Seventy years of changes in riverine woodland cover: Responses to elephants and human legacy effects in Gonarezhou National Park, Zimbabwe

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ABSTRACT

As global biodiversity decreases, the importance of protected areas for protecting biodiversity and ecosystem complexity, is rising. Increasing development and land use change means that protected areas must restrict species to their boundaries to avoid human-wildlife conflict. Populations of species therefore no longer disperse, and overpopulation can occur. In southern African savanna systems, large populations of savanna elephant (*Loxodonta africana*) are transforming woodland and reducing vegetation diversity.

While historically large, the elephant population in Gonarezhou National Park in Zimbabwe has grown at >5% annually since 1992, and densities currently exceed 2 elephants km^{-2}. Over the last 70 years, riverine woodland vegetation has undergone substantial changes. While initially it might be compelling to hold elephants responsible, Gonarezhou National Park has a complex natural and socio-ecological history to consider. Before proclamation in 1974, areas supporting woody riverine vegetation along Gonarezhou National Park's biggest river, the Runde, were widely cultivated. Some riverine vegetation was also cleared in the late 1950s to prevent the spread of tsetse fly (a vector for African Sleeping Sickness). This study makes use of aerial photography and satellite imagery of the Runde River, and its confluence with the Save River, covering the period 1948 to 2018. Using supervised classification techniques, imagery was analysed to identify vegetation types and provide an estimation of riverine woodland cover. Further analyses were conducted to assess characteristics and possible drivers of change.

Percentage cover of woody riverine vegetation along the Runde River, covering a total area of 60.2 km^2, varied greatly over time, rising initially from 14% cover in 1948 to 40% cover in 2005 with cessation of cultivation and clearing for tsetse fly after the park was proclaimed. It then decreased by 20% between 2005 and 2018 most likely due to high populations of elephants and severe droughts. Confirmation that elephants have caused a decrease in woody cover of riverine woodland within Gonarezhou National Park was gained from comparing a plot inside the park boundary with an equivalent plot outside the park boundary that has supported a lower density of elephants. Woodland cover in these plots showed a significant reduction inside the park boundary suggesting elephants have driven this decline. The area of riverine woodland which was previously cultivated (3.3 km^2 along the Runde River) supported between 1% and 12% less riverine woodland cover than areas

which were not cultivated for each year of assessment, but the differences were not significant. The area of riverine woodland cleared for tsetse fly control (0.4 km^2 along the Runde River) in the late 1950s supported between 8% and 25% less riverine woodland cover than uncleared areas in each year. Although some recovery is evident, there is a significant long-term influence of tsetse clearing on riverine woodland vegetation cover in Gonarezhou National Park.

Elephant impacts are expected to decline with distance from permanent water. However, examination of changes in woody cover along a seasonal river, offering a potential refugium, yielded variable results. By 2018 a decrease in woodland cover adjacent to the permanent water source of the Runde River was apparent, suggesting that riverine woody vegetation near permanent water is most affected by elephant damage. A hypothesis that elephant impact on woodlands is lessened where there is a concentration of alternative food sources, especially hygrophilous grassland and *Faidherbia albida* pods, was examined. Woody cover along the Runde at its junction with the Save, which has substantial alternative forage, was compared to upstream areas without such alternatives. In 2018 a decrease in woody cover is shown with distance from alternative food sources, suggesting elephants use woodland more intensively when alternative forage is unavailable. The probable influence of drought and flooding events on reducing alternative forage and woody cover, requires further consideration.

Woody cover is a crude index of change as it does not account for structure or composition of woodland below the canopy. As a result, if a significant change is detected, we can be quite confident that the change has occurred. However, if there is no significant change, this does not necessarily mean that changes have not taken place, they simply may not be detected by such a crude measure. Analysis of woodland cover serves as a starting point. Time and resource limitations meant that structure and composition could not be considered in this study. However, such measures would increase the accuracy of analysis in future studies.

Overall, this study demonstrates the importance of considering all possible influences on vegetation change. Strong evidence was provided that elephants impact upon woody vegetation change over time. However, the longer-term influences of cultivation and tsetse clearing and, availability of refugia and alternative forage cannot be disregarded. An assiduous approach is required lest we falsely attribute blame to elephants alone, the management consequences of which are profound.

1. INTRODUCTION

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services released a global assessment in 2019, detailing the threats to biodiversity worldwide. Over one million species are now threatened with extinction. The report cites five key drivers of decline, principal amongst them is changes in land use leading to loss of habitat available to flora and fauna (IPBES, 2019). This loss of habitat can be countered with protected areas, a conservation mechanism widely used across the globe (Le Saout et al., 2013; Stoll-Kleemann and Job, 2008). While 'fortress-type' biodiversity management has been criticized for excluding people who depend on the land, it is understood that together with supporting alternative livelihoods, and in coordination with community or development-based conservation approaches, it is essential to protecting biodiversity (Mombeshora and le Bel, 2009; Wilkie et al., 2006).

Protected areas dedicate land specifically to supporting biodiversity. Critical to achieving this goal is maintaining ecosystem functioning which dictates that all species at each trophic level are protected to support the overall ecosystem (DeFries et al., 2007; Le Saout et al., 2013). However, the reduced spatial scale of protected areas, particularly when fenced, creates challenges for maintaining this complexity. Processes such as migration are hindered, and where a growing population of a species might normally migrate into new space and habitat, instead we begin to see the impacts of overpopulation (Dunham, 2012; Vanak et al., 2010). Impacts up and down the trophic ladder are heightened when the species population which is growing is an ecosystem engineer (Jones et al., 1997).

Ecosystem engineers are organisms whose occurrence or activity shifts the availability of resources thereby altering ecosystem or habitat structure and functioning (Crain and Bertness, 2006; Jones et al., 2010). A supreme example for Africa is the elephant (*Loxodonta africana*) whose presence in large numbers engineer the ecosystem by transforming vegetation thus threatening biodiversity (Cumming et al., 1997; Skarpe et al., 2004; Tafangenyasha, 1997). Elephants can transform forest and woodland vegetation in a short period of time through behaviours such as bark stripping, toppling, and pollarding alongside excessive consumption of foliage when alternative food sources are unavailable. These qualities, place large elephant populations in direct conflict with the goals of many national parks, specifically, to maintain biodiversity (Guldemond and Van Aarde, 2008). Therefore, investigation of their impact helps to inform park management and may identify effective mitigation of detrimental impacts to maintain functional ecosystems.

Environmental stewardship is facing increasing uncertainty regarding future changes in environments and landscapes. Increasing pressures associated with climate change, development and changes in governance or management may drive diverse changes in ecosystem responses (Maciejewski et al., 2015; Pressey et al., 2007). Ecosystem responses to, for example climate, livestock populations, recovery of fish stocks and conservation interventions are all informed by system specific natural and socio-ecological history and context (Salafsky et al., 2019; Sutherland et al., 2004). Hence it follows that any management decision or goal should be informed by a comprehensive study of how an ecosystem came to be in its current state, thus informing management for conservation outcomes.

In observing a current pattern or relationship in ecosystem change, it may be possible to test a prediction with ongoing study. However, regarding historical change, there is no way in which to repeat a specific test and we rely on existing data, the detail and availability of which is variable, to decipher what happened (Swetnam et al., 1999). Similarly, one causal explanation cannot be tested in isolation, the environment is the product of many influences acting together (Beller et al., 2017). Often historical data, such as aerial imagery, cannot be delineated by cause, it is an aggregate of context (Swetnam et al., 1999). Such thinking sets the stage for this study.

Gona Re Zhou National Park (hereafter Gonarezhou) is a national park in South-eastern Zimbabwe with a long and complex natural and socio-ecological history. The population of elephant in the park is historically high, such that ‘Gona Re Zhou’ translates to ‘Place of Elephants’ in Shona. Riverine woody vegetation cover in Gonarezhou has undergone substantial changes over time. It seems compelling at first sight to hold growing elephant populations and their engineering effects on the ecosystem accountable for observed changes. However, if this proves to be a false or incomplete premise, we run the risk of advocating incorrect or weak management responses (Gandiwa et al., 2011; Mombeshora and le Bel, 2009; Tafangenyasha, 1997; Tavuyanago, 2016; Thomson, 1974). Therefore, a comprehensive assessment of possible drivers and historical evidence of their impact is required (Beller et al., 2017; Swetnam et al., 1999). Record keeping in the park has occurred in many formats including the collection of aerial imagery from 1948 to the present day. A time series analysis of aerial photographs and satellite imagery may be used to investigate macro changes in vegetation cover. These can then be considered in the wider historical context of the park. This study will investigate the drivers of ecosystem change over time and their influence on the vegetation with a view to informing future management

1.1. Savanna elephant impacts on woody riverine vegetation

Savanna elephants (*Loxodonta africana*) contribute most of the mammalian biomass in savanna parks (Fritz et al., 2002). Population trends of savanna elephant in Africa vary. While the southern Africa populations in Zimbabwe, Namibia, Botswana and Zambia show sustained growth, savanna elephant populations in east and west Africa continue to decline due to poaching for the ivory trade (a few of these populations are now stabilising) (Guldemond et al., 2017; Landman, 2007; Skarpe et al., 2004). In some southern African areas savanna elephant populations are increasing in excess of 4% per annum, particularly within protected areas (Cumming et al., 1997; Gobush et al., 2021). As a result, understanding their impact is becoming increasingly relevant to park managers for maintaining functioning ecosystems (Dickson and Adams, 2009).

Elephant impact on woody vegetation has been well documented since the 1960s (Beuchner and Dawkins, 1961; Laws, 1970; Leuthold et al., 1977). Aside from consumption and trampling of vegetation, elephants also engage in behaviours like toppling, uprooting, and ringbarking which results in increased tree mortality. Impacts are exacerbated by the large size of elephants which mean that even tall trees, which may avoid damage from smaller herbivores, are susceptible to elephant impacts (Cumming et al., 1997; O'Connor et al., 2007). In particular, there is no maximum size for a tree susceptible to ring barking, all adult trees are vulnerable. Therefore, vegetation subjected to sustained high densities of elephants can experience a rapid and dramatic transformation in structure (Guldemond and Van Aarde, 2008). In extreme cases this can result in local extirpation of a species if no refuge is available (O'Connor et al., 2007).

Possible refugia for woody vegetation can include distance from perennial water sources. Cow-and-calf groups are restricted to foraging within 15 km of permanent water (O'Connor et al., 2007; Western and Lindsay, 1984). Woody vegetation immediately next to perennial water does not have this refuge, a point indirectly demonstrated by the degraded state of vegetation around artificial water points (Gandiwa et al., 2012; Tafangenyasha, 1997). However, seasonal tributaries, bereft of water during the dry season may support mature riverine woodland. It is predicted that distance upstream along a seasonal river from its confluence with a perennial river will influence the degree of elephant impact on its riverine woody vegetation.

Foraging behaviour in elephants is also divergent between sexes, thus influencing the nature of their impact on woody vegetation (Skarpe et al., 2004; Skarpe and Hester, 2008). A study by Clegg (2010), in a reserve adjacent to Gonarezhou supporting similar vegetation, studied the foraging behaviour of cows and bulls. He found that browse foliage (leaves and twigs) constituted a greater proportion of the diet of cows over the annual cycle when compared with bulls, although cows also consume green grass. Adult bulls however are preferential grazers seeking soft, broad-leaved green grass. They consume an increasing amount of browse as the availability of suitable grass declines during the dry season, in drought years, or in areas where there is a limited amount of grass available. Bulls then resort to bark stripping, uprooting, or toppling of trees, despite the energetic cost, to gain access to plant parts that may ensure nutritional needs are met during times of scarcity (Clegg, 2010; Clegg and O'Connor, 2016). Under circumstances where green grass is available during the dry season, such as in wetlands or hygrophilous vegetation, it is predicted that bulls will utilise these resources thereby reducing overall impact on woody vegetation.

Fruiting pods of some species of Mimosaceae are adapted for dispersal by large mammalian herbivores by being highly nutritious (Dudley, 2000). Pods of many of these species, such as the tall African riverine tree species *Faidherbia albida,* become available during the height of the dry season. These pods are relished by elephants and other herbivore species (Barnes, 1983; Gope et al., 2015). A single adult tree of this species can produce between 5 and 290 kg of pods a season such that a large woodland of trees offers a substantial mass of forage to elephants at a time they would otherwise be exploiting other parts of woody trees and shrubs (Dunham, 1990). It is therefore predicted that utilisation of these pods by bulls during the dry season will result in less damage to surrounding woody vegetation over time.

