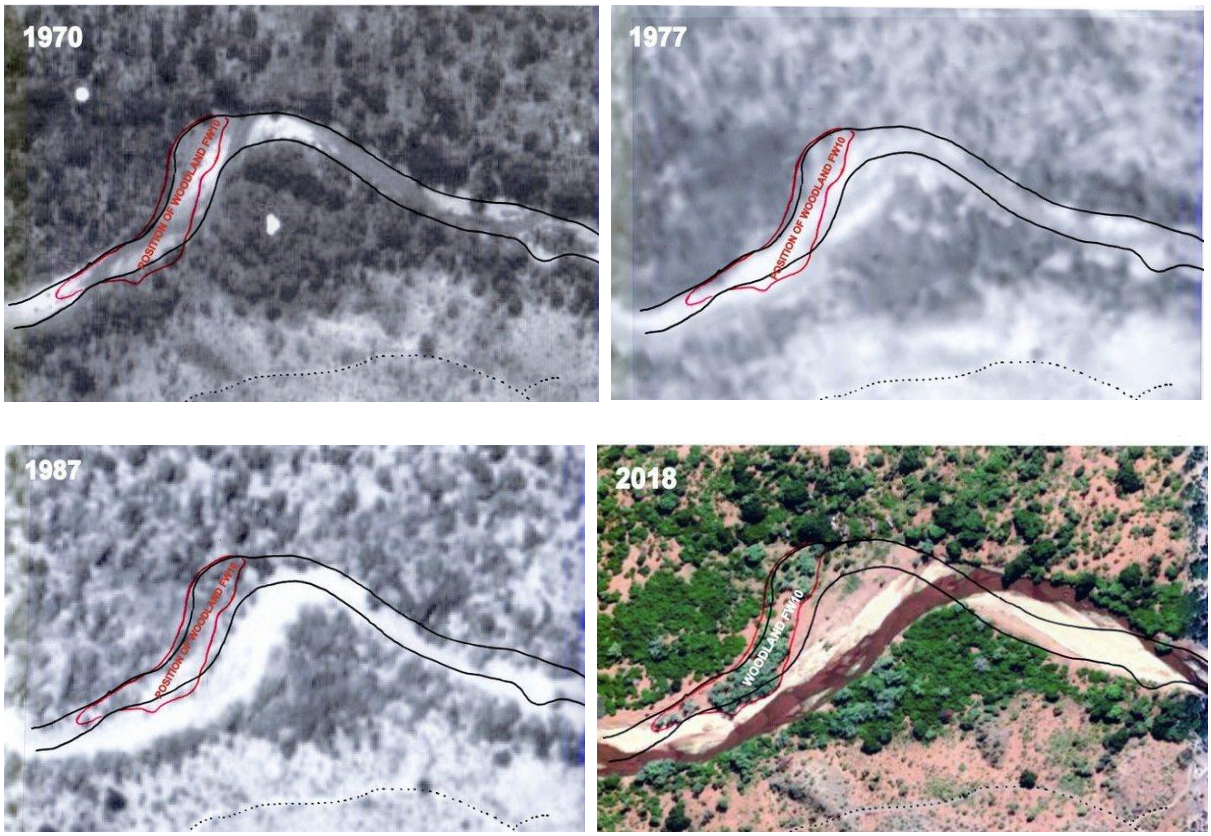


Figure 5.6: The establishment of *F. albida* woodland FW10 after 1977 on the north bank of the Luvuvhu River after the channel changed. The position of the river in 1970 is shown by black lines. The position of the woodland is shown within the red line. The woodland had established by 1987.

For all the different woodlands, photographs from a distance showed even height distributions of tall woodlands with low understorey (fig 5.8 shows 2 examples). The heights and diameters of the woodlands are shown in the box and whisker charts of fig 5.9 and show narrow unimodal distributions for all woodlands except FW4. Woodland FW4 had a bimodal distribution with 19% of trees smaller (average height 6,3 m and DBH 130 mm) and 81% larger (average height 17,5 m and DBH 483 mm). The smaller trees occurred on the northwest edge of the woodland. Overall, the smaller trees in FW4 are less than 1% of the trees that established after 1970. The taller trees of FW4 and all other woodlands had narrow unimodal height and DBH distributions with a standard deviation of <30% of average DBH. DBH was used to compare woodlands FW5, FW6 and FW7, which from aerial photographs established after 1970. A one-way ANOVA on the three woodlands showed that the null hypothesis that the population in each of the woodlands did not differ in stem diameter (measured as DBH) should be rejected (F(2,100)=27,5; p=3,0E-10) (Appendix 2).

Densities for woodlands FW4, FW5, FW6, FW9 and FW10 ranged from 31 to 64 trees per ha (table 5.4). All woodlands established on Oakleaf or Dundee soils (table 5.4).

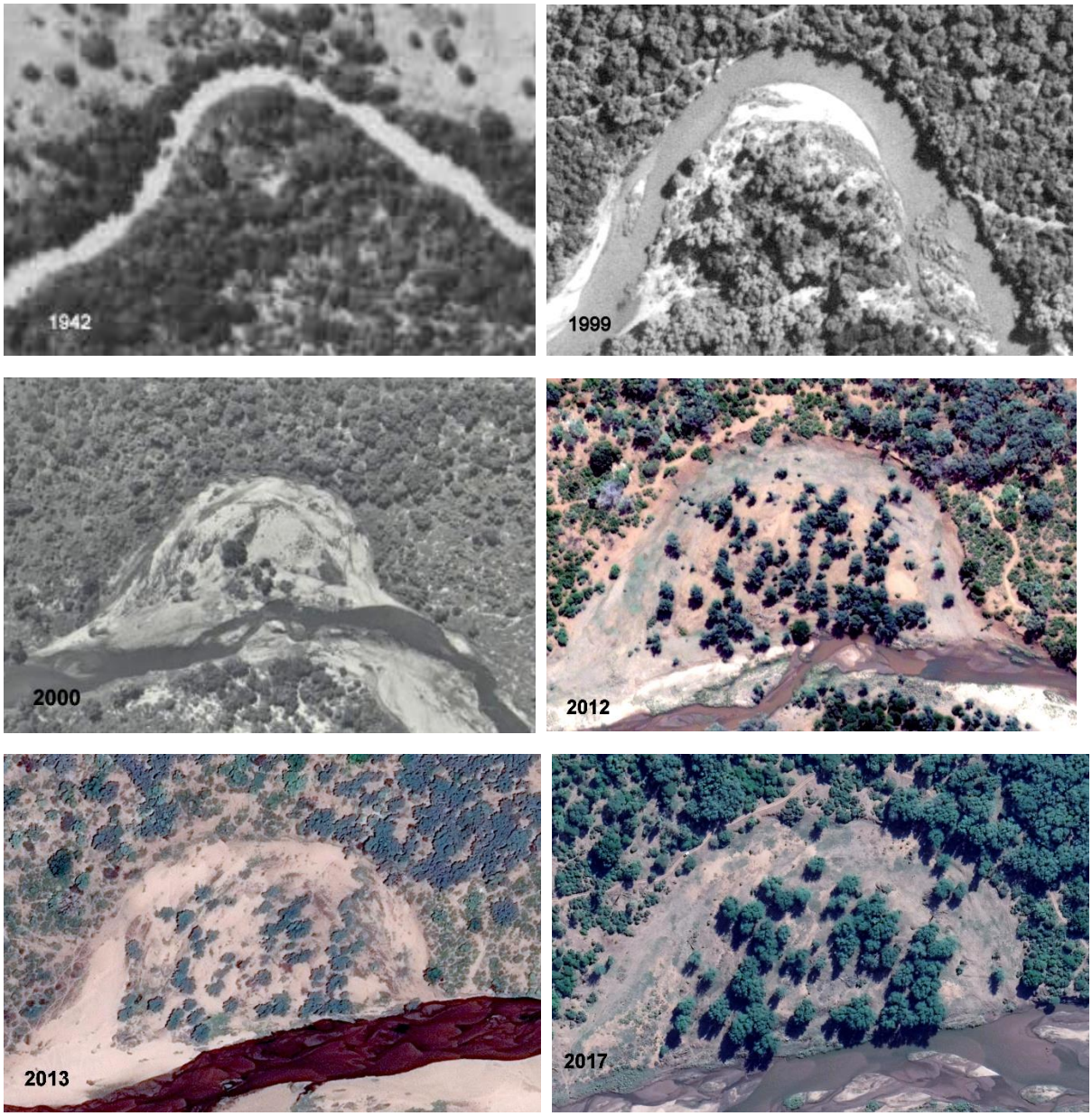


Figure 5.7: The establishment of *F. albida* woodland FW4 on the north bank of the Luvuvhu River (in the MCP) after the floods of 2000 changed the river course and removed the original woodland which was on the south bank. The flood of 2013 caused minor mortality, seen by comparing the GE imagery of 2012 and 2013.

Table 5.4: Parameters associated with the establishment of the *F. albida* woodlands

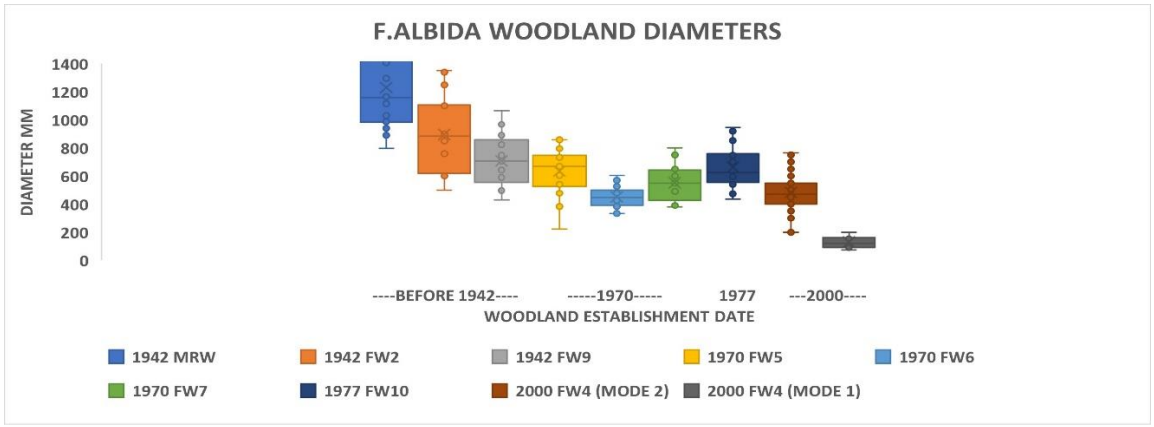
ID	WOODLAND NAME	DATE OF ESTABLISHMENT	SIZE HA	DENSITY PER HA	SOIL FORM	DISTANCE FROM RIVER METERS	ELEVATION ABOVE RIVER METERS	OTHER PARAMETERS
FW1	MANGALA SOUTH*	BEFORE 1942	25	ND	OAKLEAF	0-300	3 TO 4	RIVER PERENNIAL . PROBABLY PERIOD OF FREQUENT FLOODS. ON INNER BEND OF RIVER.
FW2	MANGALA	BEFORE 1942	35	ND	OAKLEAF	0-350	3 TO 4	RIVER PERENNIAL . PROBABLY PERIOD OF FREQUENT FLOODS. ON FLOODPLAIN EXTENDING AWAY FROM RIVER.
FW4	ISLAND*	BEFORE 1942	7	ND	OAKLEAF	0-150	3 TO 4	RIVER PERENNIAL . PROBABLY PERIOD OF FREQUENT FLOODS. ON INNER BEND OF RIVER.
	ISLAND	AFTER 2000	2,8	39	OAKLEAF	0-150	3 TO 4	PERIOD OF LESS FREQUENT FLOODS. FLOOD IN 2013. ADJACENT TO RIVER ON PORTION OF ORIGINAL FW4 WOODLAND.
FW5	MAIN	AFTER 1969	22	62	OAKLEAF	200-300	3 TO 4	DECADE OF FREQUENT FLOODS AND ABOVE AVERAGE RAINFALL. ON FLOODPLAIN AWAY FROM RIVER.
FW6	MALETENI	AFTER 1969	14	64	OAKLEAF	200-600	3 TO 4	DECADE OF FREQUENT FLOODS AND ABOVE AVERAGE RAINFALL. ON FLOODPLAIN AWAY FROM RIVER.
FW7	AIRSTRIP	AFTER 1969	5	ND	OAKLEAF	600-1000	4 TO 8	DECADE OF FREQUENT FLOODS AND ABOVE AVERAGE RAINFALL. ON FLOODPLAIN AWAY FROM RIVER.
FW8	TRAILS CAMP*	BEFORE 1942	12	ND	OAKLEAF	0-200	3 TO 4	RIVER PERENNIAL . PROBABLY PERIOD OF FREQUENT FLOODS. ON INNER BEND OF RIVER.
FW9	GWALALA	BEFORE 1942	3	47	OAKLEAF	200-300	3 TO 4	RIVER PERENNIAL . PROBABLY PERIOD OF FREQUENT FLOODS. ON FLOODPLAIN AWAY FROM RIVER. ADJACENT TO RIVERINE WOODLAND.
FW10	LUVUVHU CAMP	AFTER 1977	2,5	31	DUNDEE	0-100	3 TO 4	5 YEARS OF FREQUENT FLOODS AND ABOVE AVERAGE RAINFALL. INNER BEND OF RIVER. DENSITY REDUCED BY 2000 AND 2013 FLOODS.
	TOTAL		125,5					

* DENOTES WOODLAND ON THE SOUTH BANK OF THE LUVUVHU RIVER. AREA FROM GE IMAGERY

WOODLAND ESTABLISHED BEFORE 1942	82	
WOODLAND ESTABLISHED AFTER 1969	41	
WOODLAND ESTABLISHED AFTER 1977	2,5	
	125,5	
WOODLAND REMOVED IN 2000 AND 2013	34	OF WHICH 23,6 HA WAS IN THE MCP.
WOODLAND ESTABLISHED AFTER 2000 (FW4)	2,8	

DENSITIES WERE NOT DETERMINED FOR WOODLANDS ON THE SOUTH BANK OF THE LUVUVHU RIVER OR WHERE WOODLAND WAS REMOVED BY FLOODS OR AIRSTRP CONSTRUCTION.

Figure 5.8: *F. albida* woodlands FW4 (left) in 2010 after 10 years growth and FW6 (right) in 2017 after 47 years growth. The even height of cohorts and the monospecific character can be seen. The reverse phenology is demonstrated by the green foliage of FW4 in winter and leafless trees of FW6 in summer. The understorey of FW4 is *Urochloa mosambicensis*. The understory of FW6 is *Croton megalobotrys* and *U. mosambicensis*.



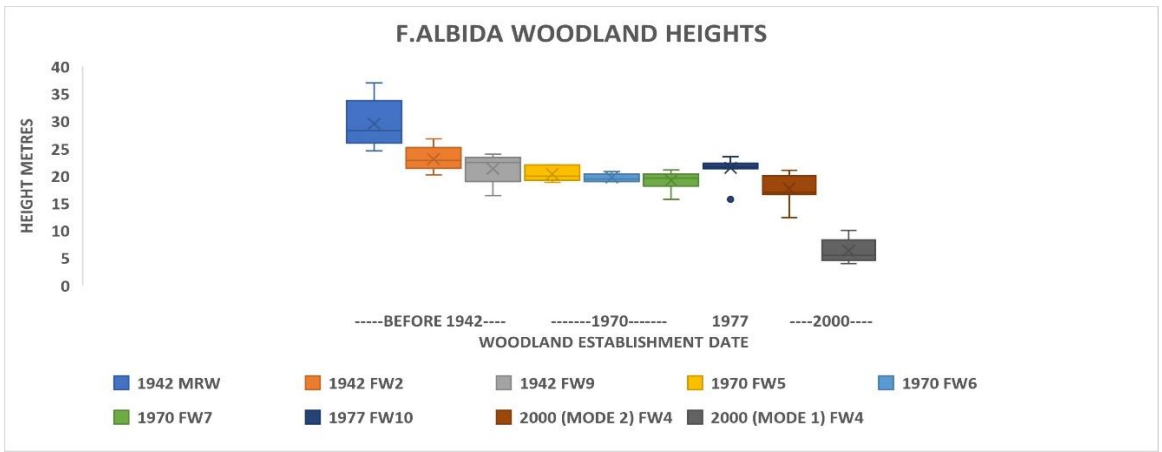


Figure 5.9: Box and whisker charts for the different *F. albida* woodlands diameters (top) and heights (bottom). Dates are when each woodland established. All woodlands, except FW4, had narrow unimodal diameter (DBH) and height distributions. FW4 had a bimodal distribution with 19% of the woodland at a small diameter and height. Sample sizes are given in table 5.1.