Woody riverine vegetation in the savanna national parks of Africa is iconic and distinct. This highly productive vegetation type supports a unique and usually rich assemblage of plant and animal species. It is also particularly threatened by elephant impact, owing to its proximity usually to permanent water (Cumming et al., 1997). This is partly due to the reliance of elephants on water and riverine environments. The vegetation type also includes large tree species, favoured for bark stripping when grazing is not available (Gandiwa et al., 2012; O'Connor, 2010; O'Connor et al., 2007). National parks generate revenue from tourism and riverine vegetation is popular with tourists both due to its aesthetic appeal and high biodiversity. Therefore, managing this vegetation type to maximize its potential also has economic implications for park management (Cumming et al., 1997; Kabii, 1996).

Elephants have severely impacted the vegetation of Gonarezhou National Park, Zimbabwe (Cunliffe et al., 2012) which may threaten the tourism potential of the park. Savanna elephant populations in the park have almost doubled since 1992. The elephant population has since grown at >5% annually rising from approximately 6,000 elephants in 1994 to 9,000 by 2009 (Dunham, 2012). Elephant population densities in Gonarezhou currently stand at >2 elephants per km^2 which far exceeds the commonly accepted <0.5 elephants per km^2 deemed suitable for maintaining woodland structure (Dunham, 2012). During the dry season, the density of elephants within riverine woodland is further increased as the foraging range of elephants within the park is concentrated on the main rivers when inland water sources dry up. Here, densities may exceed 4 elephants per km^2. This is one of the highest densities observed for savanna systems receiving a mean annual rainfall of 500-550mm (Dunham, 2012). Elephant populations require careful management to maintain ecosystem health. However, as populations in other parts of Africa decline due to poaching, international pressure to conserve elephants has forced southern African parks to place a moratorium on artificially reducing elephant populations through culling and other measures (Cumming et al., 1997; Dickson and Adams, 2009; Du Toit et al., 2003; Robson et al., 2017). Elephant culling programmes were implemented in Gonarezhou during the 1970s and 1980s to address concerns about the impact of an increasing elephant population during that period. However population reduction has not been practiced in Gonarezhou since that time despite even greater concern about elephant impacts on vegetation cover in the last few decades (Dunham, 2012; Sherry, 1970; Tafangenyasha, 1997). Any future action would be subject to close international scrutiny and would need to be evidence-based, including a clear understanding of the contribution of elephants to vegetation changes versus those resulting from other agents of change.

Other than having potentially substantial impacts on biodiversity, elephant-induced changes in riverine vegetation also have implications for tourism and the park's economic viability. The aesthetic appeal of the riverine environment of the Runde River, and surrounding features such as the Chilojo cliffs and large pans, underpin the appeal of Gonarezhou as a tourist destination. Deterioration of the vegetation of this environment is expected to impact tourism and derived revenue (personal communication, H van der Westhuizen, Director, Gonarezhou Conservation Trust). Understanding elephant impact on this environment, as the population grows, has therefore become a priority.

However, elephants are not the only engineer of riverine woodland vegetation in Gonarezhou. In the past single factor explanations have fallen short of explaining changes in ecosystem structure and functioning, resulting in poor management decisions. Any single-factor approach which ignores the complexity of interrelationships in a multi-faceted system is unlikely to prove sufficient. Other purported agents of vegetation change need to be examined so as not to falsely attribute blame to elephant populations in Gonarezhou and to evoke an appropriate management response (Challender et al., 2022; Ford et al., 2021; He and Callaway, 2009; Pressey et al., 2021).

1.2. Woody riverine vegetation impacts as driven by natural and socio-ecological history

Together with a growing population of elephants, Gonarezhou National Park has a complex natural and socio-ecological history which has influenced the distribution and pattern of vegetation in the park.

Settlement and cultivation can have a long-term influence on savanna or riverine vegetation. As plots are cleared for settlement and cultivation, native vegetation is locally removed and replaced with crops or buildings. After land is abandoned the effects of clearing can be detected for years, with areas taking a long time to recover their natural state (Gillson and Ekblom, 2009). In the 1940s Gonarezhou had not yet been declared a conservation area and a mixture of land uses prevailed. Areas of the park were settled and cultivated while other parts were used as hunting reserves. Following plans to proclaim the area a national park, people were removed from the park in 1968 before its official proclamation in 1974. Previously cultivated fields were left to regenerate naturally (Mavhunga, 2002, 2008; Tavuyanago, 2017; Tavuyanago and Makwara, 2011). These areas are likely to show varying degrees of recovery of woody vegetation over time, in contrast to possible elephant damage to extant riverine vegetation. The presence of mesobrowsers, however, may inhibit woody regeneration. Impala have been associated with poor seedling regeneration in riparian species (Moe et al., 2009; O'Kane et al., 2012; Prins and van der Jeugd, 1993). Impala populations have also grown in Gonarezhou and for this reason, the recovery of previously cultivated land may be slower than expected (Clegg and O'Connor, 2016; Dunham, 2012; O'Connor and Campbell, 1986a).

Tsetse fly (*Glossina* spp) are obligate parasites, reliant on the consumption of the blood of vertebrates. They have a profound economic impact in Africa as they are vectors of trypanosomes which cause human sleeping sickness and animal trypanosomiasis that may ultimately lead to death. In the 1930s culling of wildlife (to deny the tsetse fly a food source) and bush clearing were implemented to control the fly (Douthwaite, 1985; Pilossof, 2016). Destruction of refuge sites through bush clearing was one of a number of complementary approaches used to control tsetse fly populations (Pilossof, 2016). In Gonarezhou clearing of vegetation and insecticide use occurred to control tsetse fly in the late 1950s (Farrell, 1960; Kelly and Walker, 1976). Precise documentation of exactly where clearing occurred is unavailable. However, it is expected that this will be visible on aerial imagery which will show distinctly cleared areas of woody riverine vegetation around this time. Areas previously cleared for the control of tsetse fly may also show recovery of woody vegetation since clearing.

Individual floods can remove large proportions of established riverine vegetation through erosion of the riverbank and breakage of tree stems under the weight of flood water (O'Connor, 2010). Flooding events can also remove large reedbeds from the channel reducing the overall availability of riverine vegetation (Kupika et al., 2021; Reason and Keibel, 2004). Gonarezhou has experienced large flood events from time to time often associated with cyclones from the Indian Ocean. Cyclone Eline in 2000, for example, inflicted considerable damage to riverine vegetation to Gonarezhou as the cyclone penetrated inland (Reason and Keibel, 2004). Cumulative damage to riverine vegetation in Gonarezhou will be associated with the frequency and severity of such events over time.

1.3. Study rationale

This study responds to increasing concern about the impact of elephants owing to an exponential increase in the population since the drought in 1992. Impacts on woody riverine vegetation are explored in the context of this population increase and the socio-ecological history of the park. Woody riverine vegetation is expected to respond differently to different drivers of change over time. In areas which had been formerly transformed by cultivation or clearing for tsetse fly, recovery of woody cover since the proclamation of the park is expected but its trajectory of change may be affected by the impact of mesobrowsers, droughts or flood. Delineating human legacy effects on riverine woodland allows us to isolate and examine the impact of elephant. It is predicted that trends in riverine woody cover will differ between areas with or without elephants. Where elephants are present, it is predicted that their impact on riverine woody cover will be lessened with increasing distance from permanent water along seasonal water courses, or in areas where alternative food sources such as grasslands or seed pods are available during the dry season. All potential influences should be disentangled to determine the main drivers of vegetation change in the park. This is important to avoid falsely attributing blame for change in woody riverine vegetation solely to a growing elephant population in the park.

Historical changes can be examined using remote-sensing techniques to investigate macro changes in vegetation in the park. A comparison of remote sensing imagery over time can be used to determine the nature and extent of change and, possibly, the rate of change when more than one time stamp is available. Such patterns of change can be compared with what is observed in the field and with predictions of change. By combining this approach with an understanding of the historical, natural and socio-ecological context, it is possible to disentangle the factors responsible for the changes in woodland cover. Information on the influence that elephant populations have on riverine woody vegetation in the park can be used to inform both the management of ecosystem engineers, such as elephants, and biodiversity in Gonarezhou.

1.4. Aim

The overall aim of this study was to measure the changes in cover of woody riverine vegetation in Gonarezhou National Park since 1948 using remote-sensing imagery, and to evaluate the contribution of different agents purported to be responsible for this change.

1.5. Questions and associated objectives

Question 1: Has the woody cover of riverine woodland on alluvial soils within Gonarezhou National Park changed between 1948 and 2018?

Objective 1: To determine the amount and direction of change in woody cover of riverine woodland along the Runde River, and at its confluence with the Save River, within Gonarezhou National Park between 1948 and 2018.

Question 2: What was the extent and distribution along the Runde River of cultivation and human settlement prior to the proclamation of Gonarezhou as a national park; what effect did these land uses have on woody cover at that time, and have these land uses subsequently influenced changes in woody cover?

Objective 2: Map the areas of settlement and cultivation, determine the proportion that these areas contribute to riverine woodland, and assess whether the direction and amount of change in woody cover since proclamation of the park differs between these areas and corresponding areas that were not cultivated or settled.

Question 3: Did clearing of riverine vegetation for the purpose of the control of tsetse fly in the Chipinda area during the late 1950s have a substantial effect on this vegetation, and were the effects of clearing long-lasting?

Objective 3: Confirm that clearing of riverine woody vegetation was undertaken only in the Chipinda area. Map the extent of this clearing and determine whether recovery of woody cover subsequently occurred.

Question 4: Is woody cover lower under a long-term presence of elephants at high density compared with a corresponding area with a low density of elephants?

Objective 4: Compare woody cover of riverine woodland within Gonarezhou with that immediately upstream across the boundary of the national park.

Question 5: Has distance from permanent water along a seasonal river influenced the impact of elephants on woody cover, in the expected manner of a decrease close to permanent water and less of an effect with increasing distance?

Objective 5: Determine the direction and amount of change in woody cover along the seasonal Benji River in relation to distance from permanent water provided by the Runde River and the Benji weir.

Question 6: Has the availability of a large concentration of suitable green grass and other alternative food sources in close proximity of the Runde River influenced the long-term impact of elephants on the woody cover of riverine vegetation as compared with other sections of the river without alternative food sources?

Objective 6: Examine the change in the cover of riverine woodland vegetation away from the confluence of the Runde and Save Rivers which is an area offering a concentration of alternative food sources.

2. METHODS

2.1. Study area

Gonarezhou National Park is located in the south-eastern corner of Zimbabwe, directly bordering Mozambique and approximately 50 km north of the South African border. At 5,053 km^2, it is the second largest park in Zimbabwe (Cunliffe et al., 2012). The park is fenced along its northern and western border to reduce conflict with communities, although it is open along the Mozambique border to facilitate movement of wildlife. Gonarezhou is part of the Greater Limpopo Trans-Frontier Conservation Area which includes Kruger National Park (South Africa), Limpopo National Park (Mozambique) Gonarezhou National Park (Zimbabwe) and Banhine and Zinave National parks in Mozambique. Also nearby is the Malilangwe Conservation trust (20°59'10.09''S, 31°48'27.10''E) with whom Gonarezhou collaborates on projects and shares climate data.

The climate in Gonarezhou is characterized by lowland heat with temperatures between 30 and 40 °C recorded in all months of the year. Rainfall averaged about 515 mm per year at Chipinda pools over 29 years between 1961 and 1990 (Rainfall records per annum for years 1952-2019 are presented in Annex 1). Drought and flood events are relatively common and occasionally severe. By way of summary, rainfall records are available from 1952 onwards. In 1951/2 Gonarezhou experienced a heavy rainfall season resulting in flood. The remainder of the 1950s and early 1960s however were punctuated by minor droughts (Jones, 2018, Sparrow, 2018). In 1972 a severe drought occurred, followed by a flooding event in 1974 (December) and early 1975 (Sparrow, 2018). In 1977, cyclone Emily caused further flooding (Jones, 2018). Droughts in 1981-1983 were severe (resulting in almost no growth in vegetation). In 1992/3 Chipinda pools received just 98 mm rain (Cunliffe et al., 2012; Dunham, 2012, Sparrow, 2018). In 2000 Cyclone Eline, penetrated inland from Mozambique and caused extensive flooding and damage to infrastructure such as the Runde Bridge, which has yet to be repaired (Cunliffe et al., 2012). Further notable cyclones include Jokwe in 2008, Dineo in 2017 and Idai in 2019 (Mavhura, 2020). Further droughts have also been experienced in 2007/2008 and in 2018 and 2019.

The vegetation in Gonarezhou is influenced by the underlying geology and soils and is comprised of large swathes of woodland (Cunliffe et al., 2012). Mopane and miombo woodland dominate the north of the park with enclaves of riverine woodland vegetation on alluvial soils along the rivers. This study focuses on riverine woodland vegetation defined by Cunliffe et al. as ‘Mixed woodland on alluvium’, commonly occurring in pockets along water courses, on alluvial terraces and on flood plains and including species such as *Acacia tortilis subsp. heteracantha, Combretum imberbe, Cordyla africana, Kigelia africana, Philenoptera violacea* and *Xanthocercis zambesiaca.* In the present study this is distinguished from Mopane woodland which is dominated by species such as *Colophospermum mopane, Combretum apiculatum and Diospyros mespiliformis.* Although both are mapped, the analysis only considers riverine woodland vegetation (used interchangeably with ‘woody riverine vegetation’).

The Runde and Save rivers flow through the northern part of the park before entering Mozambique, with their confluence at an international boundary (Figure 1). The Runde River enters Gonarezhou on its north-western border and runs for approximately 80 km through the park. The westerly section of the river from where it enters the park at the broken bridge (Lat: 21°15'45.43"S, Long: 31°53'24.93"E) is defined by woodland on alluvium on both sides for 7.5 km, passing Chipinda Pools Campsite (21°17'21.00"S, 31°54'49.92"E), until it meets Chivelila Falls (21°17'40.93"S, 31°54'38.78"E). Chivelila Falls marks the beginning of a 20 km long rocky section of the Runde which does not support woody riverine vegetation. The Benji is a seasonal tributary of the Runde which also contains a Weir (21°26'25.12"S, 31°55'25.83"E) 15 km upstream. The Chivelila Falls and the Benji dissipate into a lowland section of the Runde (21°26'10.26"S, 32° 3'29.06"E) which supports woody riverine vegetation on both sides. This is broken up by Chitove Falls (21°18'43.57"S, 32°15'8.26"E) after approximately 35 km before woody riverine vegetation returns for the last 17 km where the Runde meets the Save river (21°18'30.80"S, 32°22'42.33"E) at the border with Mozambique. The junction between the Runde and Save Rivers is characterized by woody riverine vegetation, including, *Faidherbia albida* woodlands and hydromorphic grasslands. Several pans are located away from the rivers and also support woody riverine vegetation.

Figure 2 describes the distribution of woody riverine vegetation as described by Cunliffe et al. in 2012. Cultivation which occurred from around the confluence of the Benji and the Runde Rivers to the junction of the Runde with the Save, and as is evident in the aerial photography is also described. In addition, areas, identified from imagery that were cleared for tsetse fly control are shown in Figure 2. High- and low-density plots for understanding the impact of elephant on woody riverine vegetation were placed across the park boundary at the broken bridge (Figure 2).

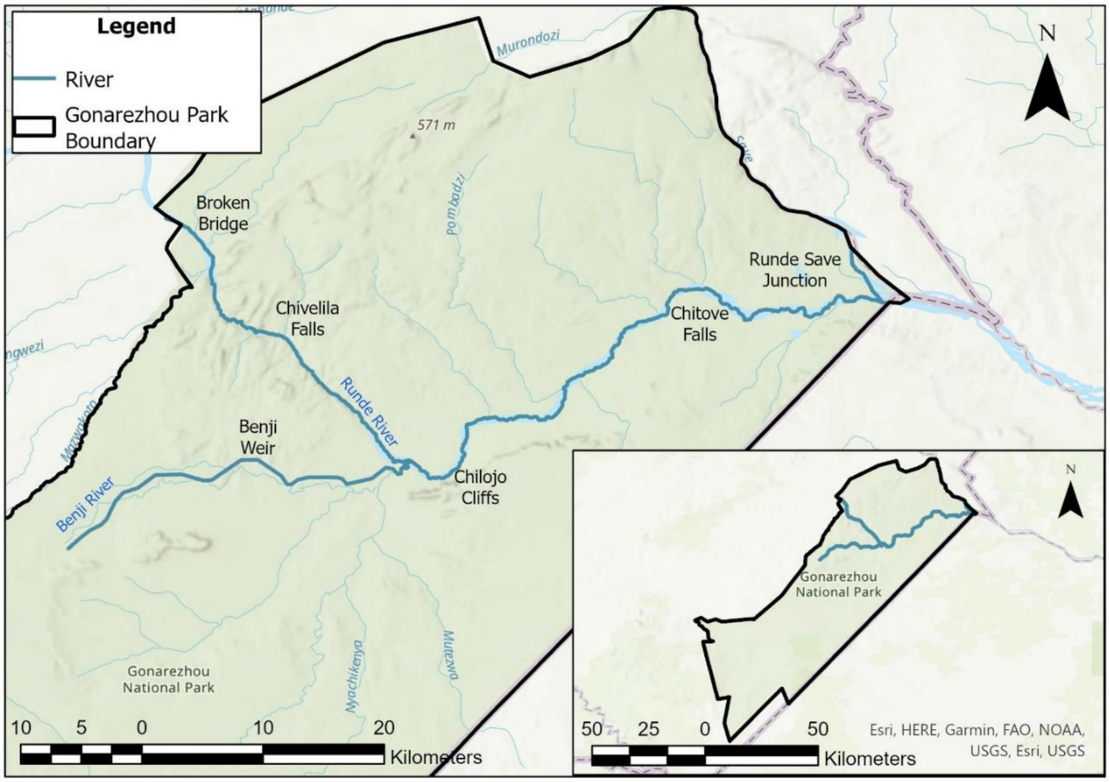

Figure 1. Gonarezhou National Park boundary and delineation of the Runde and Benji River. Key landmarks such as Broken Bridge, Chivelila Falls, Benji Weir, Chilojo cliffs, Chitove Falls, and the Runde Save Junction are also indicated. Inset map shows the location of Gonarezhou on the border with Mozambique in south-eastern Zimbabwe. The Runde River passes through the northern section of the park

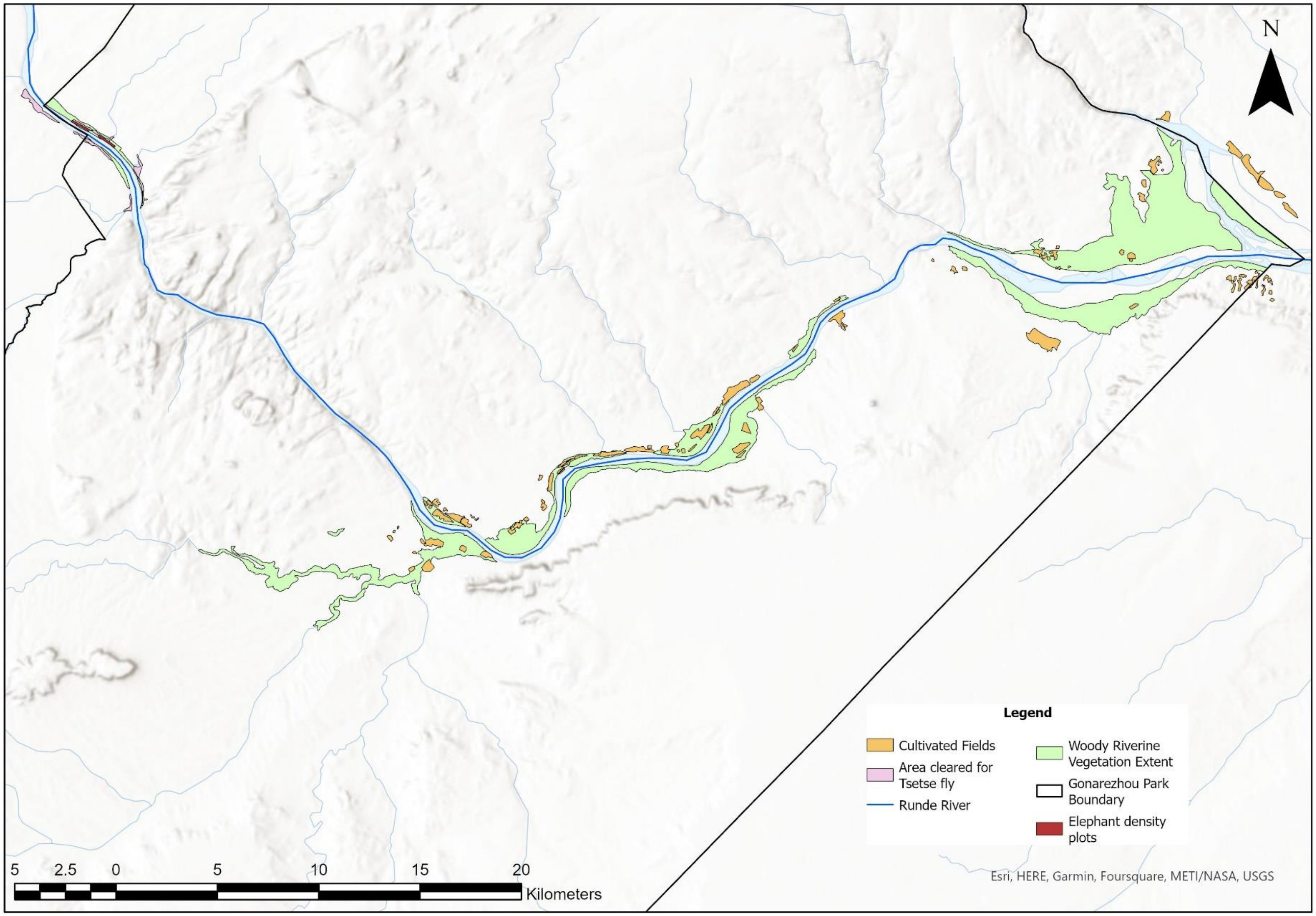

Figure 2. Map of the Runde River in Gonarezhou National Park identifying the woody riverine vegetation extent according to Cunliffe et al's 2012 delineation. Also visible are areas historically cleared for cultivation and tsetse fly control identified from aerial imagery and elephant density plots used to consider the impact of elephant on woody riverine vegetation.

2.2 Approach and methods

2.2.1 Collation of imagery

Cover of riverine woodland vegetation can be identified in aerial photography (1948-1974) and satellite imagery (2005 to 2018), which appears to vary over time.

Aerial photographs of Gonarezhou National Park were taken in 1948 (September), 1955 (Dry season), 1968 (April) and 1974 (May) and were used in this analysis. Hard copies of these images were obtained from park management and re-photographed at a resolution of 300 dpi and 24-bit depth (5504 x 5504 pixels) using a Nikon Z7 45.7 megapixel, full-frame, mirrorless, interchangeable lens camera, mounted on a copy stand. The lens was a Nikon Z 24-70 4/s lens. Hard copies of aerial photographs were rephotographed rather than scanned because rephotography provided a product of adequate resolution at a fraction of the time and cost. For 1948 and 1955, images covering only half the length of the Runde across the park were available, while imagery taken in 1968 and 1974 covered the entire length of the Runde River within Gonarezhou National Park.

Satellite imagery downloaded from Google Earth had a resolution of 96 dpi and 24-bit depth (4800 x 3600 pixels). Imagery was selected using the historical imagery slider in google earth to view older imagery. Imagery was downloaded by selecting ‘save image’ once the area of interest filled the frame. The resolution could then be selected. Imagery taken in 2005 (5^{th} October) and a combination of 2016 (29^{th} July) and 2018 (26^{th} October) were selected because the interval of approximately 11 years between these two sets is of the same order as the average 7/8-year interval between years of aerial photography. It should be noted that 2016 imagery is used for the areas upstream of the junction; however, the junction area uses imagery from 2018 as 2016 imagery for this area was not available. Unfortunately, there were no aerial photographs available for the period post-1974, and Google Earth imagery prior to 2005 was deemed to be of inadequate resolution, so there is a 31-year gap in the record.

All 133 images (photographs and satellite) were georeferenced and transformed (Helmert transformation) in ArcGIS Pro where they were given spatial coordinates (coordinate system: WGS 1984 Web Mercator) and aligned to show the riverine environment. The Helmert transformation translates the georeferenced points horizontally and vertically and rotates and scales the points to align imagery with a basemap, thus orthorectifying imagery. Further details on imagery resolutions and coverage can be found in table 1 below.

Table 1. Imagery details for imagery used in study

Date	**Number of images**	**Resolution**	**Approximate ground resolution**	**Total area covered (km^2)**	**Image type**	**Source**
September 1948	20	300 dpi and 24-bit depth (5504 x 5504 pixels)	1 pixel = 1m2	350	Greyscale	Aerial imagery, Gonarezhou archives
Dry Season 1955	12	300 dpi and 24-bit depth (5504 x 5504 pixels)	1 pixel = 3m2	751	Greyscale	Aerial imagery, Gonarezhou archives
April 1968	26	300 dpi and 24-bit depth (5504 x 5504 pixels)	1 pixel = 1.3m2	635	Greyscale	Aerial imagery, Gonarezhou archives
May 1974	34	300 dpi and 24-bit depth (5504 x 5504 pixels)	1 pixel = 1.2m2	722	Greyscale	Aerial imagery, Gonarezhou archives
5th October 2005	26	96 dpi and 24-bit depth (4800 x 3600 pixels)	1 pixel = 2m2	572	Colour	Google Earth
29th July 2016/ 26th October 2018	20	96 dpi and 24-bit depth (4800 x 3600 pixels)	1 pixel = 3m2	656	Colour	Google Earth

2.2.2 Sampling Riverine Woody Vegetation

A previous study on the vegetation cover of Gonarezhou National Park defined areas containing riverine woody vegetation as mixed woodland on alluvial soils in a vegetation mapping exercise that covered the whole park (Cunliffe et al., 2012). The polygons from this study were delineated from Landsat and Google Earth Imagery and were available for use in ArcGIS Pro. Therefore, they were used to define the sampling site. Not only was this a useful guide but also enabled this study to build on existing knowledge of the park's vegetation. To investigate changes in woody cover over time imagery from 1948 to 2016/18 was clipped using Cunliffe et al's (2012) delineation to which a 5m buffer was added to allow for any slight misalignment of imagery.