5.3.2. DECLINE PHASE

Changes in the riverine and riparian vegetation of the Luvuvhu River can be seen in the aerial photographs and GE imagery from 1942 to 2018 (fig 5.10 (a) to (f)). River course changes are shown in figure 5.11. The establishment *F. albida* (and other) woodlands occurred (covered in Chapter 5.3.1) and the floods of 2000 and 2013 changed the river course and removed significant areas of *F. albida* and other riverine and riparian woodlands.

Period 1942 to 1999. When comparing figures 5.10 (a) and (b) it is seen that the Luvuvhu River was narrow, winding and lined with mature riverine woodland during this period. The river course, riverine vegetation, and *F. albida* woodlands declined little over these 57 years. Where changes occurred, woodland established (FW10, fig 5.6). Droughts and floods occurred (fig 3.7). Markers at Baobab Hill House (Maleteni) and Crooks Corner show complete flooding of the floodplain from Mangala to Crooks Corner in 1958 (cyclone Astrid), 1966 (cyclone Claude) and 1977 (cyclone Emile). Notwithstanding these floods, there were no major changes in the river course.

Period 1999 to 2000. When comparing figures 5.10 (b) and (c) it is seen that river course changed and riverine and riparian woodland was removed, particularly the *F. albida* woodlands at Mangala (FW2) and the original Island woodland (FW4). Cyclone Eline caused floods in February 2000. This was the largest flood for at least 42 years (from and including 1958) with the highest of all flood markings at Crooks Corner and Baobab Hill House (Maleteni). The river course change at FW4 caused a sediment filled oxbow to form in the position of the previous Luvuvhu channel. The 2000 flood impact was still visible in 2010 (pers obs) as sand deposits on the western end of the Hutwini floodplain (near Mangala (FW2)) and tree trunks deposited on the floodplain.

Period 2000 to 2012. When comparing figures 5.10 (c) and (d) it is seen that woodland FW4 re-established, but there is no observable decline in the woodlands. No flooding of the Hutwini floodplain occurred and some vegetation regeneration occurred. Minor flooding of the Limpopo in 2009 pushed back up the Luvuvhu River as far as Nwambi pan but had no effect on the *F. albida* woodlands.

Period 2012 to 2013. When comparing figures 5.10 (d) and (e) it is seen that the 2013 floods caused further river course changes and removal of riverine and riparian woodland, particularly more of the *F. albida* woodlands at Mangala (FW2) (where up to 2 m of floodplain soil adjacent to the river was removed) and Trails Camp (FW8). The flood in January 2013 was the second highest Luvuvhu flood (after the 2000 flood) measured at Baobab Hill House (Maleteni). It had a cumulative impact on top of the 2000 floods. The dynamics of the 2013 flood were different; without adequate back-flooding from the Limpopo River the flow velocity and energy of the Luvuvhu River was greater than in 2000 (Enviro Africa, 2013). The western end of the Hutwini floodplain was farther inundated with coarse sand and the whole floodplain littered with large tree trunks that had been brought down by the floods. After the flood, these large tree trunks were seen washed up against surviving trees and it was apparent that they were a significant cause of woodland removal. The apparent process was large trees removed by the flood added to downstream destruction by removal of additional trees in a cumulative domino effect.

Period 2013 to 2018. Between 2013 and 2018 no flooding of the Hutwini floodplain occurred and some regeneration commenced. In April 2016 the Island (FW4) had an accumulation of dead felled and standing trees equal to 11.8% mortality. This mortality had accumulated since the floods of January 2013 and probably had been caused by those floods. Neither the Main (FW5) or Maleteni woodland (FW6) had any accumulated mortality in April 2016. There was no other observable decline in the *F. albida* woodlands.

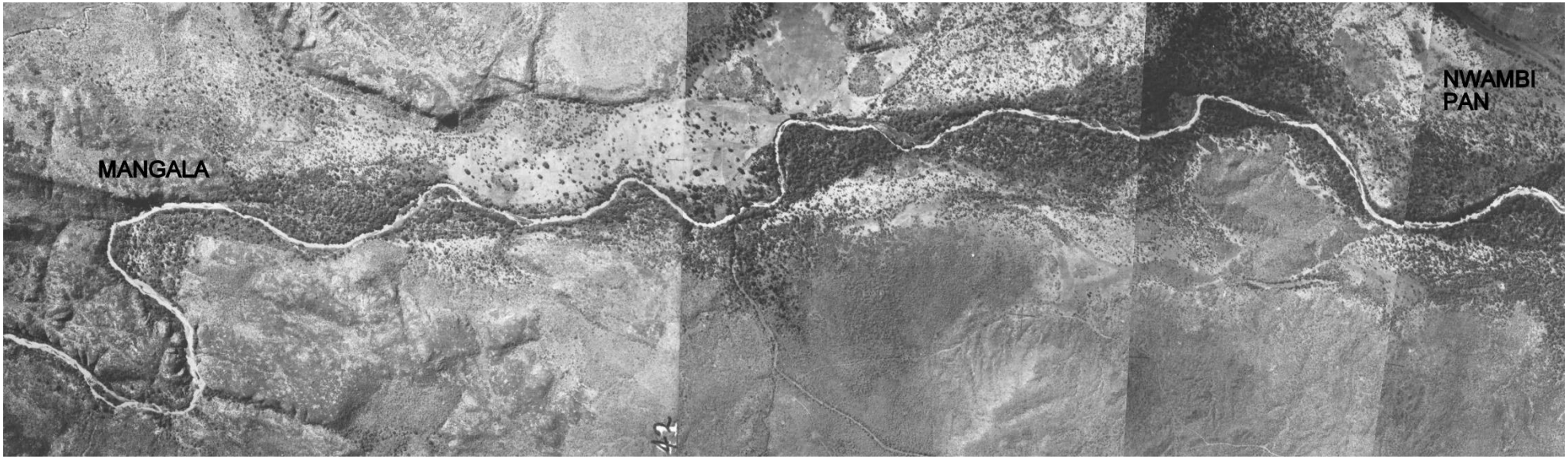


Fig 5.10 (a): 1942 aerial photograph of the Luvuvhu River between Mangala (left photo area) and Nwambi pan (right photo edge) (from Roussel, 2016).

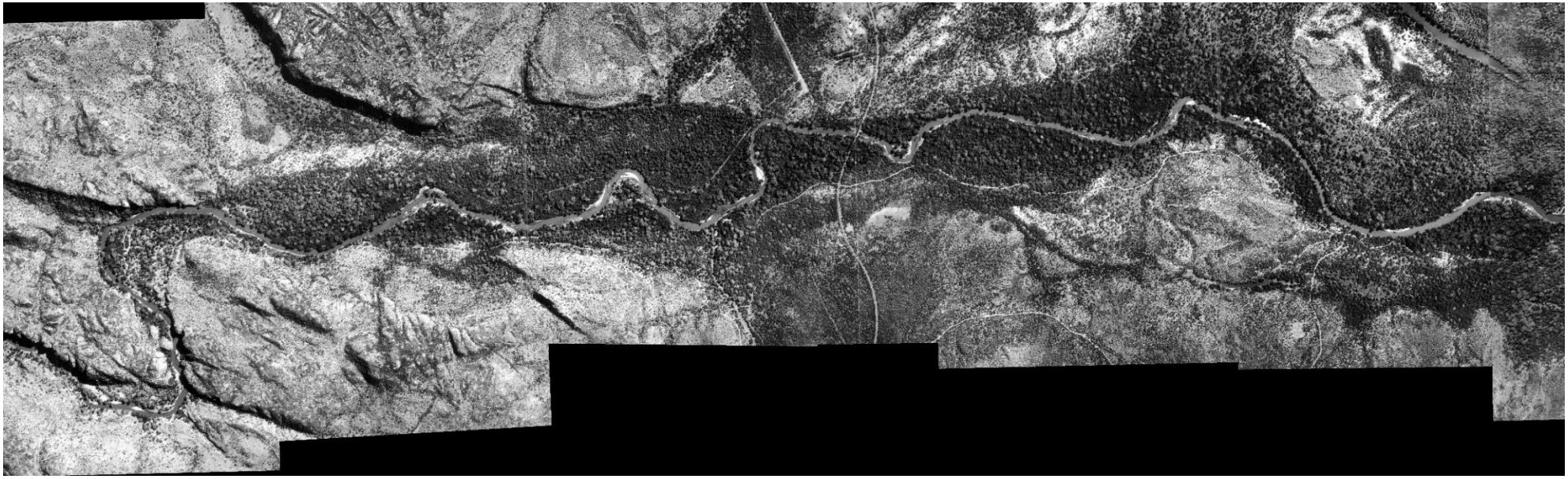


Fig 5.10 (b): 1999 aerial photograph of the Luvuvhu River between Mangala (left photo area) and Nwambi pan (right photo edge) (from Roussel, 2016).

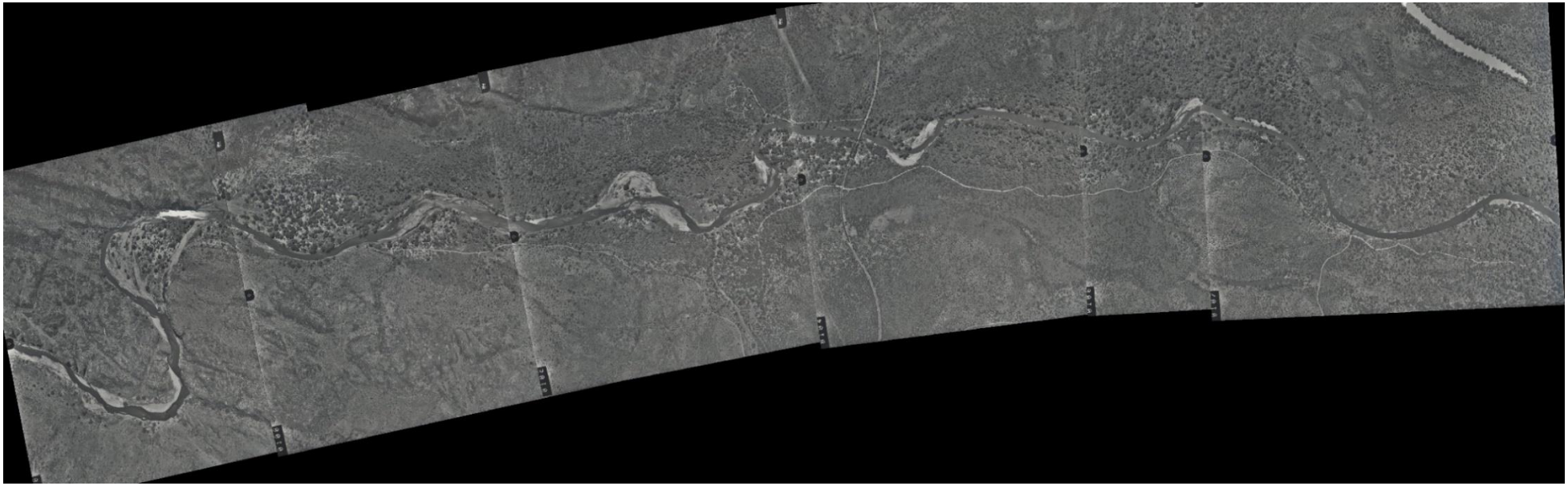


Fig 5.10 (c): 2000 aerial photograph of the Luvuvhu River between Mangala (left photo area) and Nwambi pan (right photo edge) (from Roussel, 2016).

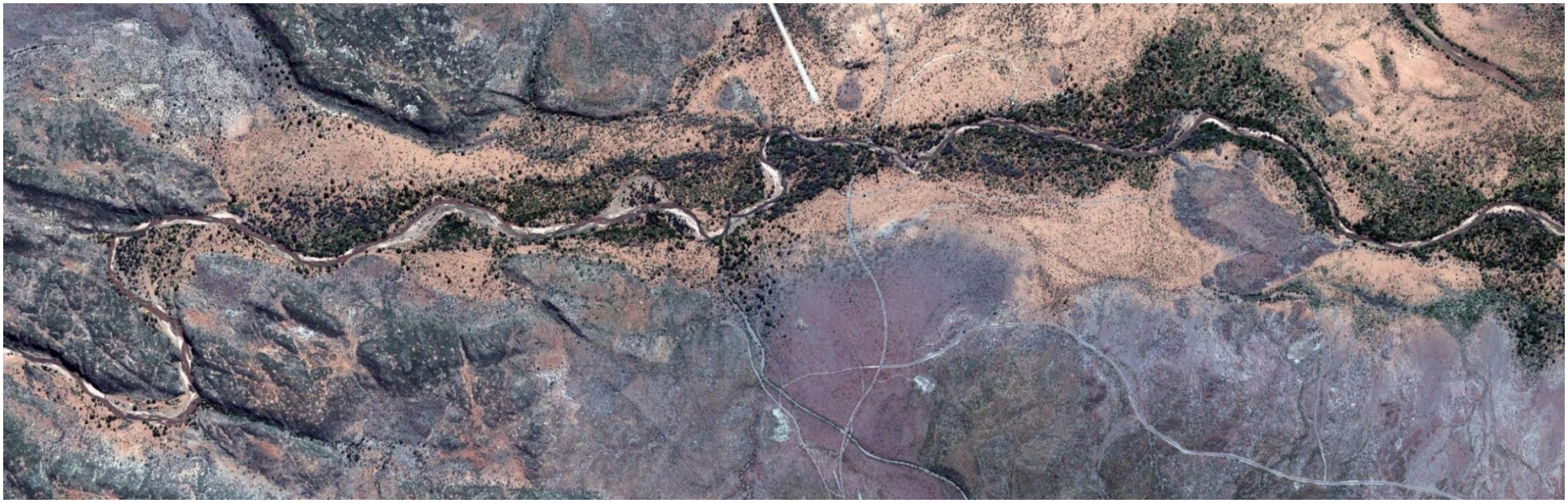


Fig 5.10 (d): 2012 GE image of the Luvuvhu River between Mangala (left photo area) and Nwambi pan (right photo edge).

Fig 5.10(e): 2013 GE image of the Luvuvhu River between Mangala (left photo area) and Nwambi pan (right photo edge).

Fig 5.10 (f): 2018 GE image of the Luvuvhu River between Mangala (left photo area) and Nwambi pan (right photo edge).

Figure 5.10 Aerial photographs and GE imagery of the Luvuvhu River between Mangala (left photo area) and Nwambi pan (right photo edge) from 1942 to 2018.

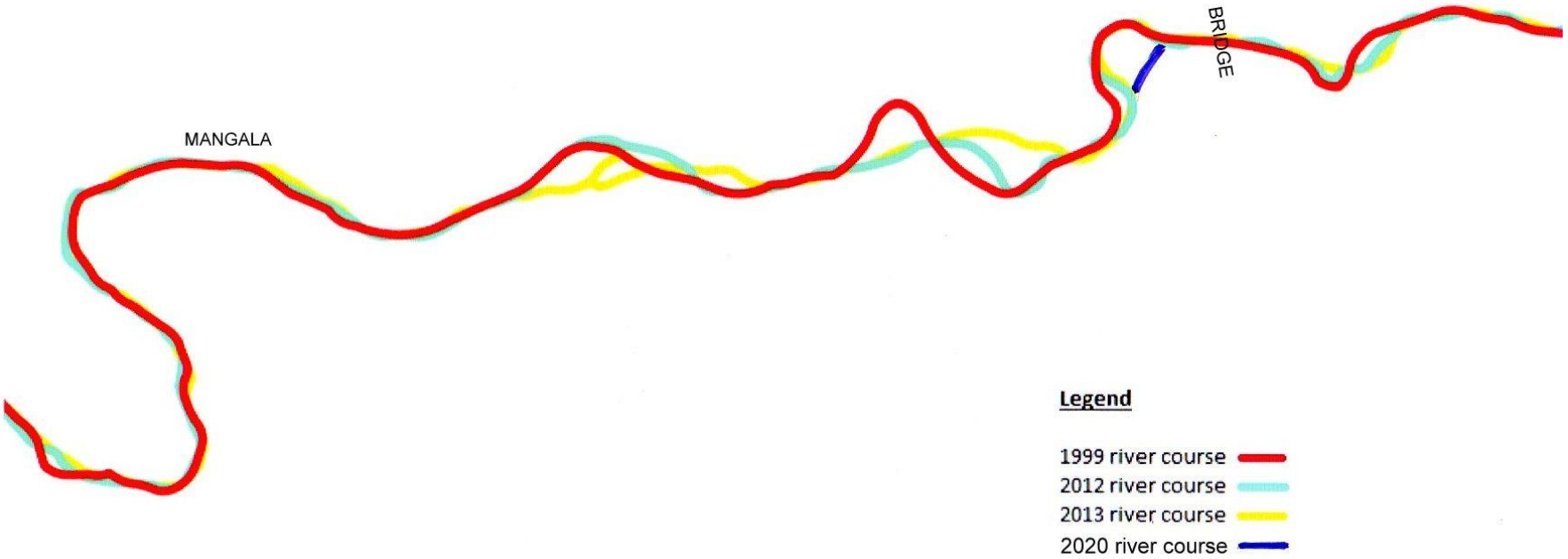


Figure 5.11: Luvuvhu River course changes between Mangala and Nwambi pan following the floods of 2000 (change red to light blue; 1999 to 2012) and 2013 (change light blue to yellow; 2012 to 2013) (from Roussel, 2016). The new channel created in 2020 (dark blue) was caused by a high river level which made the breakthrough in a channel that had been created and progressively eroded by the floods of 2000 and 2013.