2.2.3 Woodland cover classification

Georeferenced imagery in ArcGIS Pro was analysed using a supervised classification approach. Given that the 1948, 1955 and 1974 photographs were taken in black and white, and the Google Earth photographs were simple colour images, it was not possible to use a supervised classification approach based only on colour bands to identify riverine woodland vegetation cover. Therefore, supervised object-based classification with a Support Vector Machine classifier was considered a preferable approach. This defines not only the colour (3- band RBG images) but also the shapes that collections of pixels make in the imagery based on training samples. Object-based classification allowed for the training of software to also identify the shape of woodland cover in the imagery, thus enhancing the accuracy of the classification. Classifications were trained separately for each time step to account for differences between years in image quality, colour, and shadow.

To improve the accuracy of the classification, test classifications were carried out on three images from each year (covering areas between 70 and 240 km^2 depending on the size of the images and ground resolution for each year). Training samples were selected in each time step to reflect the differences in imagery quality and coloration (particularly where older imagery had faded over time). The colour balancing function in ArcGIS Pro was used to smooth any discoloration and remove lines where imagery overlapped. The object-based classification at this spatial and spectral resolution could not accurately delineate between shadow and woodland. Therefore, for consistency shadows were included as the vegetation type to which the vegetation casting the shadow belonged. The model was trained for 75% of the imagery and then run against the remaining 25% to assess how well the model classified the rest of the images before application to the wider dataset. These tests also allowed for choice of a machine learning approach which was most accurate, namely Support Vector Machine (classification definition files are attached in appendices A-F).

Eight categories, representing the most common land cover and vegetation types for the study area, were selected into which pixels were sorted by the classification. The land cover types were River (flowing water), Waterbody (still water, not flowing), Mopane Woodland (dominated by species such as *Colophospermum mopane, Combretum apiculatum and Diospyros mespiliformis)* , Woody Riverine Vegetation (defind by Cunliffe et al. as 'Mixed woodland on alluvium' including species such as *Acacia tortilis subsp. heteracantha, Combretum imberbe, Cordyla africana, Kigelia africana, Philenoptera violacea* and *Xanthocercis zambesiaca)*Alluvial Soils, Bare ground (soils with no vegetation cover, not in riverbed or alluvial), Riverbed, and Reedbed. Rocks were assigned to the land cover type in which they were situated.

2.2.4 Accuracy assessment

Training samples were assessed for accuracy against the imagery through visual comparison. I reclassified areas visually which were classified incorrectly after the classification had run using the reclassify function in ArcGISPro.

An accuracy assessment of the object-based automated classifications against visual assessment was undertaken to determine to what extent the classification corresponded to visual assessment of the study area. Using a stratified random approach, randomly distributed points were chosen in each vegetation/land cover class, where each class had a number of points proportional to its relative area. The minimum number of points was set to 100 in each time step although in most cases it exceeded 100 (between 120-140) because of the sampling strategy and number of classes. Each point had one class value from the classification to which I added a ground truth value by classifying each of these points visually. Kappa values for each time step were computed. Kappa values showed fair to moderate correlation with visual assessments (Table 2). This is appropriate for assessment of macro-scale change, and therefore I adopted the approach.

2.3 Individual study exercises

Individual exercises involved cross-tabulation of areas of interest and the classified imagery. Each study exercise involved the subsequent extraction of the number of pixels classified as woody riverine vegetation, which was then calculated as a proportion of all the pixels in the area of interest to give percentage cover values. Pixels were multiplied by the square of the pixel size to derive area values.

2.3.1 Overall change in woody riverine vegetation cover

The number of pixels classified as woody riverine vegetation, within the study area defined by Cunliffe et al. (2012) was calculated as a proportion of all the pixels in the study area. Earlier imagery for 1948 and 1955 did not cover the whole study area hence proportions were calculated to enable comparison. One datum per time step was produced, based on which changes in woody riverine vegetation cover over time could be graphically summarised and then compared between different time steps.

2.3.2 Human legacy effects

The section of the Runde between the Benji confluence and the junction with the Save supported some cultivation between 1948 and 1968 (Figure 1). To document this I identified cultivated areas as cleared patches of land with angular corners and settlement areas as those areas in which huts or buildings were evident in 1948, 1955 and 1968 photographs. These areas were digitised in ArcGIS Pro. There was no additional clearing after 1968 as the area was being prepared for the proclamation of the park in 1974. Areas that had been cleared previously were left to regenerate naturally. I compared mean woody riverine vegetation cover for the Runde between the Benji confluence and the junction with the Save that were and were not cultivated. Uncultivated areas were sampled by placing transects of 250m in width (in GIS) from the Runde-Save junction upstream for 42 km to the Benji-Runde confluence at intervals of 1 km. Transect length upstream of the junction was determined by the width of the riverine habitat, hence transect length varied. These were compared for the years after cultivation ceased:1968, 1974, 2005 and 2016/18.

Clearing for tsetse fly could be easily recognised on the 1968 aerial photographs which were taken a few years after clearing and was digitised. Cleared areas were not confounded with cultivated areas because there was no evidence of cultivation in the cleared areas in the 1948/68 aerial photographs and clearing left a particularly barren landscape. Areas for cultivation and tsetse clearing also appear geographically distinct in the available documentation which describes these activities (Cunliffe et al., 2012; Farrell, 1960). Tsetse clearing occurred west of Chivelila Falls on both the northern and southern banks. I compared the pattern of woody riverine vegetation cover in areas cleared for tsetse and the total area of woody riverine vegetation that was not cleared between the Broken Bridge and Chivelila Falls for years 1948,1968,1974, 2005 and 2016/18. 1955 imagery for this area was not available.

2.3.3 Precipitation

Rainfall records were acquired from Gonarezhou park management for years for which imagery was available. Rainfall years run from July to June annually. Malilangwe Conservation Trust is adjacent to Gonarezhou, and their records are used for years when Gonarezhou records were unavailable (1955 and 1968). No rainfall records are available for 1948. Rainfall gives an indication of leaf cover on trees, thus influencing woody cover for years where more or less rain fell.

2.3.4 Boundary contrast of elephant impact

The sections upstream and downstream of the Broken Bridge on the northern bank of the western boundary of Gonarezhou (Figure 2) provide a direct assessment of the cumulative impact of elephants within Gonarezhou as compared with an immediately adjacent section which has been subjected to little utilisation by elephants.

Within a GIS environment, plots of 0.1 km^2 in size (rectangular plots, 0.1km wide and 1km long), were placed either side of the broken bridge on the northern bank (Figure 2). The southern bank was not appropriate due to considerable land use change and settlement directly outside the park, therefore plots on the southern bank were not comparable. Percentage cover of woody riverine vegetation was calculated for years 1948, 1968, 2005 and 2016/18 to compare changes in woody riverine vegetation cover over time. 1955 imagery for this area was not available.

2.3.5 Distance of woody riverine vegetation from perennial water

To examine if the percentage of woody riverine vegetation cover was influenced by the distance from permanent water along the seasonal Benji River, transects were placed in GIS, across the river from the Runde River to the Benji weir. Transects of 100 m in width were placed in a contiguous manner along the Benji River and the length of the transects was then clipped to the width of the riverine habitat. Previously cultivated areas were excluded from the analysis. Where transects overlapped due to a bend in the river, one was removed to ensure independence. Owing to the different length of transects, percentage woody cover was used to examine the relationship with distance from the source of perennial water. Percentage cover of woody riverine vegetation was calculated for years 1955, 1968, 2005 and 2016/18 to compare changes in woody riverine vegetation cover over time. 1948 imagery for this area was not available.

2.3.6 Availability of alternative forage

The Runde-Save junction is clearly delineated from the rest of the woody riverine vegetation by Cunliffe et al.'s (2012) vegetation classification. The junction supports a relative abundance of alternative forage for elephants which was expected to reduce their impact on woody riverine vegetation. By contrast, alternative forage sources are scarce upstream of the junction along the Runde River, with the expectation that woody cover would have been negatively affected more along this stretch than at the Runde-Save junction. To examine if this expected pattern was present, transects of 250m in width were placed (in GIS) from the Runde-Save junction upstream for 42 km at intervals of 1 km. Previously cultivated areas were excluded from the sampling area. Transect length upstream of the junction was determined by the width of the riverine habitat, hence transect length varied. Within the junction area, where a large area is covered by riverine woodland, transects were restricted to a maximum length of 8.5 km which ensured they were all within strictly riverine environment. Covering the entire width of the riverine habitat ensured that variation in woodland cover in relation to distance from the river was accommodated for. Where transects overlapped due to a bend in the river, one was removed to ensure independence. Owing to the different lengths of transects, percentage woody cover was calculated for years; 1968, 1974, 2005 and 2016/18 to compare changes in cover over time. 1948 and 1955 imagery were incomplete for this area and therefore excluded.

2.4 Data Analysis

Data analysis was conducted in R (V4.0.3). Analysis was intended to examine differences based mainly on trends over time. However, as classifications were trained separately for different imagery, comparing classifications with each other does not compare like for like, such that differences between years are exaggerated by separately trained classifications. As a result, my analysis examined more closely the differences for each time interval to see if a consistent difference in woody riverine vegetation could be observed for each driver in each year. If so, the results are indicative of a long-term impact of such drivers.

Where plots differed in size, I calculated percentage cover so that these could be compared independently of area.

2.4.1. Overall change in woody riverine vegetation cover

Overall woody riverine vegetation was calculated as a percentage of total cover within woody riverine vegetation as defined by Cunliffe et al. (2012). Change in woody cover for the entire Runde River was plotted for each time step. Because there is a single datum for each time step there are no error bars.

2.4.2 Human legacy effects

Mean (± SE) woody riverine vegetation cover was plotted for areas that were cultivated in the region against areas that were not, and for areas that were cleared for tsetse in the region against areas that were not. Percentages were used as areas were not equivalent sizes. Unpaired t-tests were performed on each year to statistically test the differences between previously cultivated and uncultivated areas, and areas cleared for tsetse control and those that were not.

2.4.3 Precipitation

Total rainfall records are presented for the years for which imagery is available for this study to give an indication of weather patterns which may affect cover of woody riverine vegetation.

2.4.4 Boundary contrast of elephant impact

Change in woody cover over time for high and low elephant density were plotted (note there is a single datum per annum and therefore no error bars). To assess if woody cover differed across the boundary contrast, a frequency test was conducted between the two plots for each year, using the number of pixels which were classified as woody cover or other vegetation/land cover types. In order to provide a suitable measure for statistical testing, the number of pixels per cover type was divided by 1000, and a G-test was used to test for differences in frequency.

2.4.5 Distance of woody riverine vegetation from perennial water

Preliminary examination of the data revealed pronounced spatial variability along the sampled section of the Benji River which precluded fitting any defined non-linear function. Instead, the section was divided into equal thirds of 37 transects each, to reduce variability. That is, the first section stretched a third upstream from the Runde River, the second section was between the two permanent sources of water and therefore expected to have the highest woody cover if elephants were affected by distance from water, and the final section was the third downstream of the Benji weir. These were plotted against mean (± SE) percentage woody vegetation cover for each section. Following arc-sine transformation of percentage data, a one-way analysis of variance was conducted separately for each year to examine if the three sections differed in their mean percentage cover, with a post-hoc comparison of means conducted using Tukey's test if the analysis of variance was significant.

2.4.6 Availability of alternative forage

A plot of woody cover in relation to distance from the junction of the Runde and Save rivers was examined to see if woody cover diminished with distance from the junction, which would be consistent with an influence of alternative forage availability. The percentage of woody riverine vegetation for each transect was initially plotted against distance from the junction but results varied excessively. Therefore, to test if the junction supported a significantly different percentage cover of woody riverine vegetation to areas further away, I split the transects (n=45) into two groups, those which were in the junction polygon (n=18) and those which were not (n=27). These were plotted against mean (± SE) percentage woody vegetation cover for each group. To test if the percentage cover between these groups was significantly different I arcsine transformed the percentage data and ran an unpaired t-test for each year.

3. RESULTS

3.1. Woodland cover classification

Object-based supervised classifications of imagery for1948, 1955,1968, 1974, 2005 and 2016/18 were produced (Figures 3-8). Imagery for 1948 and 1955 was incomplete, and the figures show the extent of the woody riverine vegetation according to Cunliffe et al. (2012). This supports the majority of the woody riverine vegetation in Gonarezhou and exceeds the coverage of the imagery. Classifications gave pixels a vegetation/land cover result which allowed for calculation of woody riverine vegetation cover. In figures 3-8 Mopane woodland is visible in the riverine woodland vegetation delineation from Cunliffe et al. There is a substantial amount of Mopane woodland in this area, however on closer inspection riverine woodland vegetation is also visible. This is obscured slightly by the scale of the maps which are presented for the entire area to give an indication of overall woody riverine vegetation cover, the focus of further analyses. There is some inconsistency between classifications demonstrated at the junction area where in 1948, 1968 and 2016/18 the pans of water have been classified by the object-based automated approach as Mopane woodland (see Figures 3-8). Such inconsistencies warranted further investigation and comparison with ground truth values. An accuracy assessment, comparing machine learning classifications against visual assessment of cover was undertaken. Kappa values in table 2 demonstrate that there are inconsistencies between the classification and visual assessment. This is most pronounced in the analysis of the 1948 photographs. These are the oldest images, and the Kappa values subsequently improve to moderate by 1974 and 2005. The accuracy assessment for the 2016/18 photographs shows lower agreement than 1974 and 2005. For this year one classification was used for the composite of two different sets of imagery which impacted the accuracy (Table 2).

Table 2. Kappa values for accuracy assessment of machine learning classification demonstrating extent of agreement with visual assessment. Strength of agreement values are derived from Rwanga and Ndambuki, (2017).

Year	Kappa Values	Strength of Agreement
1948	0.189	Slight
1955	0.230	Fair
1968	0.243	Fair
1974	0.476	Moderate
2005	0.410	Moderate
2016/18	0.223	Fair

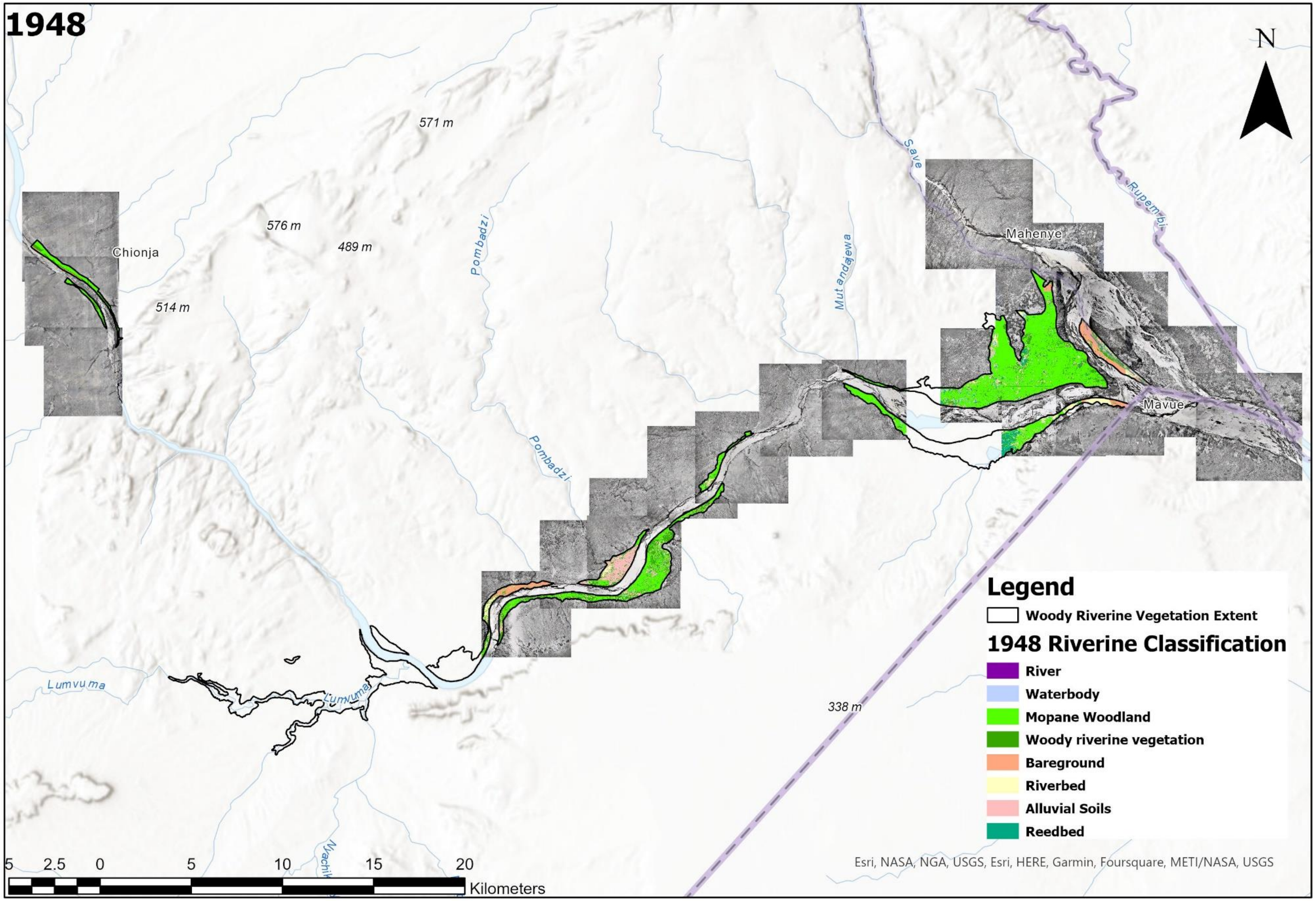

Figure 3. Aerial imagery from 1948 overlayed with the outputs of the supervised object-based classification of the woody riverine vegetation extent from Cunliffe et al (2012)

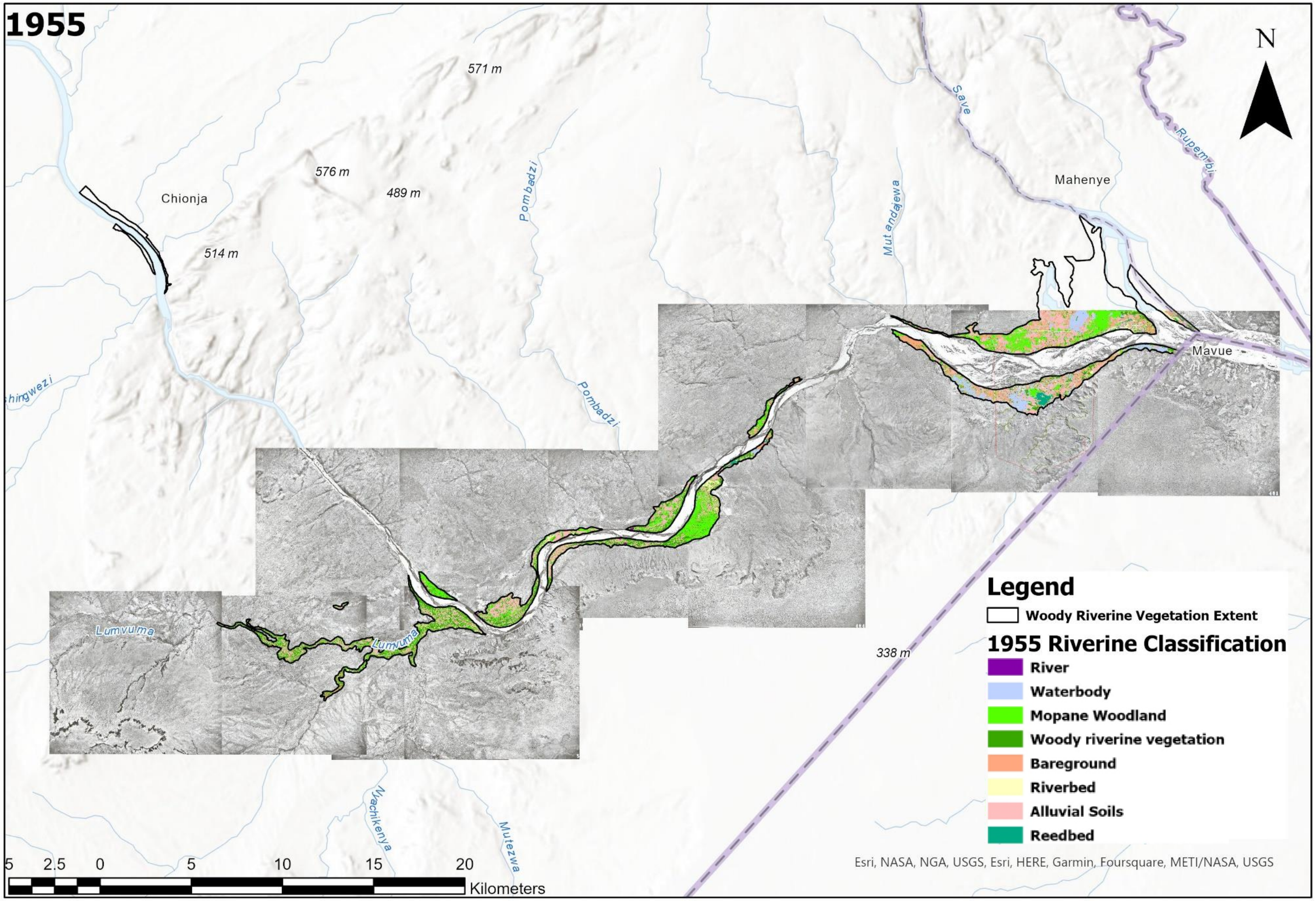

Figure 4. Aerial imagery from 1955 overlayed with the outputs of the supervised object-based classification of the woody riverine vegetation extent from Cunliffe et al (2012)

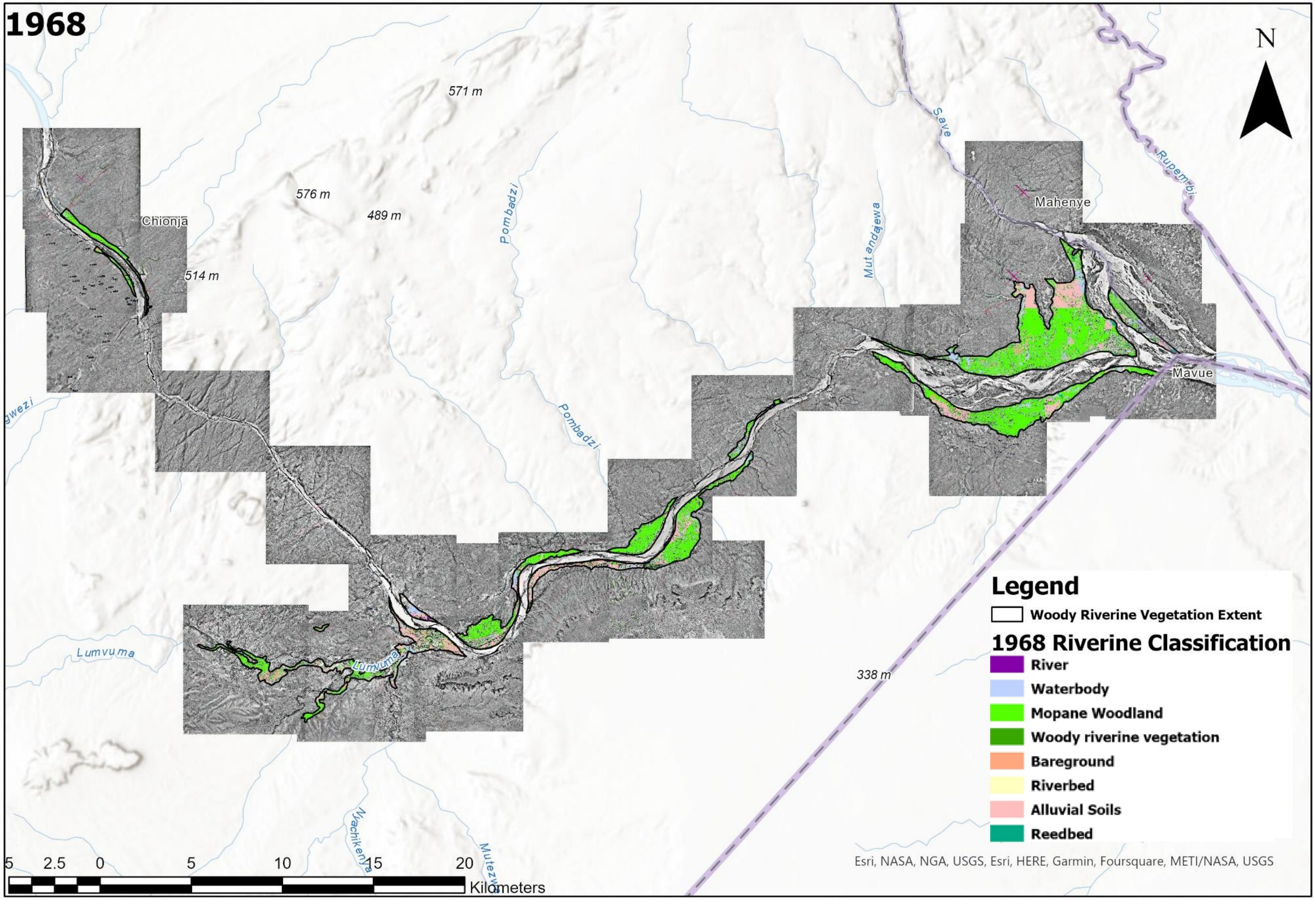

Figure 5. Aerial imagery from 1968 overlayed with the outputs of the supervised object-based classification of the woody riverine vegetation extent from Cunliffe et al (2012)