Effect of the floods on river morphology. In the 57 year period from 1942 to 1999 the Luvuvhu River changes were gradual and minimal. However, the floods of 2000 and 2013 caused dramatic river course changes and woodland removal. The macro channel of the 5,5 km section of river from Mangala to the bridge widened from an average of 54 m to an average of 110 m (increase of 56 m). The river progressively straightened out changing from a narrow meandering river to a wide relatively straight river. The 10,7 km section from the bridge to Crooks Corner widened from an average of 44,5 m to 48 m (increase of 3,5 m) as most of the flood water had spread out over the floodplain. About 35 ha of mixed riverine woodland was removed with most being in the section from Mangala to the bridge. In addition, about 37 ha of monospecific *F. albida* woodland from woodlands FW1, FW2, FW4 and FW8 was removed of which 23,6 ha of this was within the MCP. Figure 5.12 shows the areas of woodland removal in FW2, FW4 and FW8. These woodlands were in the floodplain adjacent to the river in areas vulnerable to flood impact. A high river level in March 2020 completed the change in the river course at FW8 (fig 5.11), creating another dry oxbow.

Drought effect. There is no evidence of drought affecting the *F. albida* woodlands. Unpublished data from van Coller in 1994 (reported by Botha, 2001) on *F. albida* mortality after the 1991/92 drought revealed that only 0,5 individual trees died per kilometre of river compared with 20,8 dead trees per kilometre for *Ficus sycomorus*.

Elephant effect. Mature tree mortality was recorded in woodlands FW4, FW5 and FW6 over 33 months from April 2016 to December 2018 (sample size 205 trees), with the cause of mortality allocated to elephant and other unknown. The tree mortality was about 0,5% pa (elephants) and 0,2% pa (other causes). Elephant mortality was 1 tree pushed over (500 mm diameter) and 2 trees snapped off (both 450 mm diameter).

The bark stripping impact of elephants was determined from 65 trees in the Maleteni woodland (FW6) in 2016. Eighty one percent of trees were bark stripped less than 10% of their circumference and only 2% of trees were bark stripped more than 75% of their circumference (fig 5.13). No mortalities from complete ring barking were observed. No insect attack was observed in the areas exposed by bark stripping. In October 2020, however, after 3 seasons of below average rainfall and an increased elephant population (by observation as there was no KNP census after 2017), there was an unmeasured observable increase in elephant bark stripping. There was no sign of senescence.

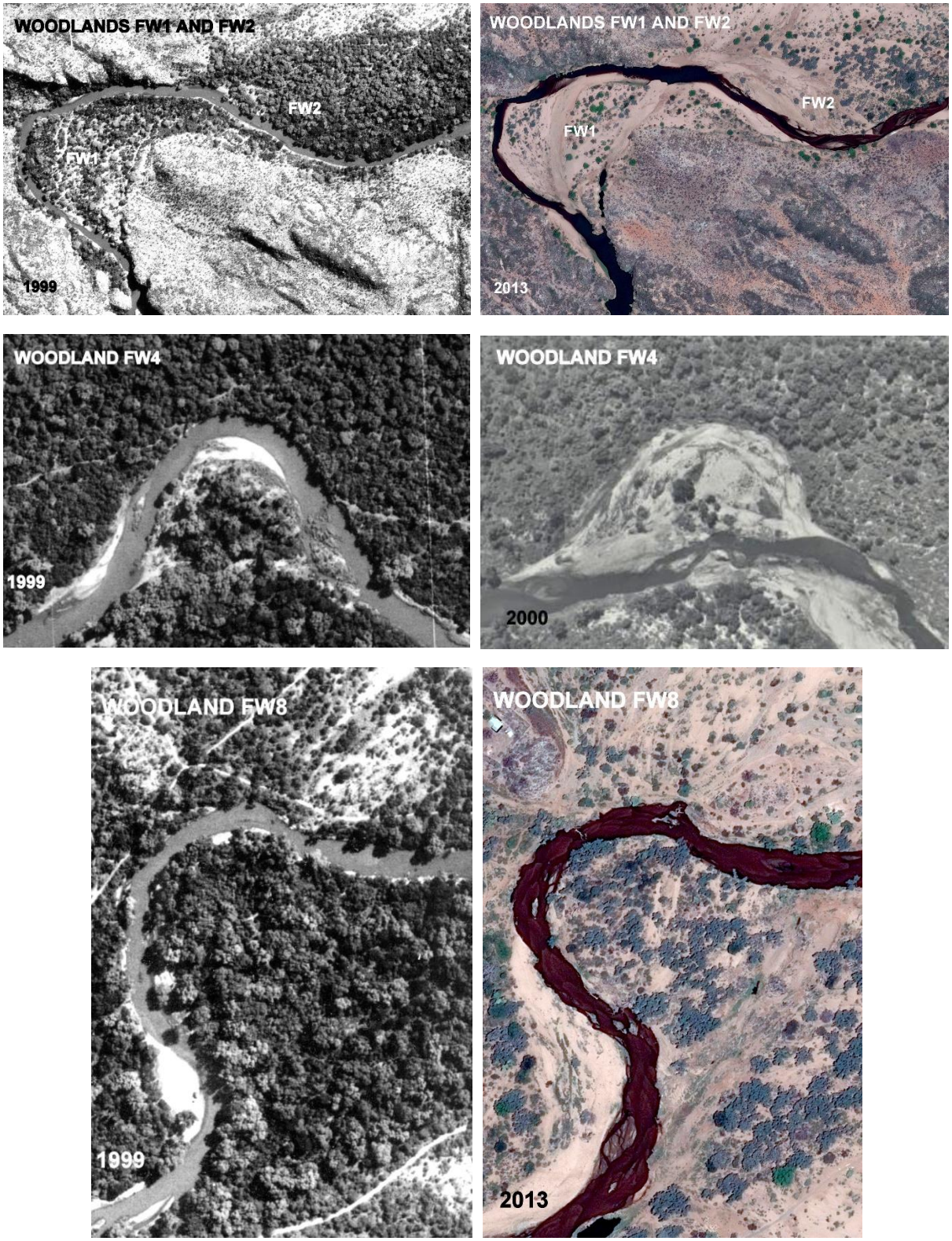


Figure 5.12: The dramatic effect of the combined floods of 2000 and 2013 on woodlands FW1 and FW2 (top), woodland FW8 (bottom) and flood of 2000 on woodland FW4 (middle).

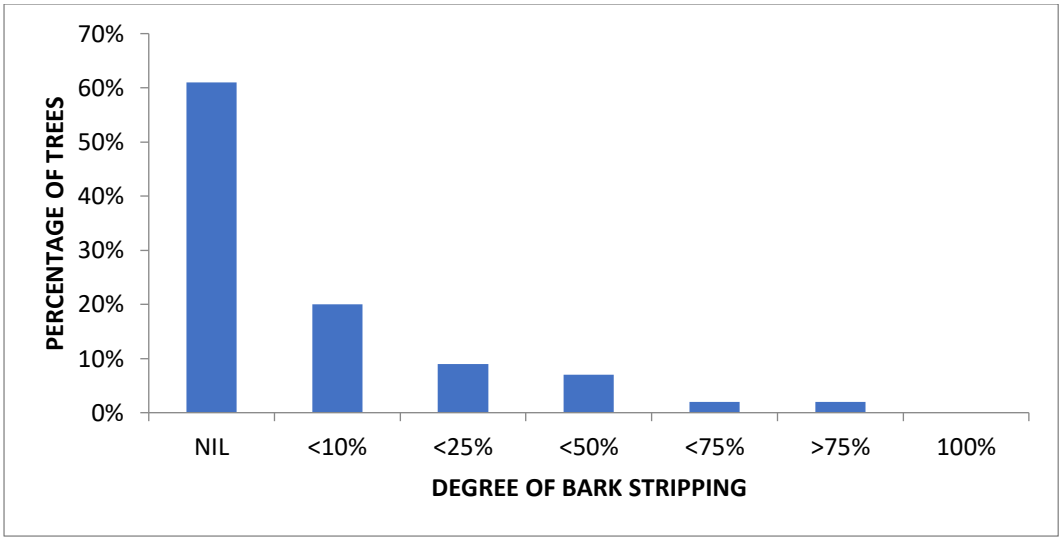


Figure 5.13: Extent of elephant bark stripping in woodland FW6 in 2016. Sample size of 65 trees.

5.3.3. REGENERATION PHASE

The floods of the Luvuvhu River in 2000 and 2013 removed about 35 ha of mixed riverine woodland on both sides of the river and 23,6 ha of *F. albida* woodland in the MCP, which created areas available for woodland regeneration. In addition, other open areas of the floodplain were potentially available for regeneration. In September 2013, eight months after the floods, I observed an abundance of *F. albida* seedlings in areas of the Luvuvhu floodplain. Since my arrival in the MCP in 2006 I had covered much of the MCP on foot and had never seen *F. albida* seedlings on this scale. The inference was that the floods had initiated the regeneration.

Regeneration only within the MCP was examined. Regeneration was observed occurring in the Luvuvhu River and floodplain between Mangala and the bridge. The spatial distribution of areas where regeneration occurred was patchy, occurring in open areas created by the floods and open patches within mature woodlands at low densities, with the lowest density of widely spaced seedlings occurred on the young Dundee soils in the broad river channel created by the 2013 floods. Areas below the density threshold for regeneration into woodlands were excluded (for example, regeneration in the broad river channel). Areas where significant regeneration occurred were Group 1 (about 8,1 ha) and Group 2 (about 15,5 ha) where floods had created suitable areas for regeneration.

Table 5.2 gives details of the different regenerating areas, and the sample patches and transects within these areas. The smallest patch of regeneration meeting the density criterion was 1000 m^2 (FR5) in an open patch within woodland FW5. Regeneration occurred on both Oakleaf and Dundee soils on terraces less than 4 m above river level and within 250 m of the river. All these areas were flooded in January 2013. No regeneration was observed in closed canopy woodland or farther away from the river.

Figure 5.14: A typical patch of *F. albida* seedlings (regeneration patch FR4) in October 2015. All seedlings in this patch were less than 500 mm in height at a density greater than 4000 per ha.

GROUP 1 AREAS (FR3, FR4, FR5, FR8)

A photograph of area FR4 in 2015 (fig 5.14) was typical of the regeneration of seedlings and saplings. A decline in density had already occurred before measurements commenced in 2016 (pers obs). Most group 1 patches had a very high percentage of seedlings (<500 mm) (fig 5.15). The Oxbow patch (FR3A) had more taller saplings, some of which may have existed before the 2013 flood. It was the only patch with a high percentage of saplings (77%) and was selected specifically because it was unique in this respect. The size of patch FR3A was only 10% of the Oxbow area (FR3). The remaining 90% of the Oxbow area was visually better represented by transect FR3B, which had a higher percentage of seedlings.

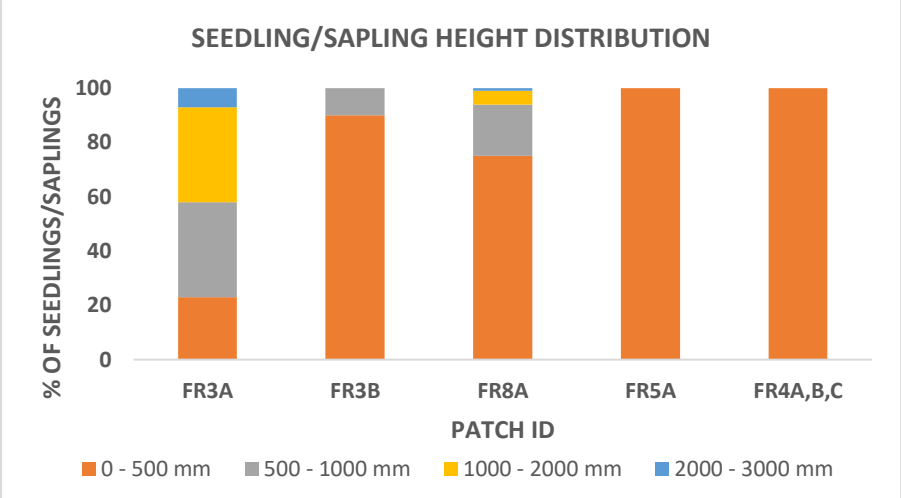
Height distributions are dynamic, influenced by the temporal change in numbers of seedling and saplings in each height class through mortality, new germination, recruitment to the next size class and browsing in a complex inter-relationship. Temporal change in numbers and density of seedlings and saplings is a more reliable measure of regeneration progress. Seedling and sapling densities in 2016 ranged from 122 per ha to 3636 per ha (fig 5.17). In all Group 1 areas there was a significant decline in the numbers of seedlings and saplings over the period April 2016 to October 2018 ranging from 33% to 100% (fig 5.17) with a corresponding decline in the seedling and sapling density. This decline occurred steadily and not as a result of any episodic events. The decrease in number of seedlings is net of any new germination. With the limited success of tagging seedlings, new germination could not be quantified. Seedlings rapidly produced a tap root longer than the aerial height (excavated seedlings, pers obs). *Faidferbia albida* saplings tend to sucker if disturbed. Some seedling regrowth occurred from root stock up to 400mm below soil level where porcupines had excavated and browsed the root off. These regrowths were seldom identified and counted as seedlings.

Heavy browsing was evident (fig 5.16). Shoot diameters browsed ranged from 1 mm to 50 mm indicating a range of browsing by mesoherbivores and elephants.

The Oxbow patch (FR3A). FR3A contained a significantly higher percentage of saplings greater than 1000 mm in height than all other areas (fig 5.15). From April 2016 to October 2018 the total number of seedlings and saplings declined from 142 to 95 (an overall decline of 33% in 31 months) (fig 5.17). This decline was mainly in the greater than 1000 mm size class which decreased from 60 to 17 (70% decline), while the number of seedlings and saplings 1000 mm or less decreased from 82 to 78 (5% decline). The overall result was a reduction in total number of seedlings and saplings, a reduction in average height and a shift in the size distribution to smaller sizes. Size distribution changes cannot be seen in isolation.

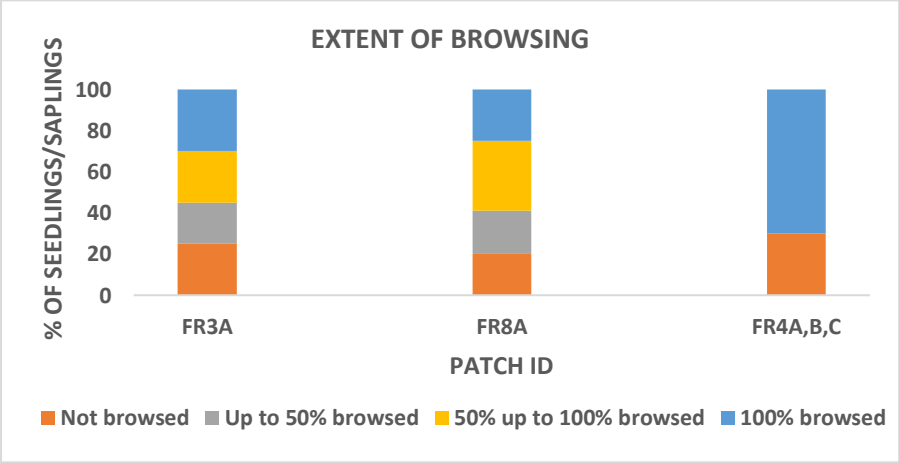
By January 2000 the number of saplings greater than 1000 mm had declined even farther (60 in April 2016 to nine in January 2020, an 85% decline). The annual fluctuation in height of these 9 saplings (which had been tagged) over this period is shown in figure 5.18. The April 2016 height range of 1200 - 2600 mm (average 1833 mm) reduced to 1500 – 3400 mm (average 2300 mm) in January 2020, a modest average growth of 130 mm per annum compared to the height growth rate of 1100 mm per annum for woodland FW4 between 2000 and 2016 (height shown in figure 5.9; “FW4 2000 mode 2”). These surviving nine larger saplings showed evidence of severe elephant browsing and none managed to secure any significant height growth.