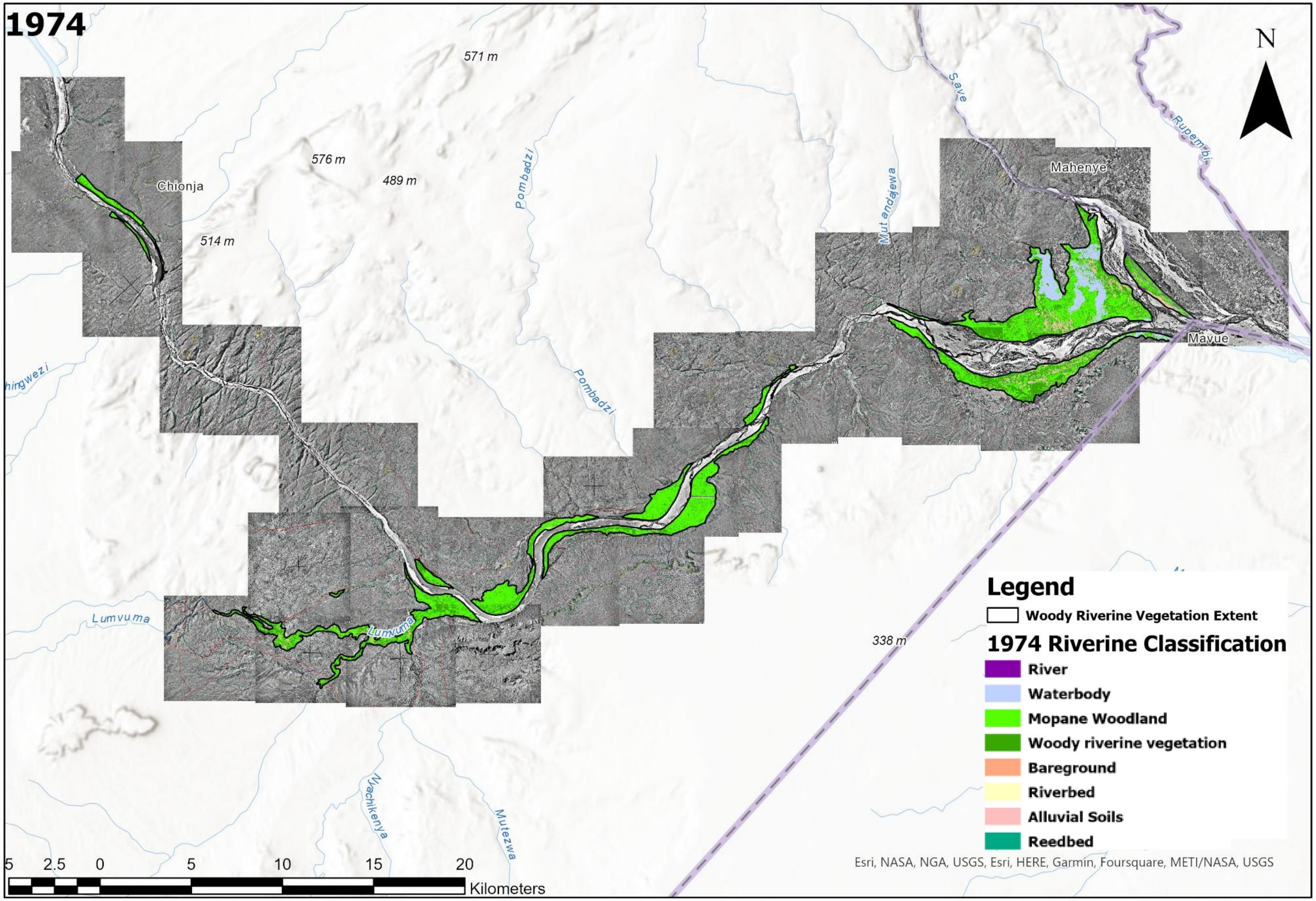

Figure 6. Aerial imagery from 1974 overlayed with the outputs of the supervised object-based classification of the woody riverine vegetation extent from Cunliffe et al (2012)

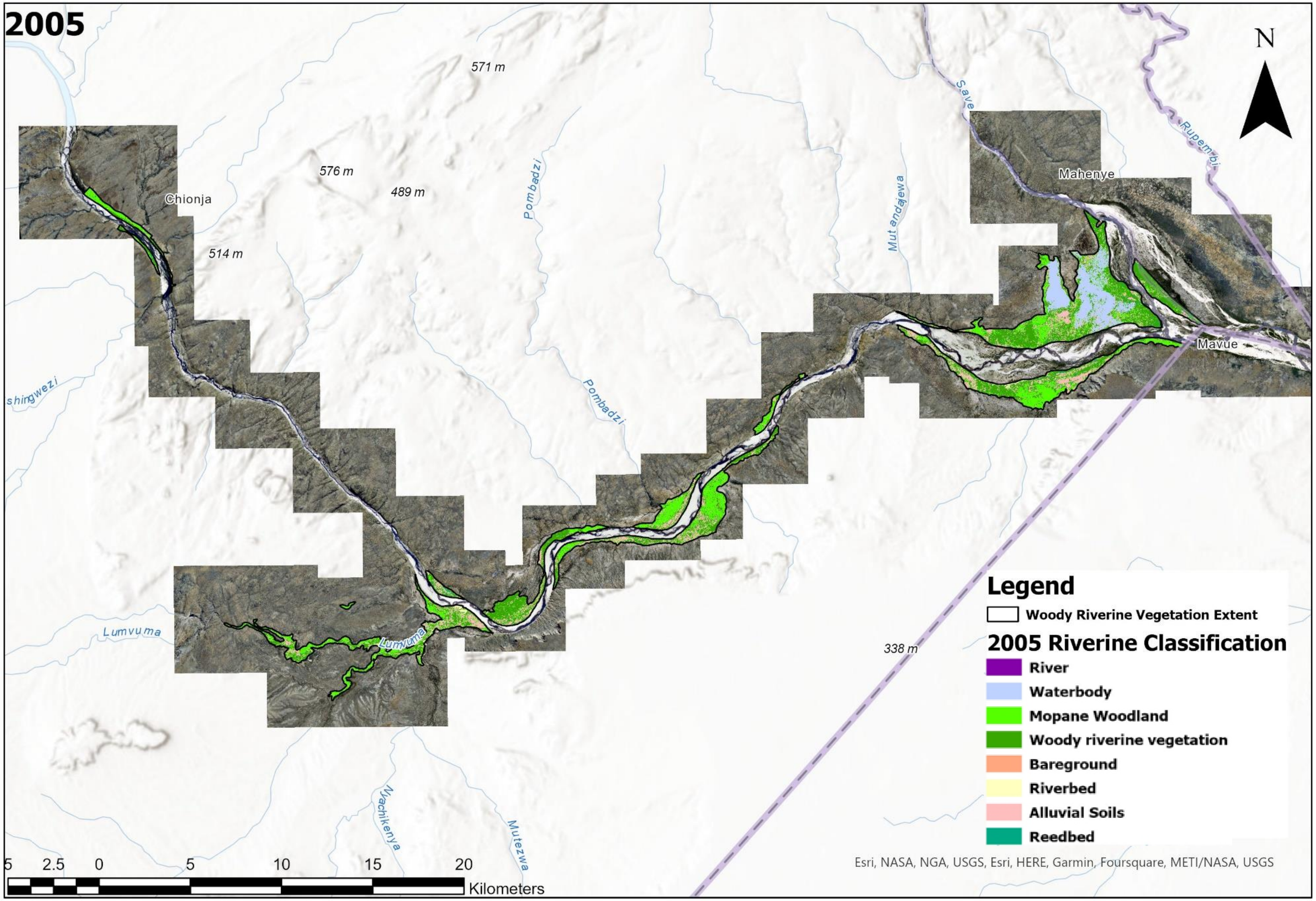

Figure 7. Aerial imagery from 2005 overlayed with the outputs of the supervised object-based classification of the woody riverine vegetation extent from Cunliffe et al (2012)

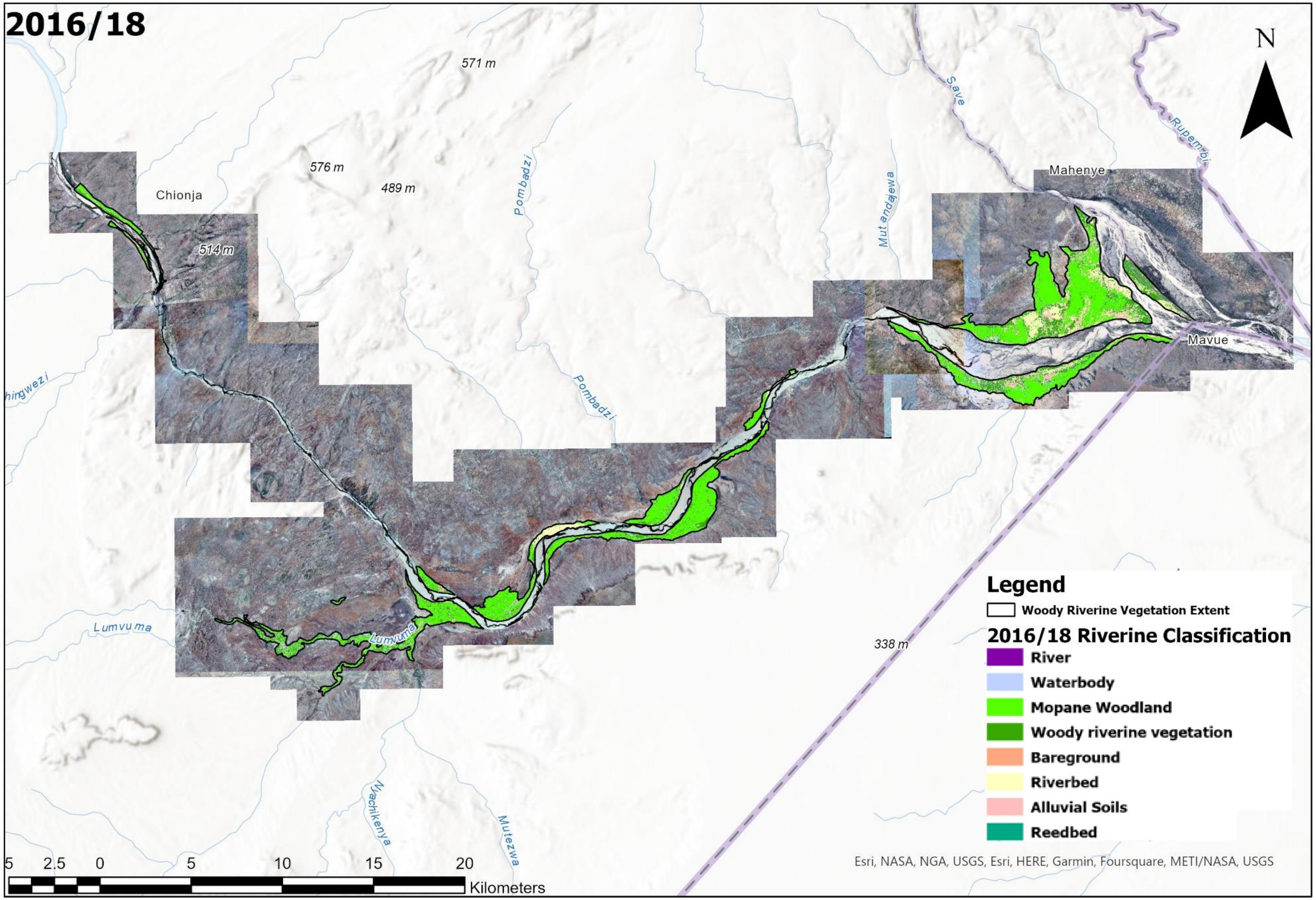

Figure 8. Aerial imagery from 1916/18 overlayed with the outputs of the supervised object-based classification of the woody riverine vegetation extent from Cunliffe et al (2012)

3.2. Overall change in woodland cover

According to Cunliffe et al's (2012) delineation, woody riverine vegetation covers a total area of 60.2 km^2 of Gonarezhou along the banks of the Runde River and its tributaries. From the broken bridge to Chivelila Falls 1.8 km^2 of woody riverine vegetation is supported. Downstream, from the end of Chivelila Falls, where the Benji meets the Runde, and to the Runde Save Junction woody riverine vegetation covers a total of 42.1 km^2. The junction between the Runde and Save supports 16.2 km^2 of woody riverine vegetation (Figure 2).