Camera traps. Figure 5.19 shows the number of animal visits per day for the ten most common species that visited the Group 1 patches, and the relative abundance of the three most important browser species (visits per day adjusted for group size). In ranking order, the important browsers were elephant, impala and nyala. These were the only species recorded browsing the seedlings or saplings.

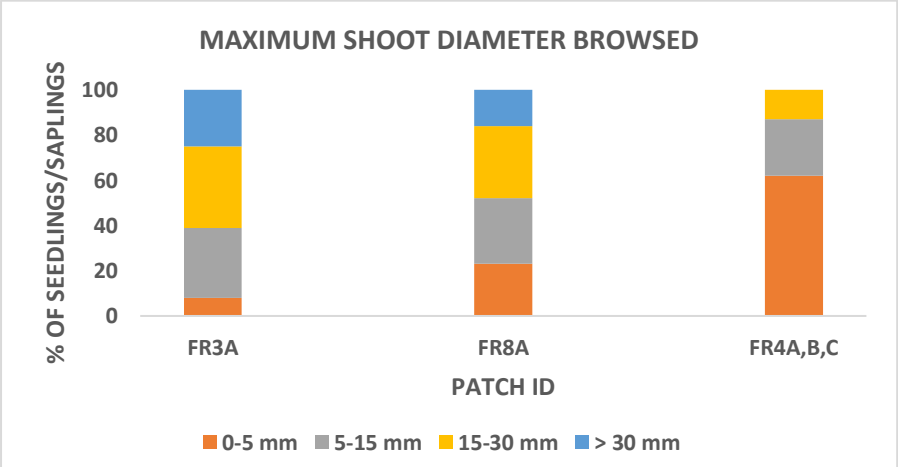


SAMPLE SIZE: FR3A, 111 FR3B, 153 FR8A, 126 FR5A, 81 FR4A,B,C, 180

Figure 5.15: Group 1 patches seedlings and saplings height distribution in April 2016.

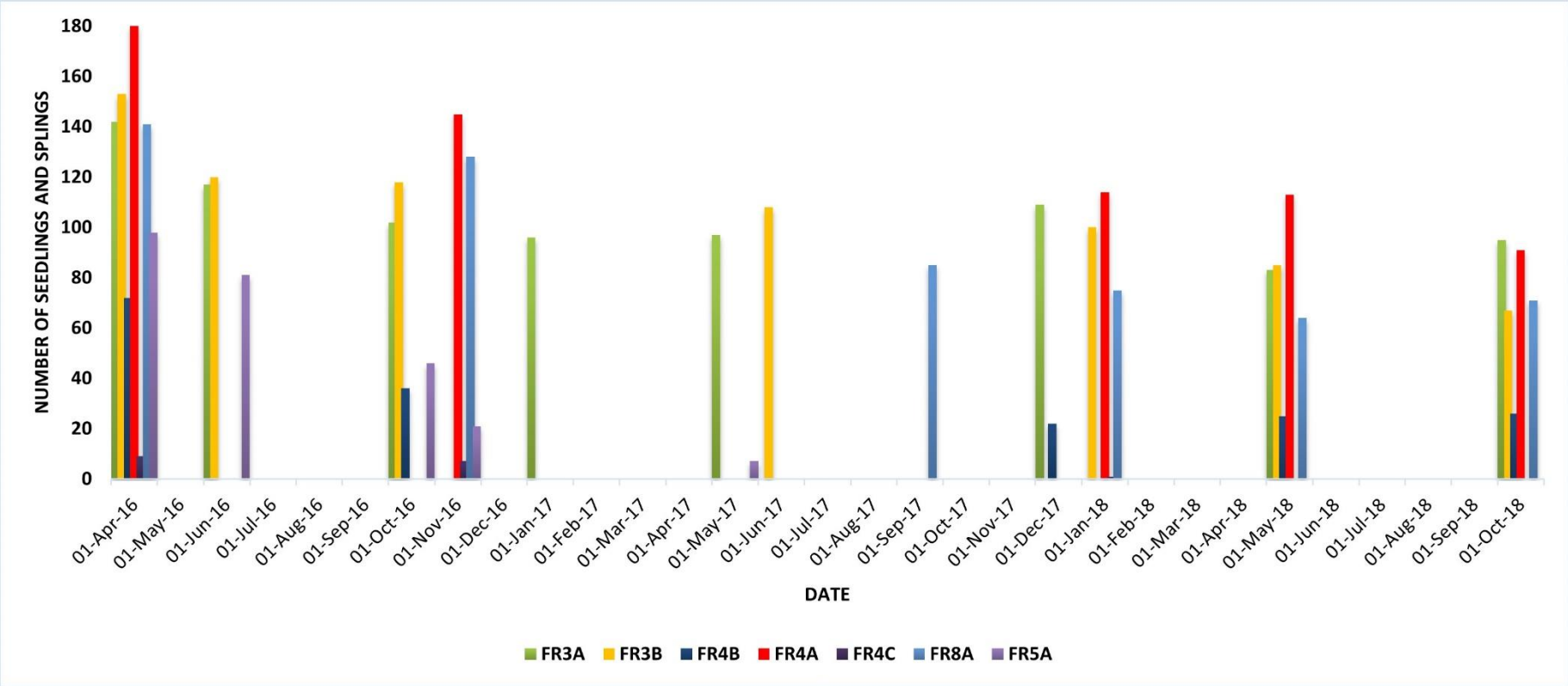


SAMPLE SIZE: FR3A, 111 FR8A, 126 FR4A,B,C, 180



SAMPLE SIZE: FR3A, 84 FR8A, 95 FR4A,B,C, 53

Figure 5.16: Group 1 patches extent of browsing (top) and maximum shoot diameter browsed (bottom) in April 2016. Patches FR3A and FR8A had the highest percentage of shoots >15 mm diameter browsed, indicating browsing by elephants.



NUMBER OF SEEDLINGS APRIL 2016	142	153	72	180	9	141	98
INITIAL DENSITY PER HA APRIL 2016	476	727	1978	3636	122	1064	1567
PERCENTAGE DECLINE TO OCT 2018	33%	56%	71%	50%	100%	50%	100%

Figure 5.17: Decline in number of Group 1 seedlings and saplings from April 2016 (initial density) to October 2018. All patches declined and some disappeared.

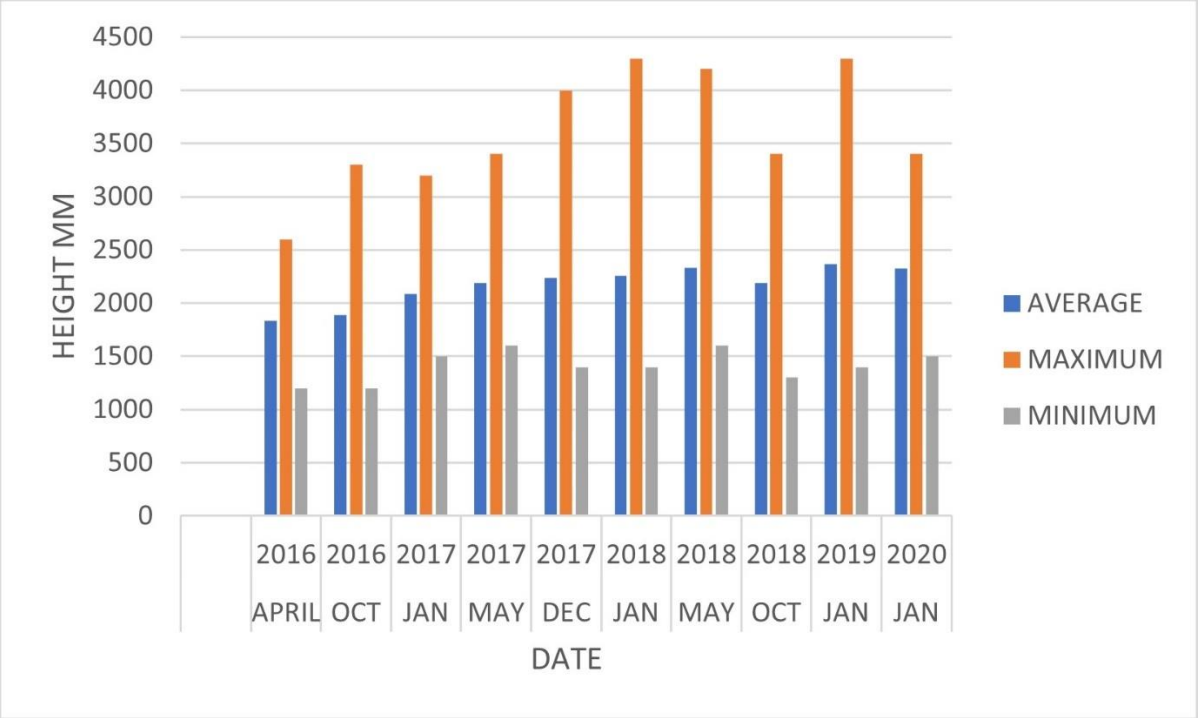


Figure 5.18: Height changes in 9 tagged saplings of regeneration patch FR3A that survived from June 2016 to January 2020 and were > 1 m on both dates. The average height increase was 130 mm per annum over this period. Only 15% of the >1 m saplings in June 2016 survived to January 2020. The initial sample size was 60 saplings >1 m.

Elephants. Observations showed that the elephants visited the regeneration areas when utilizing a route which passed through the regeneration patches both ways when going to the Luvuvhu River to drink, mud bath and dust bath. Most of their time was spent feeding in the mixed riverine woodlands. The riverine woodlands around group 1 areas are serviced by a few major elephant paths and to reach the most preferred drinking and mud bathing spots the elephants had to pass through these mixed riverine woodlands. The regeneration areas were on one of their routes.

The camera traps, observations and other photographic evidence showed that within the regeneration patches the elephants fed on all sizes of *F. albida* seedlings and saplings. Seedlings were totally removed when an elephant loosened the soil around the seedling with its foot and pulled the seedling out with its trunk. Saplings were browsed by all ages of elephants up to a twig diameter of about 50 mm, and in a couple of instances adult elephants broke off a stem up to a diameter of about 100 mm. Time spent in the patches varied from passing through to 15 minutes feeding activity. Most of the browsing was done by herds, not bulls.

There was no evidence that the elephants preferentially selected for the *F. albida* regenerating patches. Adjacent to the patches are mixed species woodlands, and many different species up to about 4 m in height showed evidence of severe elephant browsing which maintained much of this woodland at that height. The main species in this category were *Ziziphus mucronata* and *Croton megalobotrys*.

Mesoherbivores. Impala, nyala and porcupine were the only browsers observed browsing. Impala and nyala browsed the seedlings and the small side shoots of the saplings. Camera trap recordings and observations showed impala browsed much more frequently than nyala.

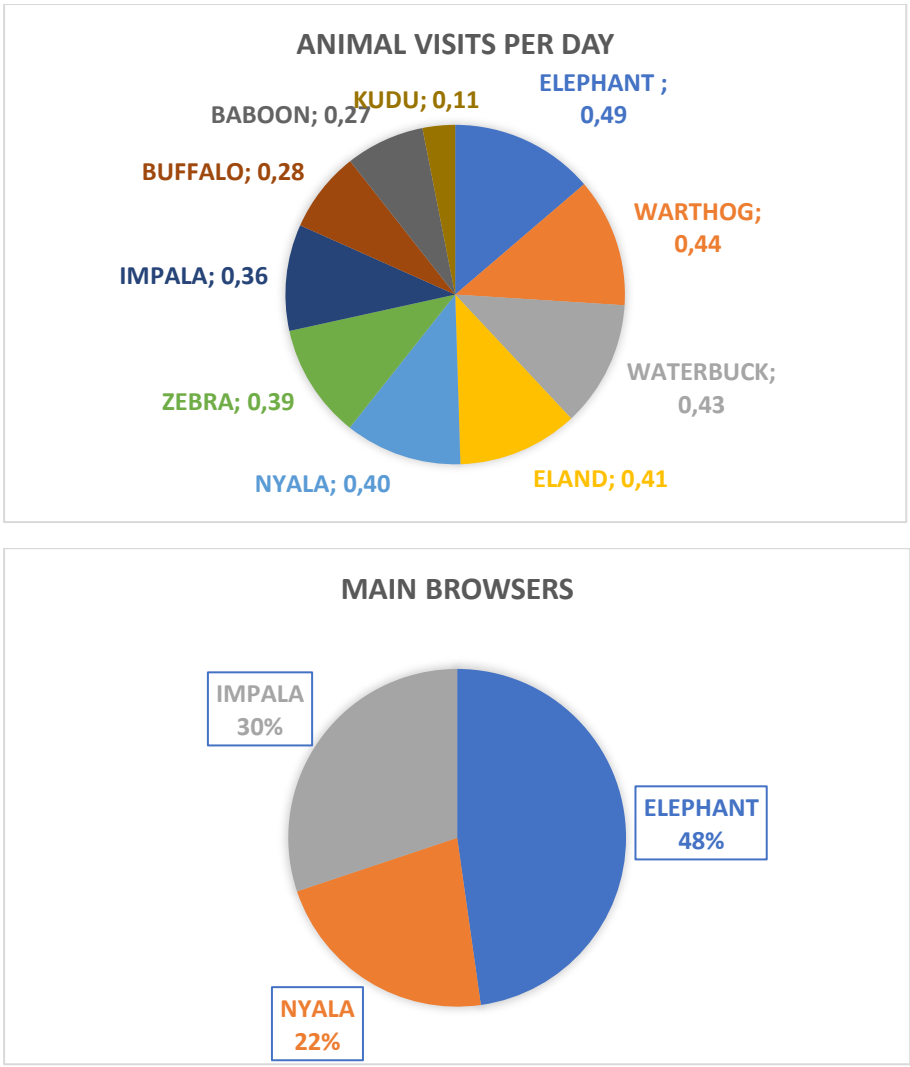


Figure 5.19: Animals visiting the Group 1 patches as determined by the camera traps (top) expressed as animal visits per day. The main browsers (bottom) are animal visits per day weighted by average group size. Browser biomass was not taken into consideration because the time spent browsing by each browser could not be determined. A total of 387 animal visits were recorded.

Examination of physical signs of seedling and sapling damage identified porcupines as stem browsers. Very few porcupine visits were captured by the camera traps, but their excavations of seedlings and saplings were often seen. Porcupines removed seedlings and saplings of up to 20 mm diameter at depths of up to 400 mm leaving a below ground cut off root (pers obs). Although these indicators were unmistakeable, it was difficult to assess how long these physical signs remain observable. Using conventional animal tracking techniques, it was possible to judge whether multiple excavations were done at the same time or not. Usually, the porcupine excavated several saplings in a single feeding event (called single event mortality). Some resprouting from below soil level could have occurred. Examples of such single event mortalities in different patches were:

June 2016: FR4A; 4% of all seedlings and saplings in the patch in a single event putative mortality.

June 2016: FR3A; 1% of all seedlings and saplings in the patch in a single event putative mortality.

October 2016: FR3B; 11% of all seedlings and saplings in the transect in a single event putative mortality.

GROUP 2 AREA (FR2A)

The Group 2 area was situated 5 kms upriver from the Group 1 areas in a direct line opposite the exit of the Luvuvhu River from Lanner gorge where flood velocities were severe and was the largest area of riverine and riparian woodland removed by the floods. Up to 2 m of the deep Oakleaf soils were removed by the 2013 flood leaving a lower layer terrace of the Oakleaf soils for regeneration. This was an abiotic condition differentiating it from Group 1 areas. About 15,5 ha of woodland was removed and the area became available for subsequent regeneration (fig 5.3). Seedling and sapling measurements in patch FR2A commenced in 2017. The *F. albida* regeneration was not monospecific but occurred with other species and the *F. albida* density was lower than the criterion for monospecific woodlands. Initial observations in 2016 erroneously concluded that *F. albida* regeneration was not occurring.

It is not certain that the Mangala area before 2000 was monospecific *F. albida* woodland. In 2016 the remaining established woodland and isolated trees that survived the floods were *F. albida*. However, personal observations were that *Vachellia tortilis* and *F. albida* regenerated close to the Mangala lookout site (close to FR2A) after 2000 but were removed by the 2013 flood. An aerial photo taken before 2000 appeared to indicate a *F. albida* dominated woodland (confirmed by Scott-Ronaldson, KNP Pafuri Section Ranger, pers comm).

FR2A was sampled in September 2017 and in September 2018. In contrast to group 1 areas, several different species were regenerating. In abundance and height ranked order of >1000 mm saplings these were *V. tortilis* (66%), *F. albida* (20%), *Croton megalobotrys* (11%), *V. xanthophloea* (2%) and *Vachellia robusta* (1%) (fig 5.20). The saplings of the two main species (*V. tortilis* and *F. albida*) were taller than any group 1 regeneration with a few 6 m in height, showing significant growth had occurred after 2013. Also, in contrast to group 1 regeneration, the number of *F. albida* seedlings and saplings increased (by 35%) between Sept 2017 and Sept 2018 although the increase only occurred in the <1000 mm height class (fig 5.21).

Mesobrowsers. No camera traps were installed at the Mangala patch, so a ranking of browser species could not be done. No analysis on <1000 mm seedlings and saplings was done. Some porcupine excavations and related mortality of seedlings and saplings were observed.

Saplings greater than 1000 mm. For *V. tortilis* only the >1000 mm saplings were counted. Between September 2017 and September 2018 *V. tortilis* saplings increased by 19% (fig 5.22) but with a significant increase in the >4000 mm height class. *F. albida* saplings showed no overall increase but with a distribution shift to more > 4000 mm saplings.

Elephants. Browsing by elephants occurred on the >1000 saplings, indicated by browsed stem and shoot diameters up to 50 mm and stem breakages up to 100mm. There was a clear selection for *F. albida* (88% of saplings browsed) over *V. tortilis* (6% of saplings browsed) (fig 5.23). Many *F. albida* had their main stem broken off.

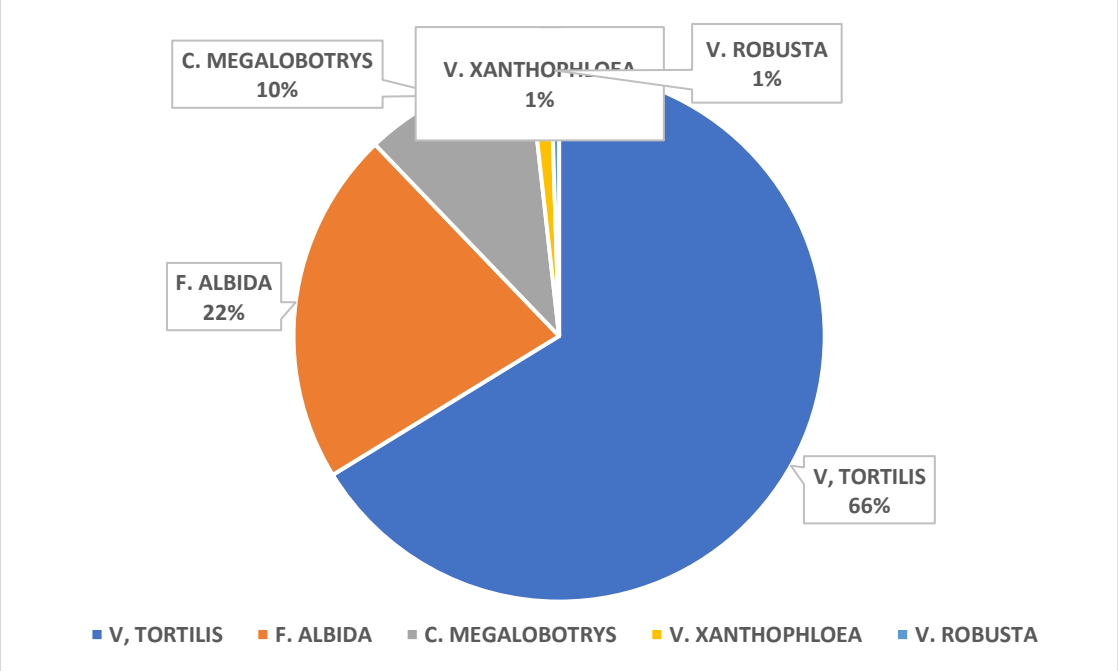


Figure 5.20: Percentages of > 1 m saplings of different species regenerating in patch FR2A (Mangala). Regeneration was dominated by *V. tortilis*. 166 saplings were sampled.

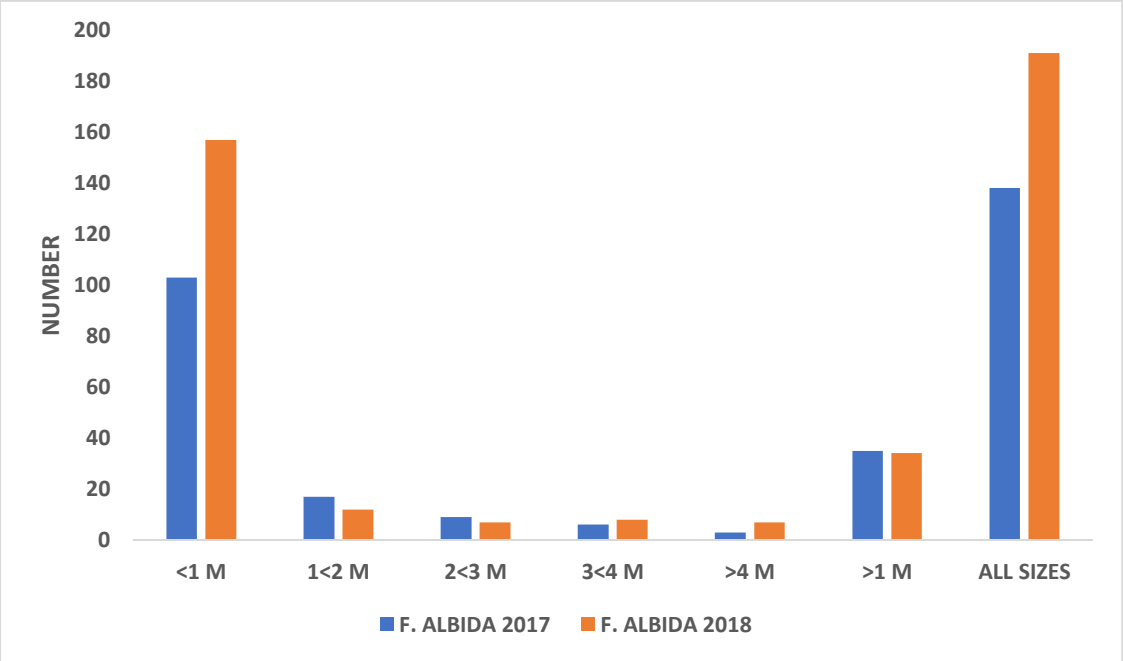


Figure 5.21: The total number of *F. albida* seedlings and saplings in patch FR2A increased from 138 in Sept 2017 to 191 in Sept 2018 (38% increase) (shown as ALL SIZES on the figure). The increase occurred in the < 1 m class. There was a shift to taller saplings in the > 1 m class. The FR2A patch was 41,42 ha (table 5.2).

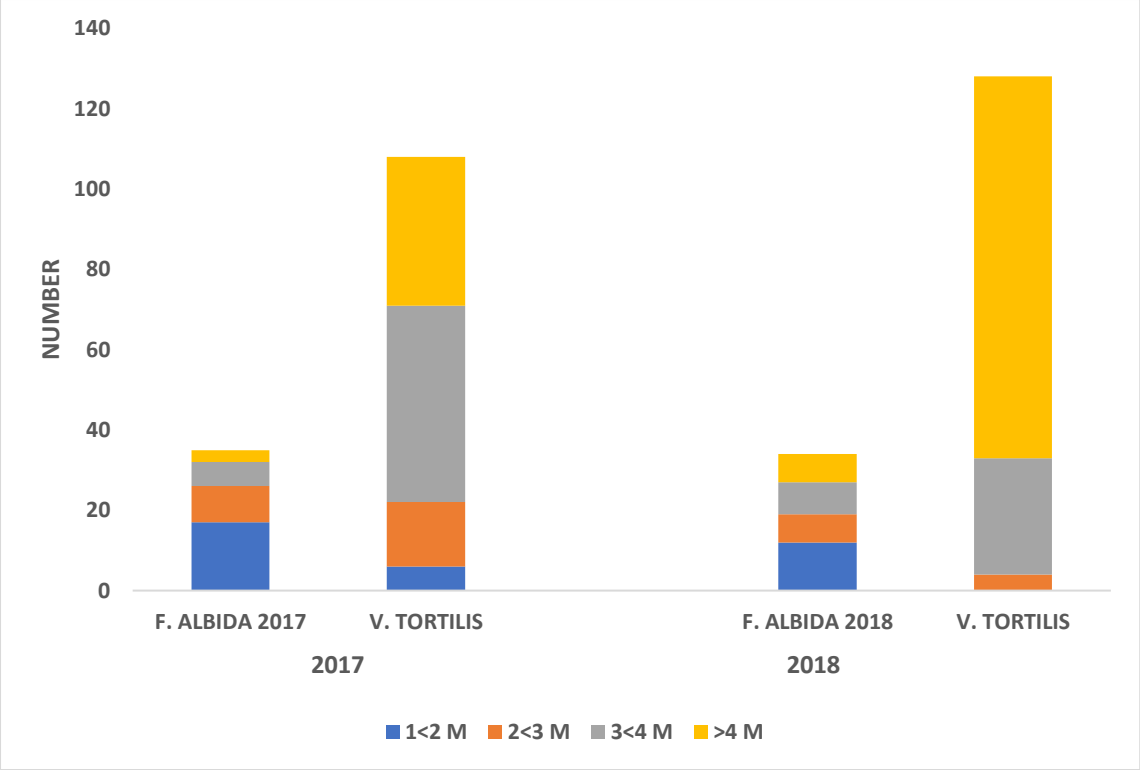


Figure 5.22: Comparative change in number and size distribution of > 1 m *F. albida* and *V. tortilis* saplings between 2017 and 2018. The number of *V. tortilis* saplings increased with a significant shift to the > 4 m size class. The number of *F. albida* saplings remained constant with a shift to the > 3 m size class.

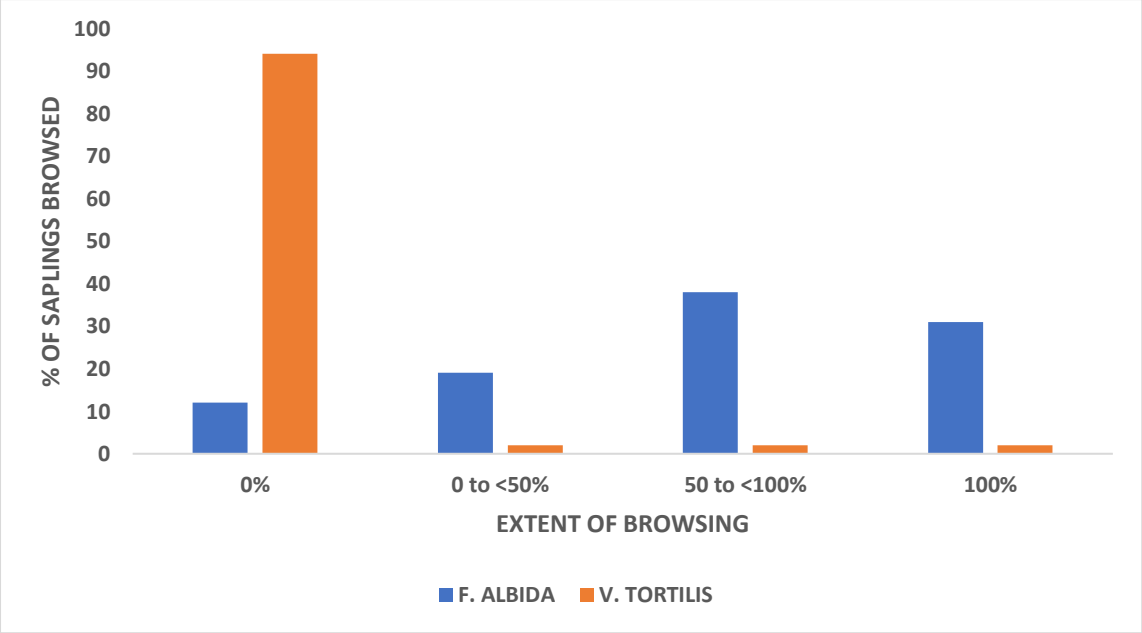


Figure 5.23 Extent of browsing of > 1 m *F. albida* and *V. tortilis* saplings. There is a clear selection for *F. albida*. Stem and shoot diameters up to 50 mm were browsed and stem breakages up to 100mm diameter occurred. 146 saplings were sampled.

5.4. DISCUSSION

5.4.1. ESTABLISHMENT PHASE

The conditions and the effect of the ecological drivers during the periods the woodlands established were different for the different woodlands. The date after each woodland established was determined from aerial photographs.

Woodland establishment before 1942. The woodlands that established before 1942 (FW1, FW2, FW4, FW8 and FW9) (82 ha) were on deep Oakleaf soils in the floodplain adjacent to the river. The environment when they established would have been quite different compared to today. The two dams on the Luvuvhu River (Albasini Dam (1956) and Nandoni Dam (2005)) had not been built and water abstraction from the Luvuvhu River would have been minimal. The Luvuvhu was a narrow, winding, perennial river which flooded regularly. The first record of the river not flowing was in 1964 (Joubert, 2007). Anthropogenic influences in the catchment of the river were minimal. The human population in the catchment of the Luvuvhu is unknown but probably mirrored the population of South Africa which grew by a factor of 4,6 between 1939 and 2000 (South African Department of Statistics). These woodlands established in areas that were not farmed by the Makuleke people and there were no elephants.

Woodland establishment after 1970. The woodlands that established in the Hutwini/Maleteni section of the Luvuvhu floodplain after 1970 (FW5, FW6, FW7) (41 ha) were on deep Oakleaf soils. The establishment coincided with four episodic events:

1. Suitable land became available when the Makuleke people were removed from the area in 1969. The Makuleke people living at Head Kraal farmed the Hutwini/Maleteni floodplains where Oakleaf soils were suitable for both crops and woodlands. They relied on regular flooding to irrigate their farming areas and kept the area clear of trees, except for the occasional large tree. The monospecific *F. albida* woodlands only established on a portion of the previously farmed area for reasons that have not been researched.
2. There was a decade of above average rainfall and frequent floods after 1970. This would have kept the water table in the floodplain high. Regular floods were a requirement for successful establishment of *F. albida* woodlands in the Mana Pools floodplain of the Zambezi River (Ncube *et al.*, 2013) and the Hoanib River, Namibia (Jacobson, 1997).
3. The elephant population was low (maintained by culling until 1994). Elephants would have had minimal impact on establishing woodlands. Elephants in sufficient numbers can prevent woodlands establishing. In Ruaha National Park, Tanzania, Barnes (1983) attributed declining *F. albida* woodlands to elephants preventing regeneration. In the Hoanib River, Namibia elephants destroyed small *F. albida* trees in the DBH range 20 – 200 mm (Jacobson, 1997). Between 1985 and 1995 the average Makuleke elephant population from the annual KNP August census was 40 (0,17 per km^2) and is likely to have been similar between 1970 and 1985. Analysis of KNP census data also showed that the elephants did not concentrate in the floodplains until after 2000, probably due to the continued existence of a landscape feared and avoided by elephants. The elephant population grew significantly after 1994 by which time the woodlands were well established.
4. The mesobrowser populations were low, especially impala as the ubiquitous browser in the area. Impala had their greatest impact on seedlings and small saplings and little impact once the saplings became large. In Chobe National Park, Botswana, the survival of *F. albida* seedlings was negatively related to impala densities and not to other browsers (Moe *et al*., 2009).