Percentage cover of woody riverine vegetation over the entire Runde River system in Gonarezhou increased from 14% in 1948 to a maximum of 40% cover in 2005 but by 2016/18 cover had decreased to approximately 20% (Figure 9). Over a 70-year period there had therefore been no net loss of woody riverine vegetation cover.

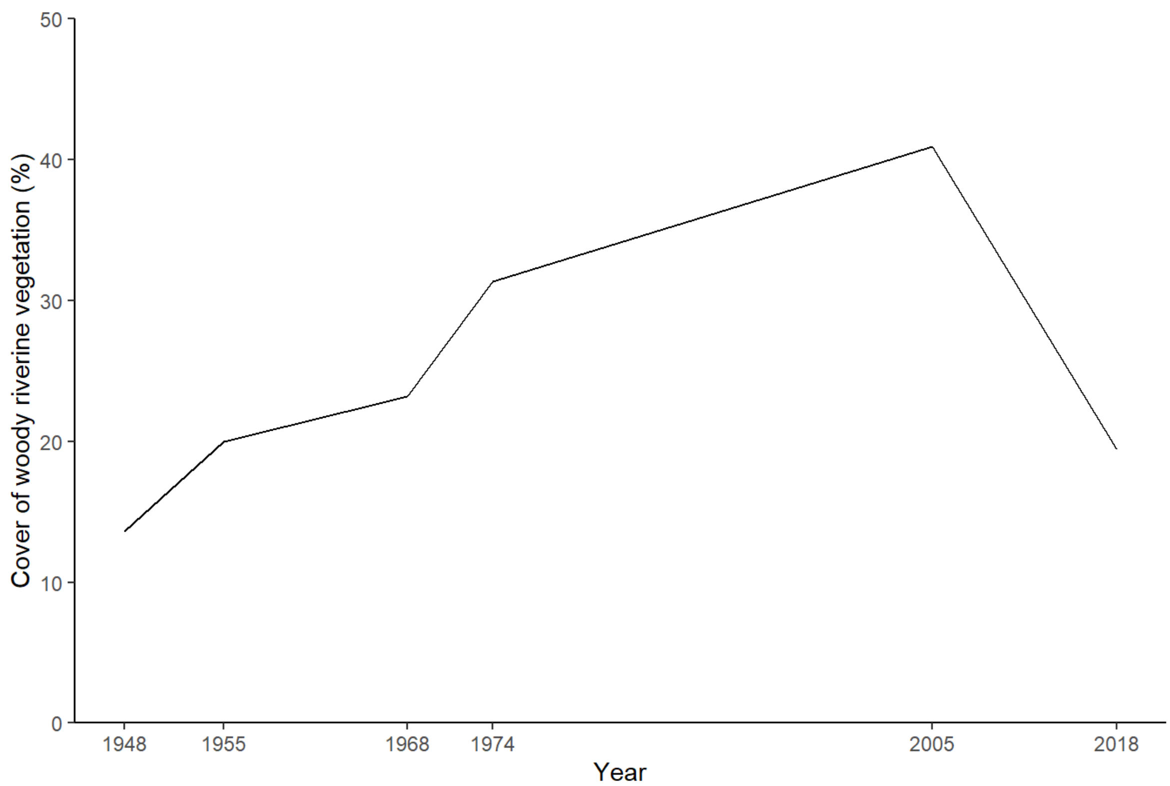

Figure 9. Overall percentage cover of woody riverine vegetation along the Runde River in Gonarezhou National Park

3.3. Human legacy effects

3.2.1 Cultivation

Clearing for cultivation could be identified between the confluence of the Benji and the Runde right up to and including the junction where the Runde meets the Save on both the north and the south banks (Figure 2). The greater share of cultivated lands was adjacent to but outside the alluvial soils of riverine woodland. The total area of previously cultivated woody riverine vegetation identified in imagery, therefore, is 3.3 km^2. Previously cultivated woody riverine vegetation encompasses <5% of the total woody riverine vegetation between the confluence of the Benji and Runde and the Runde-Save junction.

Woody cover was 12% less on cultivated fields than on uncultivated areas in 1968 just before people were displaced from the park (Figure 10, Table 3). Thereafter, the difference between the two closed to a difference of 1% cover in 2005, but increased to 5% difference in 2016/18, but an unpaired t-test revealed no significant differences between cultivated and uncultivated areas (Table 3).

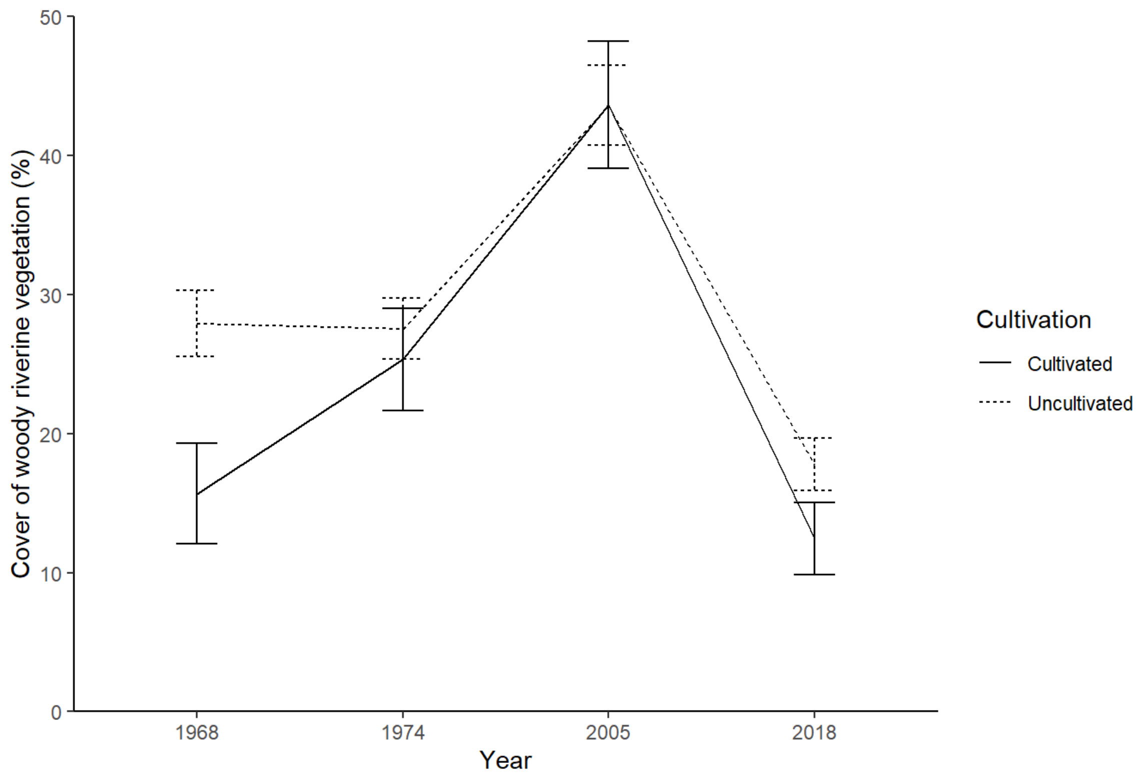

Figure 10. Mean percentage cover (± standard error) of woody riverine vegetation for areas which were previously cultivated and those which were not cultivated

Table3. Results of unpaired t-test with equal variance around the mean comparing mean percentage cover of riverine woody vegetation between previously cultivated and uncultivated areas

Year	T-statistic	df	p-value	95%CI
1968	-2.7198	96	0.0078	-21.1661, -3.3057
1974	-0.4919	96	0.6239	-11.1246, 6.7062
2005	0.0084	96	0.9933	-11.1624, 11.2573
2016/18	-1.6215	96	0.1082	-11.9197, 1.2015

3.2.2 Clearing for tsetse fly control

Clearing for tsetse could only be discerned for the area from the broken bridge to the Chivelila Falls, affecting around 0.4 km^2 of woody riverine vegetation on both the northern and the southern banks (Figure 2). Of the total woody riverine vegetation in the area (1.8 km^2), the area cleared for tsetse makes up 20% of the total woody riverine vegetation cover.

In 1948 imagery, areas of land which were cleared for control of tsetse fly in the 1960s show different woodland cover to those areas that were not cleared in the 1960s,. However, these differences decreased before clearing occurred in the 1960s. The effects of clearing can be seen in 1968 when areas that were not cleared have 16% higher woody riverine vegetation cover rising to a 25% difference by 1974 (Figure 11). Woody riverine vegetation cover in areas that were cleared increases to within 10% of areas which were not cleared by 2005 before diverging again to a 12% difference in cover by 2018. Overall, areas that were cleared for the control of tsetse fly have a lower percentage cover of woody riverine vegetation. This difference suggests that clearing had a long-term effect on woody riverine vegetation cover similar to that of cultivation described above. However, as the difference in cover in 1948 is already apparent before clearing it is possible that differences are not only attributed to clearing but also to growing conditions in locations where clearing later occurred. Statistical testing of differences with an unpaired t-test yields significant results for 1948, 2018 and a marginally significant result for 1974 suggesting that clearing does appear to have a long-term effect on woody riverine vegetation, but not consistently so, therefore other drivers of change may also have influenced this result (Table 4).

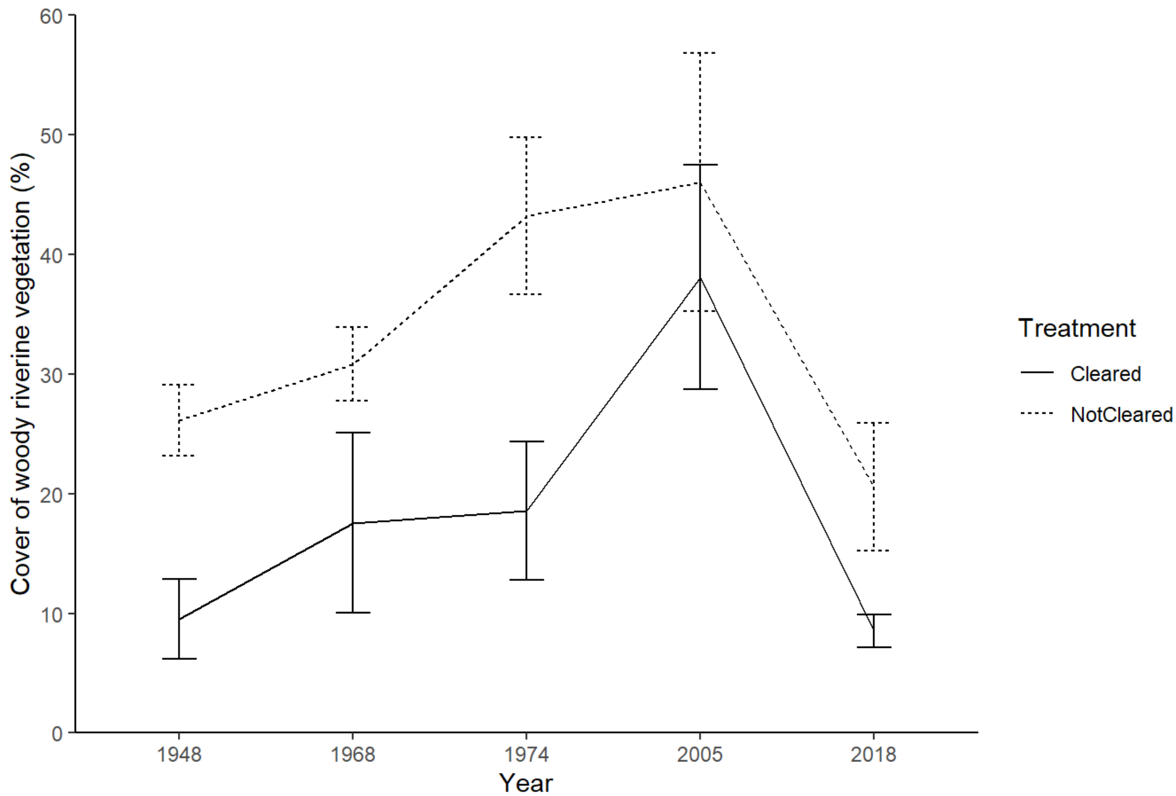

Figure 11. Mean percentage cover (± standard error) of woody riverine vegetation cover for areas which were cleared for tsetse control and those that were not

Table 4. Results of unpaired t-test with equal variance around the mean comparing mean percentage cover of riverine woody vegetation between areas cleared for tsetse fly control and those that were not

Year	**T-statistic**	**df**	**p-value**	**95%CI**
1948	-2.6526	6	0.0379	-31.9016, -1.2865
1968	-0.9627	6	0.3729	-47.0106, 20.4648
1974	-2.2377	6	0.0666	-51.5939, 2.3044
2005	-0.4443	6	0.6724	-51.5760, 35.7254
2016/18	-3.3944	6	0.0146	-24.1402, -3.3692

3.4. Precipitation

Rainfall records relevant to the years of imagery are summarised in table 5.