The woodlands had narrow unimodal DBH distributions with different means which were likely to be due to differences in the Oakleaf soils, elevation on the floodplain, ground water depth, alluvial soil depth and distance from the river between these woodlands.

Woodland establishment after 1977. Woodland FW10 established after 1977 (2,5 ha) on young Dundee soils adjacent to the river which previously had been the river course. The flood of January 1977 (Cyclone Emile) probably caused the change in the river channel and created the area where woodland FW10 established. Regular flooding would not have been necessary for the establishment of this woodland due to its proximity to the Luvuvhu River and easy access to ground water. The elephant population was likely to have been less than the average 0,17 per km^2 which existed between 1985 and 1995 and was also not concentrated in the floodplain in that period. The mesobrowser populations were also low.

Woodland establishment after 2000. Woodland FW4 re-established after 2000 (2,8 ha) on a portion of the same area as the original FW4 woodland which was removed by the 2000 floods. The 2000 floods also initiated the successful regeneration of this woodland. Woodland FW4 was close to the Luvuvhu River, on deep Oakleaf soils, with normal rainfall although there was no additional flood until 2013. Between 2000 and 2005 the Makuleke elephant population from the annual KNP census was 205 (0,9 per km^2). The mesobrowser populations had probably also increased but neither the elephant nor mesobrowser populations were enough to prevent the woodland re-establishing, but could have contributed to the low density of woodland FW4.

All the woodlands, except for FW4, exhibited unimodal height and DBH characteristics, and each woodland consisted of even ages trees. FW4 exhibited a bimodal distribution with each mode as a unimodal distribution. Unimodal woodlands of age cohorts occur elsewhere. In Ruaha National Park, Tanzania, three river sections with mature *F. albida* woodlands on alluvial soils similarly showed strong unimodal DBH distributions with no young trees (Barnes, 1983). Similar woodlands occurred in Mana Pools, Zimbabwe (Gope *et al*., 2014).

The average height of 17,5 m of the dominant mode of woodland FW4 in 2016 reflects a growth rate of about 1,1 m per year after the floods of 2000 which is in line with growth rates reported elsewhere (Barnes and Fagg, 2003) and reflects the favourable conditions for the re-establishment of woodland FW4. The woodland densities of all the woodlands (31 to 64 trees per ha) are, however, in the lower range of densities reported elsewhere (Barnes and Fagg, 2003). In comparison, in the middle Zambezi Valley, *F. albida* woodland densities of 33/ha, 89/ha and 120/ha were recorded for trees of approximate ages of 100 years, 16 years and 10 years respectively (Gope *et al*., 2014). No conclusion is drawn from this difference.

5.4.2. DECLINE PHASE

In the period 1942 to 1999 there was no overall decline in the *F. albida* woodlands. The floods that occurred in this period did not have a detrimental effect. With its deep tap root to access ground water, *F. albida* was also not impacted by the three drought periods that occurred.

The floods of 2000 and 2013 large infrequent events that and caused the episodic removal of woodlands on those dates. The flood of 2000 was the largest on record. The 2013 flood was classified as a 1:100 year event (Enviro Africa, 2013) and was very destructive because there was minimal back flooding from the Limpopo River to cushion the flood and the impact was cumulative as it occurred soon after the 2000 flood.

Decline of the woodlands was not caused by any other ecological drivers. Elephant impact through tree pushover and trunk snapping was minimal. This was consistent with experiences elsewhere (Jacobson, 1997; Dunham, 1989; Guy, 1976). Only woodland FW4 showed slightly higher mortality than would be considered normal and this occurred between 2013 and 2016 and was probably caused by the 2013 floods. Natural mortality in the woodlands between 2016 and 2018 was minimal. There was no sign of senescence. The MCP woodland ages in 2016 were greater 74 years (FW1, FW2), about 46 years (FW5, FW6, FW7), about 39 years (FW10) and 16 years (FW4). *Faidherbia albida* are reported to live to 150 years (Barnes, 2003), and recorded in Mana Pools, Zimbabwe at more than 100 years old (Gope *et al.*, 2014). The individual *F. albida* trees in the mixed riverine woodlands of the MCP averaged 29,5 m in height and 1110 mm in diameter, which based on these demographics makes them older than any of the monospecific *F. albida* woodlands. The mixed riverine woodlands existed in 1942.

Bark stripping was not significant and there was no ring barking. Bark stripping is cumulative and may become more important as the trees get older. Signs of increased bark stripping were observed in October 2020 following three successive drought seasons. In Ruaha National Park, Tanzania, about 40% of mature *F. albida* trees were assumed to have been killed by elephants, due to elephant bark stripping of live trees (Barnes, 1983). This level of impact is not reported elsewhere.

The monospecific woodlands were in the Luvuvhu floodplain which is an area of high elephant activity but there was no evidence that they are selected for by elephants, except for the nutritious pods. There was abundant food for elephants in the mixed riverine woodlands, and two species in particular, *Ziziphus mucronata* and *Croton megalobotrys*, were heavily utilised (pers. obs.).

5.4.3. REGENERATION PHASE

The floods of 2013 initiated the regeneration. Flood initiated regeneration historically occurred in Mana Pools, Zimbabwe. The construction of Kariba Dam significantly reduced the flooding causing a lack of regeneration of *F. albida* woodlands on the floodplain and old islands in the Zambezi River (Ncube *et al.*, 2012). The size distribution of established woodlands could be linked to flood periods prior to the building of the Kariba Dam. Regeneration shifted to new river islands created by an altered Zambezi River morphology and new lower flood height regime (Gope *et al.,* 2014).

The conditions under which the initial establishment of the *F. albida* woodlands in the MCP occurred should be a template for successful regeneration. It is postulated that the woodlands that established before 1942, after 1970, after 1977 and after 2000 occupied all the available suitable sites on those dates. The removal of woodlands by the floods of 2013 created new open areas for regeneration to occur. The largest areas available for regeneration were:

- 8 ha in group 1 areas on Dundee and Oakleaf soils; FR3 (Dundee soils), FR4 (Oakleaf soils), and FR8 (Dundee soils);
- 15 ha in the group 2 area (Mangala, FR2) on Oakleaf soils with the upper soil layer removed by the 2013 flood;
- 31 ha along the length of the expanded river channel between Mangala and the bridge on newly deposited Dundee soils.

In group 1 areas there was an elephant and mesobrowser browse trap (impala, porcupine, nyala in ranked order) from which most seedlings did not escape and which caused a decline in the number of seedlings. For the few seedlings that progress to saplings there was an elephant browse trap from

which saplings did not escaped and which caused a declined in the number of saplings. Elephants and mesobrowsers populations in 2013 were much higher than when the woodlands established.

The group 2 area appeared to be progressing to a low density mixed species woodland dominated by *V. tortilis*, with *F. albida* as a secondary species, which may be a succession process leading ultimately to a *F. albida* woodland. Elephants selectively impacted *F. albida* more than *V. tortilis*. The impact of impala was not determined but porcupines excavated both seedlings and saplings.

No monospecific *F. albida* regeneration patches that achieved the density criterion occurred in the expanded river channel.

Rainfall was normal within the context of the high rainfall variability and there were no floods after 2013 but this did not appear to have affected the regeneration, or any effect was masked by the impact of browsers.

5.5. SUMMARY

5.5.1. ESTABLISHMENT PHASE

Woodlands existed in 1942 and new woodlands established after 1970, after 1977 and after 2000. Five main ecological drivers played a role, as summarised in table 5.5. It is difficult to rank the role of the ecological drivers but if the Makuleke people had not been removed the woodlands would not have established after 1970.

Table 5.5*:* Ecological drivers that affected the establishment of the monospecific *F. albida* woodlands

ESTABLISHMENT PERIOD	ANTHROPOGENIC FACTORS	CLIMATE and HYDROLOGY	GEOLOGY and SOILS	ELEPHANTS	MESOBROWERS
BEFORE 1942 (82 ha) (FW1, FW2, FW4, FW9)	No effects. No dams or upstream water extraction.	Narrow Luvuvhu River with frequent floods to sustain the woodlands.	Suitable Dundee and Oakleaf soils.	No elephants to prevent woodland establishment.	Unknown effect. Population probably small relative to area of establishing woodland.
AFTER 1970 (41 ha) (FW5, FW6, FW7)	Removal of the Makuleke people released areas previously farmed for establishment of woodlands.	Narrow Luvuvhu River with frequent floods to sustain the woodlands. Ten years of above average rainfall.	Suitable Oakleaf soils.	Few elephants to prevent woodland establishment.	Unknown effect. Population probably small relative to area of establishing woodland.
AFTER 1977 (2,5 ha) (FW10)	No effect.	No negative or positive effects.	Suitable Dundee soils. Ideal position adjacent to the river.	Few elephants to prevent woodland establishment.	Unknown effect. Population probably small relative to area of establishing woodland.
AFTER 2000 (2,8 ha) (FW4)	No effect.	Establishment started after the flood in 2000.	Suitable Oakleaf soils. Ideal position adjacent to the river.	Elephant population increasing but insufficient to prevent woodland establishment.	Unknown effect. Population increasing.

5.5.2. DECLINE PHASE

The decline of the monospecific *F. albida* woodlands was a result of two extreme floods of the Luvuvhu River which occurred in February 2000 and January 2013. Woodlands FW1, FW3, FW4 and FW8 were affected. The elephant and mesobrowser impacts were minimal and there was no senescence. This is summarised in table 5.6.

Table 5.6: Ecological drivers that affected the decline of the monospecific *F. albida* woodlands

Anthropogenic	No effect confirmed.
Climate and hydrology	The extreme floods of Feb 2000 and Jan 2013 caused a decline of the woodlands.
Elephants	The decline was not caused by elephants.
Mesobrowsers	The decline was not caused by mesobrowsers.
Senescence	No early senescence occurred.
Soils	Soil played no role.

5.5.3. REGENERATION PHASE

The main ecological drivers that affected the regeneration are summarised in table 5.7. In comparison to when the woodlands established, the elephant and mesobrowser populations had increased.

Table 5.7: Ecological drivers that affected the regeneration of the monospecific *F. albida* woodlands

	MONOSPECIFIC CHARACTER	CLIMATE (FLOODS)	GEOLOGY AND SOILS	ELEPHANTS	MESOBROWSERS	REGENERATION PROGRESS
GROUP 1 (FR3,FR4, FR5,FR8)	Monospecific seedlings and saplings	Appeared to be initiated by 2013 flood.	Oakleaf and Dundee soils.	Browse trap exists.	Browse trap exists.	Regeneration declining. Expected to disappear.
GROUP 2 (FR2A)	Mixed species seedlings and saplings. *V. tortilis* dominant. *F. albida* a secondary species.	After 2013 but may not have been initiated by 2013 flood.	Eroded Oakleaf soils. Seed bed may have been been removed.	Regeneration slowly escaping the browse trap. Elephants selecting for *F. albida* .	Regeneration slowly escaping the browse trap but not conclusive.	Low density mixed species woodland establishing. *F. albida* at low density.

6. CONCLUSION AND RECOMMENDATIONS

6.2. THE TALE OF TWO WOODLANDS

The monospecific *V. xanthophloea* and *F. albida* woodlands are both icons of the MCP and important components of the Makuleke Ramsar Wetland ecosystem and its ecotourism assets. Their current spatial distribution in different areas of the floodplains was determined by the historical influence of various ecological drivers.

The dynamics of these two woodlands over a period of 78 years are summarised in tables 6.1 and 6.2 in response to the dynamics of the main ecological drivers and are schematically represented in figure 6.1. Table 6.3 gives a comparison of the basic characteristics, life histories and responses to ecological drivers. The dynamics of the two woodlands were different and all were affected by gradual changes in driver dynamics as well as episodic driver events.

The establishment phase of both woodlands followed episodic events and created woodlands where the trees within each woodland were cohorts of the same age, and in some cases different woodlands were also the same age.

The decline of the *V. xanthophloea* woodlands was caused by direct elephant impact and stress induced premature senescence. In contrast, the removal of portion of the *F. albida* woodlands followed major episodic flood events.

The regeneration phase of both woodlands was initiated by the episodic flood event in 2013 and created patches of seedlings and saplings that were cohorts of the same age, but regeneration progress was terminated or severely affected by mesobrowsers and elephants.

The demographic bottleneck model (fig 2.1) was applicable to the MCP woodlands (stage 1; seed production and seed dispersal was not studied). Six key ecological drivers were identified – the answers to the research questions as summarised in chapters 4.5 and 5.5 – and their roles differentially affecting the different woodlands through the different phases, both positive and negative are summarised in table 6.4. These key ecological drivers were:

- anthropogenic factors
- climate and floodplain hydrology
- geology and soils
- elephants
- mesobrowsers
- senescence

Other secondary ecological drivers were identified as wind, fire, and wood boring insects.

In neither woodland was the regeneration of new monospecific woodland replacing the woodland that had declined. The regenerating area of V*. xanthophloea* woodland in 2018 was less than 10% of the area of mature woodland that existed in 2005. The mature V*. xanthophloea* woodland was continuing to decline while the regenerating areas had yet to break through the elephant browse trap. The regeneration of monospecific *F. albida* woodland had been halted and reversed by the browse traps of elephants and mesobrowsers. Some *F. albida* was regenerating into a mixed species woodland.

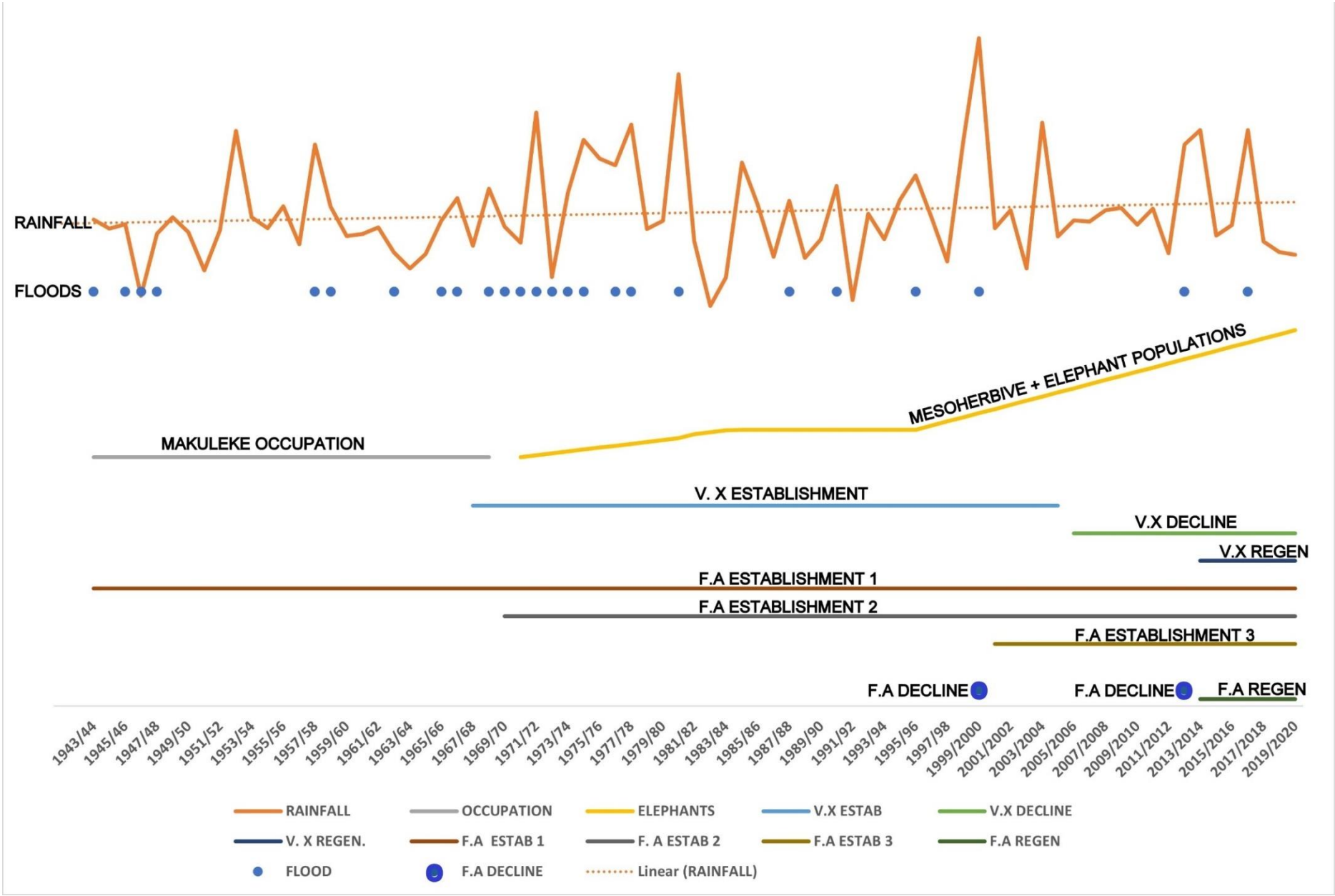


Figure 6.1: Schematic representation of the different ecological drivers over time affecting the dynamics of the monospecific *V. xanthophloea* and *F. albida* woodlands.

Table 6.1: *V. xanthophloea* woodland response to key ecological drivers timeline

ECOLOGICAL DRIVER	1942 - 1969	1969	1970 - 2000	2000	2001 - 2013	2013	2013 - 2020	POST 2020
ANTHROPOGENIC FACTORS	Makuleke people farmed the suitable areas, and removed trees.	Makuleke people removed from the area.	Farming ceased. Area incorporated into KNP. MPC a protected area.	MCP a protected area.	MCP a protected area.	MCP a protected area.	MCP a protected area.	MCP a protected area.
CLIMATE			Above average rainfall and frequent floods.	Major flood in February 2000.	Below average rainfall. Fewer floods.	Major flood in January 2013.	Rainfall average. Minor flood in 2017 Sub-optimal areas not flooded.	Unpredictable but fewer floods expected.
GEOLOGY AND SOILS	Area of suitable soils farmed.	Area of suitable soils farmed up to 1969.	Area of suitable soils available for woodland establishment.		Small areas of suitable soils availble.		Small areas of suitable soils available.	
ELEPHANTS	None.	Very few.	Very few but increasing.	Increasing.	Increasing.	High elephant densities.	High elephant densities.	Increasing elephant densities expected.
MESOBROWSERS	Very few.	Very few.	Very few but increasing.	Increasing.	Increasing.	High densities.	High densities.	High densities expected.
SENESCENCE					Premature senescence.		Premature senescence.	Senescence will continue.
WOODLAND RESPONSE	No woodland established due to farming activity.	No woodland established due to farming activity.	Period of woodland establishment in optimal and sub-optimal areas due to ideal climate and frequency of flooding 1970 - 1980.	Flooding had no detrimental effect on mature woodlands. No record of mass regeneration.	Mature woodland declined from 2005 due to impact elephant Woodlands in sub-optimal conditions disappeared due to premature senescence.	Flood had no detrimental effect on mature woodlands. Limited regeneration commenced in areas outside existing woodlands.	Mature woodland decline accelerated, due to elephants and senescence. Elephants the major driver of decline. Some regeneration areas eliminated due to mesobrowsers and sub-optimal conditions. Other regeneration impacted but may not escape the elephant browse trap. Surviving regeneration areas less than 10% of area of original woodlands.	Mature woodland decline will continue with elephants as the major driver. Existing surviving regeneration may not escape the elephant browse trap. Future regeneration dependent primarily on limited availability of prime habitat, enabling flood and climate conditions and reduced top down browse control.

Table 6.2: *F. albida* woodland response to key ecological drivers timeline

ECOLOGICAL DRIVER	1942 - 1969	1969	1970 - 2000	2000	2001 - 2013	2013	2013 - 2018	POST 2018 (PROJECTED)
ANTHROPONENIC FACTORS	Makuleke people farmed some suitable areas, and removed trees. Woodlands in some areas not farmed.	Makuleke people removed from area.	Farming ceased. Area incorporated into KNP. MCP now a protected area.	MCP a protected area.	MCP a protected area.	MCP a protected area.	MCP a protected area.	MCP a protected area.
CLIMATE			Above average rainfall and frequent floods.	Major flood in February 2000.	Below average rainfall. Fewer floods.	Major flood in January 2013.	Average rainfall. 2017 flood did not reach regeneration areas.	Unpredictable but fewer floods expected.
GEOLOGY AND SOILS	Some areas of suitable soils farmed.	Some areas of suitable soils farmed.	Farmed areas available for woodland establishment.		Areas of suitable soils available where floods removed woodland.		Areas of suitable soils available where floods removed woodland.	
ELEPHANTS	None.	Very few.	Very few but increasing.	Increasing.	Increasing.	High elephant densities.	High elephant densities.	Increasing elephant densities expected.
MESOBROWSERS	Very few.	Very few.	Very few but increasing.	Increasing.	Increasing.	High densities.	High densities.	High densities expected.
SENESCENCE					None.		None.	None.
WOODLAND RESPONSE	Woodland established before 1942 persists. No woodland in farming areas.	Woodland established before 1943 persists. No woodland in farming areas.	Period of woodland establishment in suitable previously farmed areas due to ideal climate and frequency of flooding 1970 - 1980	Major areas of woodland removed by floods. New Luvuvhu channel cut. Floodplains flooded and regeneration commenced at FW2 and FW4.	Regeneration progressed to establishment. FW2 and FW4 regeneration reached woodland status.	Major areas of woodland removed by flood. New Luvuvhu channel cut. Some flood mortality in FW4. All other regeneration after 2000 removed. Floodplains flooded and new regeneration commenced.	FW4 woodland growth continued. Regeneration after 2013 unable to escape the mesobrowser and elephant browse traps. Regenerating saplings in major decline. FW2 regenerating to mainly *V. tortilis* woodland.	Mature woodland will persist. Regen after 2013 will not escape the browse trap. FW2 will become mainly *V. tortilis* woodland. Any future regeneration will be dependent primarily on enabling flood and climate conditions, and reduced top down browse control.
					Minimal elephant impact on mature woodland.	Minimal elephant impact on mature woodland.	Minimal elephant impact on mature woodland.	Minimal elephant impact on mature woodland expected.

Table 6.3: Comparison of *V. xanthophloea* and *F. albida* monospecific woodlands

	VACHELLIA XANTHOPHLOEA	*FAIDHERBIA ALBIDA*
	SPECIES GENERAL CHARACTERISTICS	
1	Family Mimosaceae. Bipinately compound leaves. Thorns.	Family Mimosaceae. Bipinately compound leaves. Thorns.
2	Normal phenology. Loses leaves in winter.	Reverse phenology. Loses leaves in summer.
3	Short life expected to be less than 70 years.	Long life probably in excess of 150 years.
4	Grows in low lying wet or damp areas.	Grows on free draining alluvial soils.
5	Shallow root system, and vulnerable to drought.	Deep root system, and able to survive droughts.
6	Not fire resistant.	Fire resistant.
	SEEDLINGS AND SAPLINGS GENERAL CHARACTERISTICS	SEEDLINGS AND SAPLINGS GENERAL CHARACTERISTICS
7	Mass germination flood initiated.	Mass germination flood initiated.
8	Fast growing, about 1 m per year.	Fast growing, about 1 m per year.
9	Subject to mesoherbivore browsing causing a browse trap.	Subject to mesoherbivore browsing causing a browse trap.
10	Subject to elephant browsing causing a browse trap.	Subject to elephant browsing causing a browse trap.
11	Coppice when stem broken.	Coppice when stem broken.
	DYNAMICS UNDER MAKULEKE CONDITIONS	DYNAMICS UNDER MAKULEKE CONDITIONS
	HABITAT AND ESTABLISHMENT	HABITAT AND ESTABLISHMENT
12	Occurred mainly on Arcadia soils, some on Duplex soils.	Occurred mainly on Oakleaf soils, some on Dundee soils.
13	Monospecific woodlands established after episodic events of above average rainfall, frequent floods , minimal browsing, Makuleke people removed.	Monospecific woodlands established after episodic events of above average rainfall, frequent floods , minimal browsing, Makuleke people removed.
	WOODLAND DECLINE	WOODLAND DECLINE
14	Woodlands not removed by the floods.	Extreme floods the major cause of woodland decline.
15	Elephants were a major cause of mature woodland decline by pushover.	Elephant impact on mature woodlands minimal.
16	Elephant bark stripping but no ring barking.	Elephant bark stripping but no ring barking.
17	Porcupine bark stripping with limited ring barking.	No porcupine bark stripping.
18	Trunk invaded by woodborer where bark stripped.	Trunk not invaded by woodborer where bark stripped.
19	Susceptable to wind induced felling.	Not susceptable to wind induced felling.
20	Susceptable to fire induced mortality where flamable understory exists.	Not susceptable to fire induced mortality, no flamable understory.
	REGENERATION	REGENERATION
21	Regeneration initiated by floods of 2000 and 2013.	Regeneration initiated by floods of 2000 and 2013.
22	Elephant and small browsers browsed seedlings.	Elephant, small browsers and porcupine browsed seedlings.
23	Larger regeneration area allowed some seedlings to escape the browse trap. Some recruitment into saplings.	Smaller regeneration area, difficult for seedlings to escape browse trap. Minimal recruitment into saplings.
24	Saplings may be able to escape the elephant browse trap.	Saplings unable to escape the elephant browse trap, except FW2 (Mangala).
25	Regeneration on "sub-optimal" Duplex soils may fail.	No regeneration on soils other than Dundee and Oakleaf.
26	Regeneration not replacing the decline in mature woodlands.	Regeneration not replacing the mature woodland that was removed.

Table 6.4: The main ecological drivers affecting the dynamics of the *V. xanthophloea* and *F. albida* woodlands

	V. XANTHOPHLOEA	*F. ALBIDA*
QUESTION 1: ESTABLISHMENT		
RELEVANT DATES	No woodlands were established in 1942 (earliest photographs). Woodlands established after 1970.	Some woodlands were established before 1942 (earliest photographs). New woodlands established after 1970, after 1977 and after 2000.
ANTHROPOGENIC	Removal of the Makuleke people in 1969 released suitable areas previously being farmed. Trees had previously been removed in farmed areas.	Removal of the Makuleke people in 1969 released suitable areas previously being farmed. Trees had previously been removed in farmed areas.
CLIMATE	Frequent floods and above average rainfall during 1970 to 1980 created ideal climatic conditions.	Frequent floods and above average rainfall during 1970 to 1980 created ideal conditions for establishment after 1970. Establishment after 1977 was adjacent to the Luvuvhu River, so climate was less important. Floods in 2000 cleared the FW4 woodland, and created ideal conditions for new FW4 woodland to establish close to the river.
GEOLOGY AND SOILS	Arcadia soils combined with the climate created ideal conditions for establishment after 1970.	Oakleaf soils combined with the climate created ideal conditions for establishment after 1970 Dundee soils adjacent to the river were ideal for establishment after 1977. Oakleaf soils of FW4 close to the river were ideal for establishment after 2000.
ELEPHANTS	Few elephants existed so establishing woodlands could escape the elephant browse trap.	Few elephants existed so establishing woodlands could escape the elephant browse trap.
MESOBROWSERS	Few mesobrowsers existed so establishing woodlands could escape the mesobrowser trap.	Few mesobrowsers existed so establishing woodlands could escape the mesobrowser trap.
QUESTION 2: DECLINE		
RELEVANT DATES	Decline commenced in about 2005 and was a continuous phenomenon.	Decline occurred in 2000 and 2013.
CLIMATE	Fewer floods. Possible climate effect caused premature senescence.	Decline due to the major floods of 2000 and 2013. About 77ha was removed. (37 ha *F. albida*). The FW4 woodland 13 year old regeneration after 2000 suffered some mortality from the 2013 floods but growth of trees continued.
GEOLOGY AND SOILS	The largest non elephant induced mortality occurred on higher elevation floodplain in areas of Duplex soils(in 2000) and without regular floods. Considered to be sub-optimal conditions.	Geology and soils had no effect.
ELEPHANTS	The increased elephant population made elephant induced mortality (tree pushover) the largest driver.	Elephant impact minimal.
MESOBROWSERS	Ring barking by porcupines caused mimimal mortality.	No mesobrowser impact.
SENESCENCE	Adverse climate, few floods and soils caused premature senescence. Decline started at about 35 years. Expected woodland life of less than 70 years	No climate induced scenescence was observed. Expected woodland life of more than 150 years.
WIND	One instance of multiple trees felled by a windstorm.	No wind induced mortality.

Table 6.4 (continued): The main ecological drivers affecting the dynamics of the *V. xanthophloea* and *F. albida* woodlands

	V. XANTHOPHLOEA	*F. ALBIDA*
QUESTION 3: REGENERATION		
RELEVANT DATES	Post 2013 floods	Post 2013 floods
CLIMATE	Large flood in 2013 created ideal initial climatic conditions twhich initiated regeneration. Conditions deteriorated with subsequent lower rainfall and no floods.	Large flood in 2013 created ideal initial climatic conditions to initiate regeneration.
GEOLOGY AND SOILS	Arcadia and Duplex soils combined with the climate created initial suitable conditions. With no regeneration under existing canopy, limited area for regeneration was available. With deteriorating climatic conditions regeneration on Duplex soils declined due to moisture stress in combination with browsing impact.	Oakleaf soils combined with the climate created ideal conditions, except at FW2 where up to 2 meters the top soil layer was removed. With no regeneration under existing canopy, mainly areas cleared by the flood were available for regeneration.
ELEPHANTS	The increased elephant population eliminated some areas of regeneration at seedling and sapling stages. Other areas had not escaped the elephant browse trap.	The few saplings that were able to escape the mesobrowser trap were unable to escape the elephant browse trap.
MESOBROWSERS	The increased mesobrowser population eliminated some areas of regeneration at seedling stage.	Most seedlings were unable to escape the mesobrowser (mainly impala and porcupine) browse trap.
QUESTION 4: LANDSCAPE SCALE REGENERATION		
	The mature woodlands were in decline. The area of regenerating saplings in 2020 was less than 10% of mature woodland that existed at its peak in about 2005. Saplings had not escaped the elephant browse trap to progress to mature woodland.	The mature woodlands post 2013 were not in ongoing decline. Woodlands removed in 2000 and 2013 created areas for regeneration to commence. Regeneration had not been able to escape the browse traps and was not replacing woodland removed in 2000 and 2013. Only a limited number of saplings in locations difficult for elephants to access were surviving but these were not monospecific woodlands. FW2 was regenerating to a mixed woodland dominated by *V. tortilis* . The regeneration will not replace woodland removed by the floods.

6.3. THE FUTURE

Ecosystem dynamics are notoriously difficult to predict. Floodplains are a complex adaptive system. History can only act as a template that can help create future scenarios. The historical roles of the ecological drivers affecting the MCP woodlands have been demonstrated. Four deserve special mention regarding the future.

A recent study of the megaherbivore response to drought in the Greater Kruger National Park concluded that the elephant population is not close to experiencing resource limitations (Smit *et al*., 2020). Under this scenario both existing woodland species will experience increasing impact, decline of the *V. xanthophloea* woodlands will continue, and any future regeneration of both woodlands if not on a large scale, is unlikely to succeed. In Amboseli National Park, Kenya, elephants were the only factor preventing *V. xanthophloea* woodland recovery (Western and Maitumo, 2009).

The mesobrowser population is unlikely to reduce. Any future regeneration will need to escape the mesobrowser browse trap.

A changing flood regime poses an additional threat. This could be due to climate change or anthropogenic influences. In recent years regular releases of water from Nandoni Dam have been necessary to keep the Luvuvhu River in the MCP flowing in the dry season (Dr Eddie Riddell, Manager: Aquatic Biodiversity Management, KNP, pers comm). This is likely to be an ongoing requirement. Luvuvhu floodplain water table levels from DWA boreholes indicated that the bank aquifer and floodplain water table are supplied by lateral flow from the Luvuvhu River base flow and small or medium sized floods (reported in Botha, 2001). A study by the DWA (Louw, 1994) predicted the construction of the Nandoni Dam on the Luvuvhu River in 2005 would decrease base flow by 40%. The widening of the macro channel by the floods of 2000 and 2013 and the retention and controlled release of water from the dam will affect the flood regime with less frequent floods and possible lowering of the floodplain water table. This is likely to accelerate premature senescence in the *V. xanthophloea* woodlands and negatively affect regeneration of both woodlands. Increased water extraction from the Limpopo River and its tributaries is likely to have a similar effect on the Limpopo floodplain.

When the woodlands established, they appeared to have occupied all available suitable habitat. Neither woodland species regenerated under canopy so regeneration can only occur following substantial decline of the woodlands and subsequent availability of suitable habitat. While the existing woodlands persist, optimal habitat for new regeneration will be limited.

The *V. xanthophloea* woodlands have a life expectancy of about 70 years under good conditions. The current woodlands are about 50 years old but in decline, which commenced at about 35 years, due to the impact of an increasing elephant population and premature senescence.

F. albida woodlands appear to have a life expectancy of about 150 years, although this is not well documented in the literature. With its deep root system, it is well adapted to the MCP climate and flood regime provided the floods are not extreme.

The two woodlands each appear to be in a long-term cycle of establishment, decline and regeneration as monospecific woodlands. This cycle is probably less than 100 years For *V. xanthophloea* and in excess of 150 years for *F. albida* but dependent on a favourable climate and flood regime, and fewer elephants and mesobrowsers.

6.4. RECOMMENDATIONS

Anthropogenic factors external to the MCP will play an overarching role affecting ecological drivers through such influences as climate change, damming and abstraction of river water, poaching and artificial barriers influencing animal movements. Elephants are the main ecological driver within the MCP that will affect the future. Conservation policies can influence some of these ecological drivers, especially policies with regard to elephants. Elephants are acknowledged as ecosystem engineers and keystone species, and the increasing population in the MCP has been shown to be a major ecological driver of the dynamics of the *V. xanthophloea* and *F. albida* woodlands and therefore the Makuleke Ramsar Wetlands ecosystem. The MCP with the Limpopo and Luvuvhu Rivers, the wetland pans and the floodplain vegetation, is likely to remain a concentration point for elephants seeking a refuge with abundant resources of water and food. If climate change results in hotter and drier conditions this could farther concentrate an increasing elephant population in the MCP in the future. Understanding the dynamics of the MCP elephants is key.

This study addressed the *V. xanthophloea* and *F. albida* woodlands. The *V. xanthophloea* woodlands are under threat from elephants. The MCP has amazing vegetation diversity and elephants are likely key ecological drivers of many of the other tree species. A broader research project that carefully monitors the elephant population (using regular censuses), elephant spatio-temporal movements (using satellite tracking and camera traps) and woodland demographics of an expanded range of woodland species would contribute significantly to Makuleke Ramsar Wetland monitoring and an adaptive elephant management policy for the MCP. This project should incorporate elephant impact mitigation measures such as elephant exclusion zones (physical barriers), and elephant reduction zones (the creation of fear landscapes avoided by elephants).

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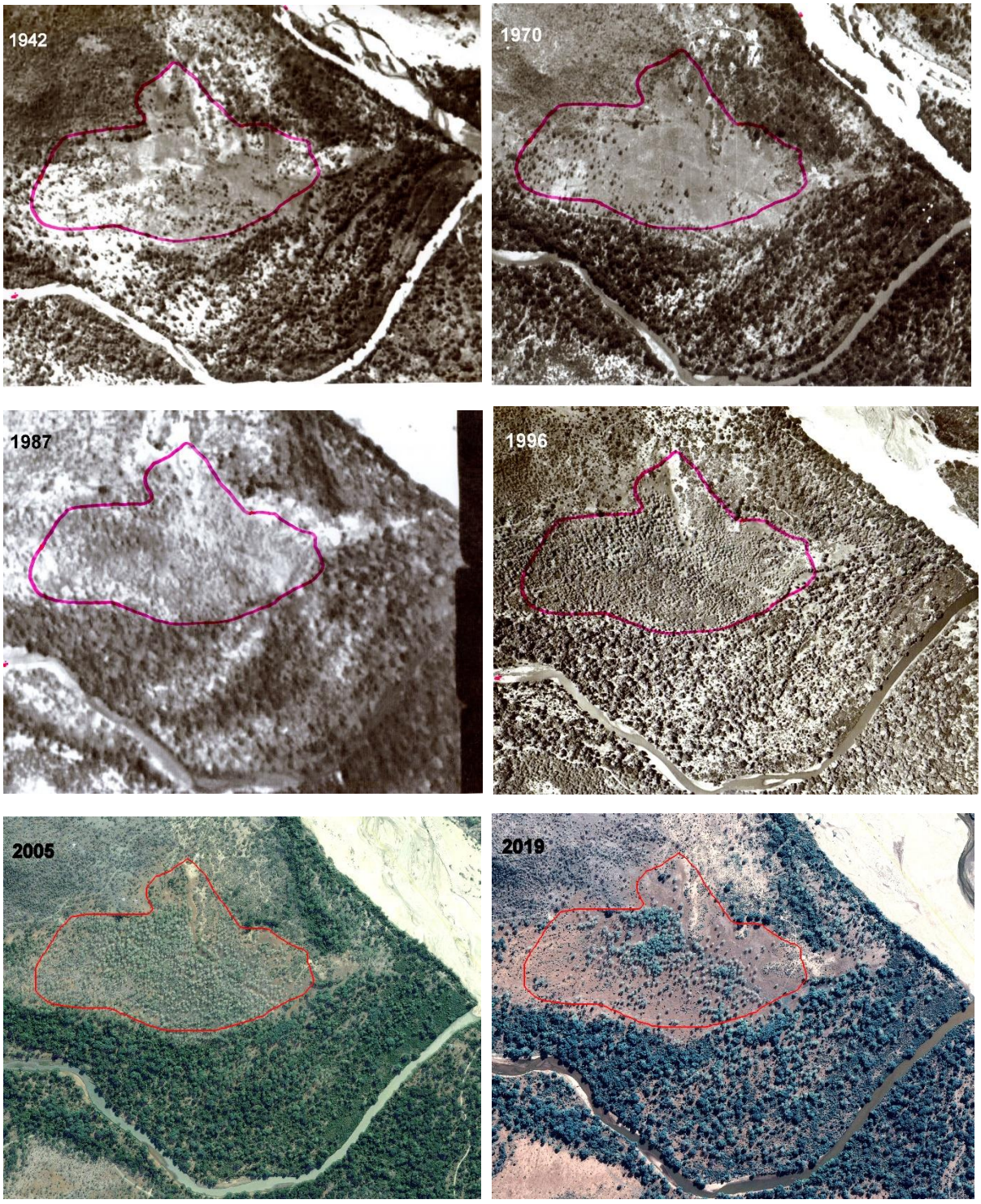
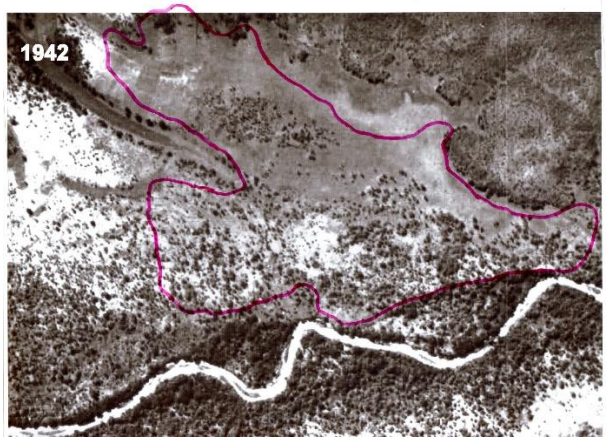
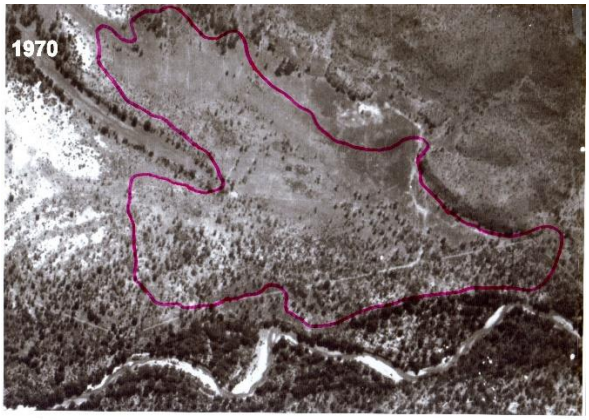
APPENDIX 1 SEQUENTIAL AERIAL PHOTOGRAPHS (1942, 1970, 1987, AND 1996) AND GOOGLE EARTH IMAGERY (2005 AND 2019) FOR WOODLANDS VW8, VW9 AND VW1 ILLUSTRATING THE ESTABLISHMENT PHASE (FROM 1970 TO ABOUT 2005) AND DECLINE PHASE (AFTER ABOUT 2005) OF THESE WOODLANDS

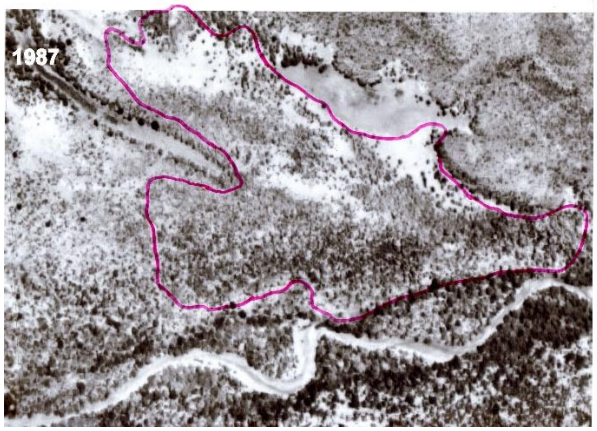
WOODLAND VW8

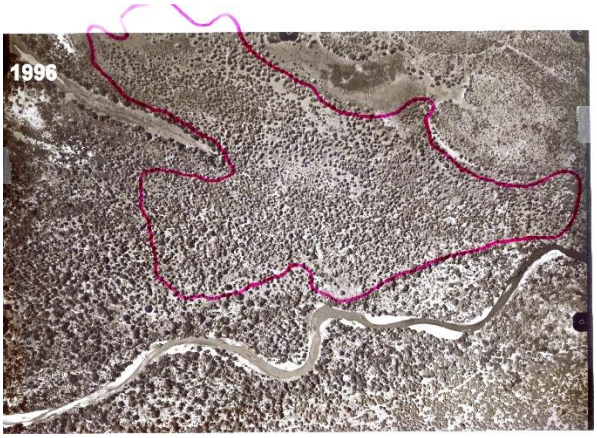


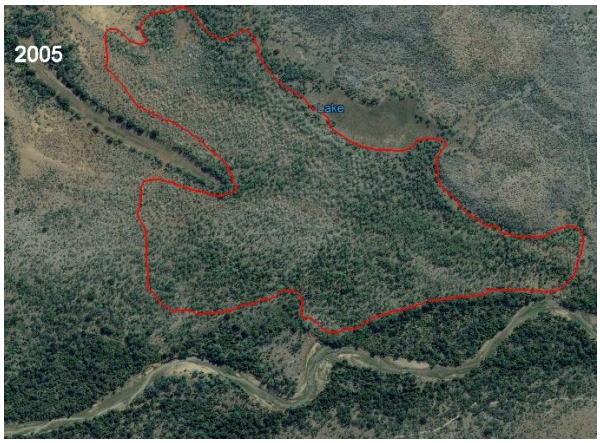
WOODLAND VW9



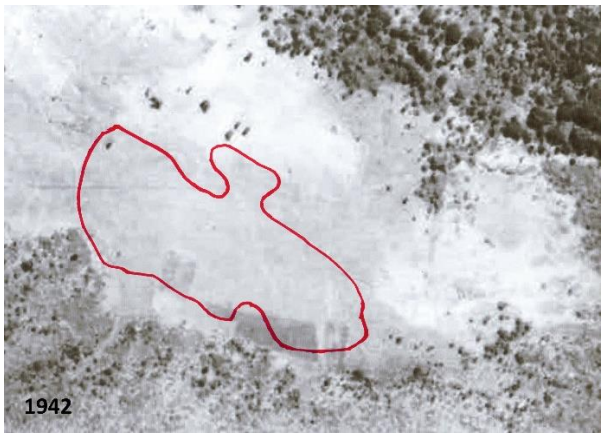


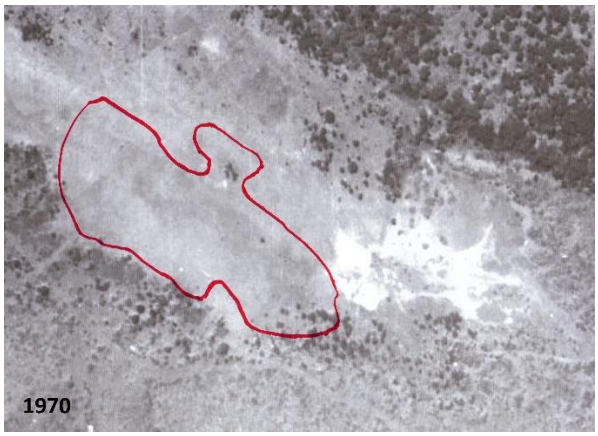


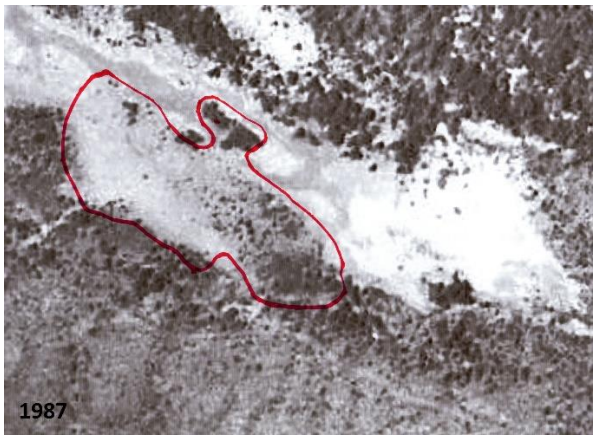


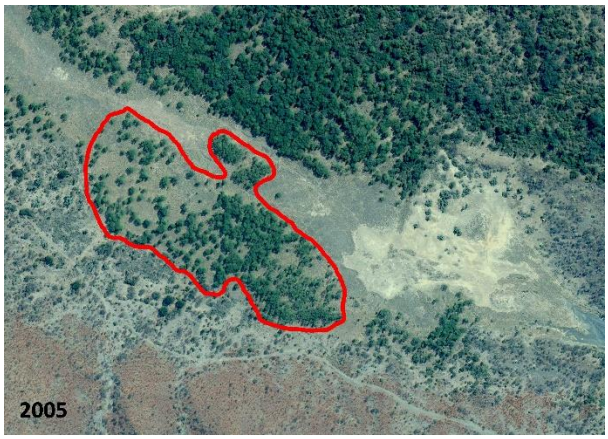


WOODLAND VW1









APPENDIX 2 ONE-WAY ANOVA ANALYSES

2.1: Summary of one-way Anova on the diameters of *V. xanthophloea* woodlands using the Excel single-factor ANOVA program, alpha 0,05

SUMMARY

GROUPS	COUNT	SUM	AVERAGE DIAMETER mm	VARIANCE	STANDARD DEVIATION
VW1	12	5436	453	1416	38
VW2	15	6409	427	7326	85
VW3	15	6739	449	4086	64
VW5	23	13137	571	13577	116
VW6	16	7472	467	11708	108
VW8	15	7055	467	4730	69
VW9	25	12333	493	12936	113

ANOVA: WOODLANDS VW1, VW2, VW3, VW5, VW6, VW8, VW9

SOURCE OF VARIATIOR	SS	df	MS	F	P-value	F crit
BETWEEN GROUPS	263812	6	43969	4,88	0,00018	2,18
WITHIN GROUPS	1026341	114	9003			
TOTAL	1290152	120				

ANOVA: WOODLANDS VW1, VW2, VW3, VW6, VW8, VW9 (VW5 EXCLUDED)

SOURCE OF VARIATIOR	SS	df	MS	F	P-value	F crit
BETWEEN GROUPS	46651	5	9330	1.18	0,325	2,31
WITHIN GROUPS	727651	92	7909			
TOTAL	774302	97				

2.2: Summary of one-way Anova on the diameters of *F. albida* woodlands using the Excel single-factor ANOVA program, alpha 0,05

SUMMARY

GROUPS	COUNT	SUM	AVERAGE DIAMETER mm	VARIANCE	STANDARD DEVIATION
FW5	29	18428	635	23694	154
FW6	56	25244	451	5617	75
FW7	18	9940	552	14618	121

ANOVA: WOODLANDS FW5, FW6, FW7

SOURCE OF VARIATIOR	SS	df	MS	F	P-value	F crit
BETWEEN GROUPS	673414	2	336707	27,50	3,0E-10	3,09
WITHIN GROUPS	1224315	100	12243			
TOTAL	774302	102				