Table 5. Rainfall quantity by year for available imagery of Gonarezhou. Rainfall years run from July to June annually. Where a specific date for the imagery is available it is included. Malilangwe rainfall records are used when Gonarezhou records are unavailable. Malilangwe Conservation Trust is directly adjacent to Gonarezhou

Imagery Date	Rainfall Year	Rainfall (mm)	Source Location
1955 (Dry season)	1956	616.5	Malilangwe Conservation Trust
1968 (April)	1969	598.7	Malilangwe Conservation Trust
1974 (May)	1975	666.1	Chipinda Pools, Gonarezhou
2005 (5th October)	2006	513.6	Chipinda Pools, Gonarezhou
2016 (29th July)	2017	529.0	Chipinda Pools, Gonarezhou
2018 (26th October)	2019	215.4	Chipinda Pools, Gonarezhou

Rainfall records for years in which imagery was taken are important in understanding the amount of leaf cover in imagery. Leaf cover in each year is dependent on the rainfall in the preceding season and is retained for longer during wet periods. Given these figures (Table 5) we would expect to see a slight decline in woody cover between 1955 and 1968 given that there is less rainfall in 1968, increased cover in 1974, followed by a marginal decline in cover in 2005. 2016 should have higher cover and severe decline should be evident in 2018. Instead, we see a relatively steady increase in woody cover between 1955 and 2005 before a dramatic decline in the period 2016/18. The 2016/18 decline aligns with reduced rainfall records for the 2018 year. The majority of the imagery is taken in the dry season, with the exception of 1974 which is taken early in the wet season and 2016. Where rainfall records do not align with observed trends in woody riverine vegetation cover it is indicative that other drivers of change are influencing patterns of woody riverine vegetation change.

3.5. Boundary contrast of elephant impact

Figure 12 below shows the percentage cover for woody riverine vegetation in a plot with a high density of elephants and a plot with a low density of elephants over time. Woody cover changed markedly on the two plots over time with conspicuously lower cover on the plot accessible to elephants in 1974 and in subsequent years (Figure 12; Table 6).

Woody riverine vegetation cover was high in both high and low elephant density plots, in 1948 percentage cover was lower in the low elephant density plot however the difference in woody riverine vegetation cover did not significantly differ (Table 6). Woody riverine vegetation cover in both plots decreases considerably, by 34% and 16%, respectively, by 1968. This decline is attributed to clearing for the purpose of controlling tsetse fly in the late 1950s and early 1960s. From 1968 to 1974, woody riverine vegetation had increased by 30% in the lower elephant density plot, compared with a 16% increase in the high-density plot. By 2005, percentage woody cover in the low-density elephant plot had increased a further 19%, but by only 4% in the high-density elephant plot. Between 2005 and 2018, woody riverine vegetation cover decreased in both plots by 20%, which may be attributed to drought in the area. Woody riverine vegetation cover in the high elephant density plot is consistently significantly lower than the low elephant density plot from 1974 onwards (Table 6). Elephants have therefore resulted in a lower cover of woody vegetation over time.

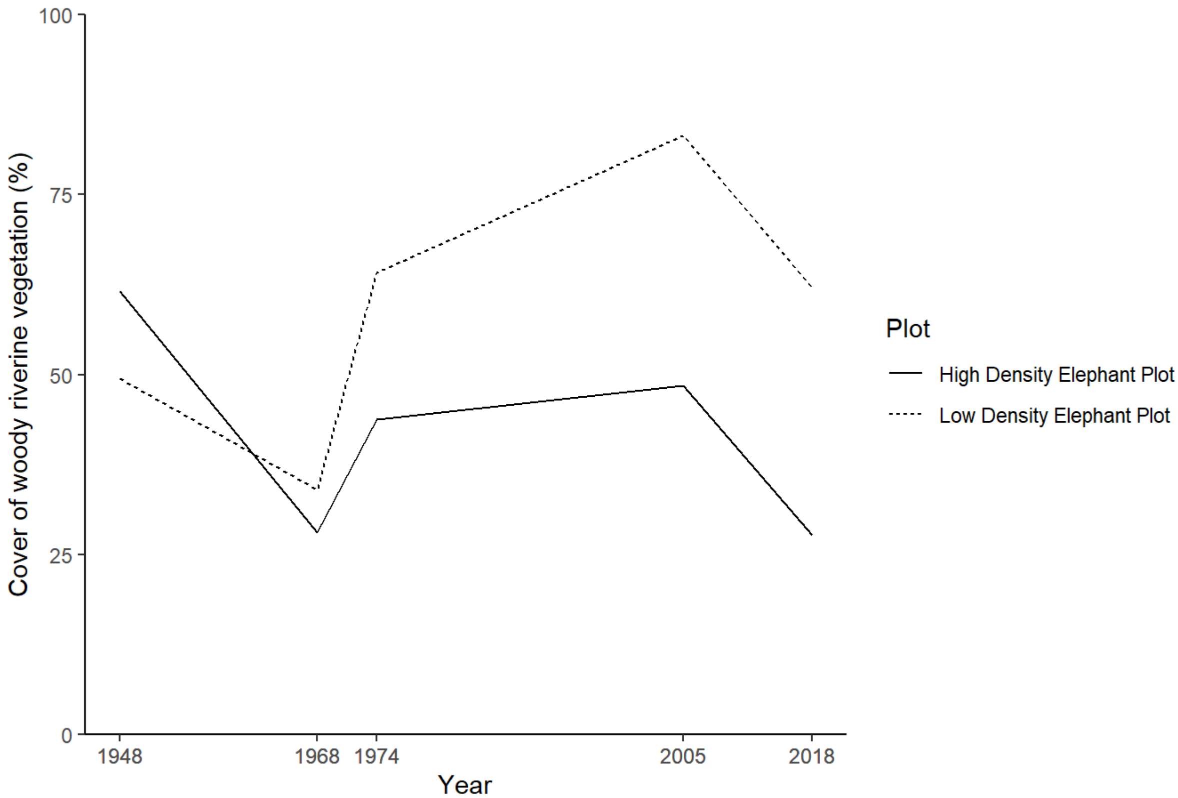

Figure 12. Percentage cover of riverine woody vegetation in high density elephant plot and low-density elephant plot.

Table 6. Result of G-test comparing pixel numbers of woody riverine vegetation between high- and low-density elephant plots for each year

Year	G Statistic	χ^2 degrees of freedom	p-value
1948	2.7504	1	0.0972
1968	0.5464	1	0.4598
1974	6.3724	1	0.0116
2005	15.8020	1	0.0001
2016/18	18.4310	1	0.0000

3.5. Distance of woody riverine vegetation from perennial water

Distance from perennial water sources yielded an initially complex output when the percentage cover of woody vegetation was plotted against distance from the weir for each year. Figure 13 shows considerable variation with no discernible trend. Variation looks highest between 5 and 10 km from the Weir. The 15 km mark is where the Benji meets the Runde, therefore between 5 and 10 km represents the midpoint between the two perennial water sources. However, when the data were aggregated into three groups of equal length, namely the weir, midpoint and Runde sections, a clearer pattern emerges (Figure 14).

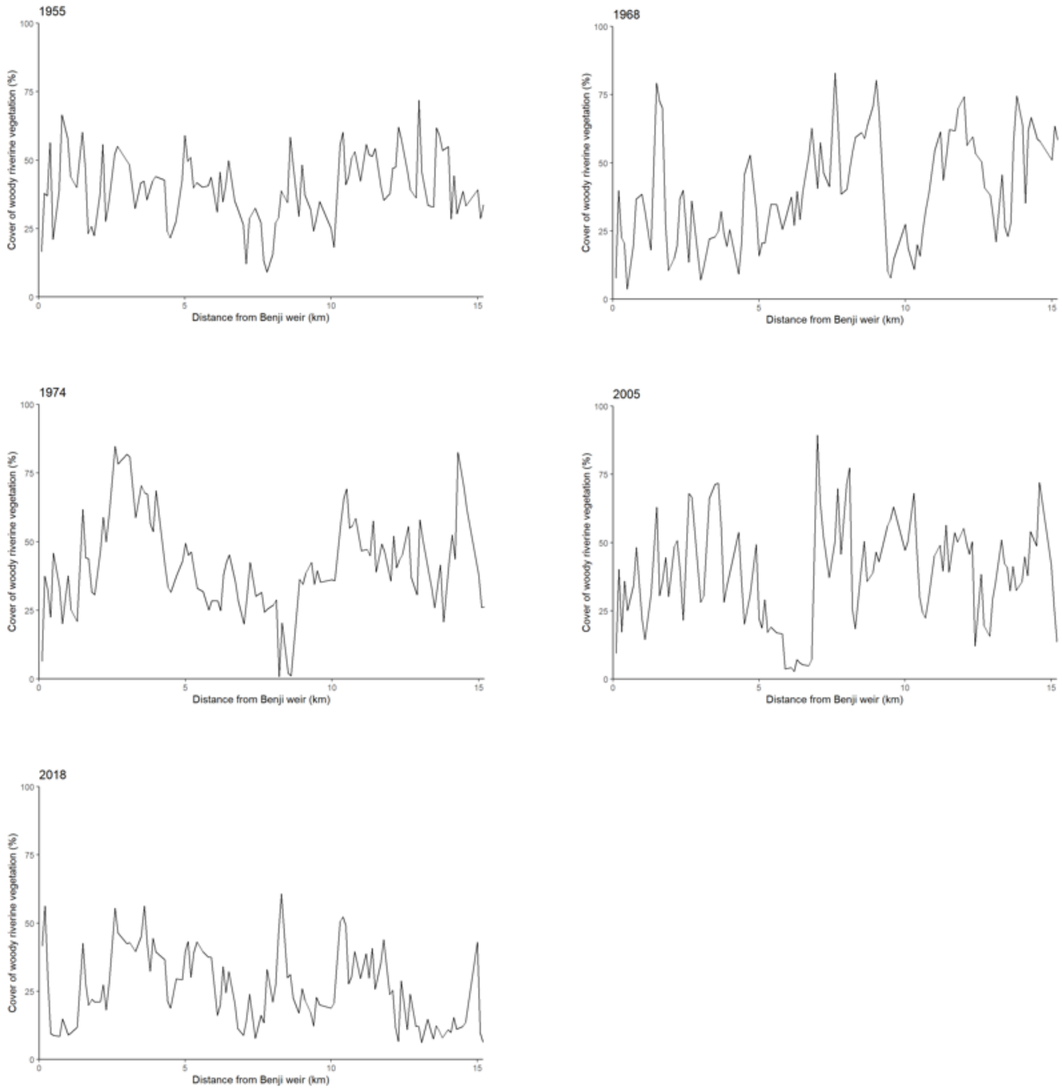

Figure 13. Distance plots showing the change in the percentage cover of woody riverine vegetation in transects at increasing distance from the Benji weir for five different time steps. The point farthest from the Benji weir is the confluence of the Benji and the Runde Rivers, a perennial water source

The cover of riverine woody vegetation differed between the weir, the midpoint and the Runde sections in all years except 2005 (Table 7). In 1955 and in 1974 the midpoint has the lowest cover of riverine woody vegetation, whereas the Runde and weir sections did not differ from one another (Table 7 and 8). In 1968 the Weir section had significantly lower woody vegetation cover than the midpoint and the confluence with the Runde (Table 8) while in 1974 the midpoint had significantly lower woody vegetation cover than the Weir and the Runde. In 2018, woody vegetation cover overall appears lower in all locations and lowest at the Runde. One discernible pattern is that woody vegetation cover at the confluence with the Runde has consistently decreased since 1974 (Figure 14). Woody cover along the Runde section was consistently highest and always as high as the other two sections, but by 2018 it was the lowest suggesting vegetation near this perennial water source may have experienced greater use than the rest of the Benji.

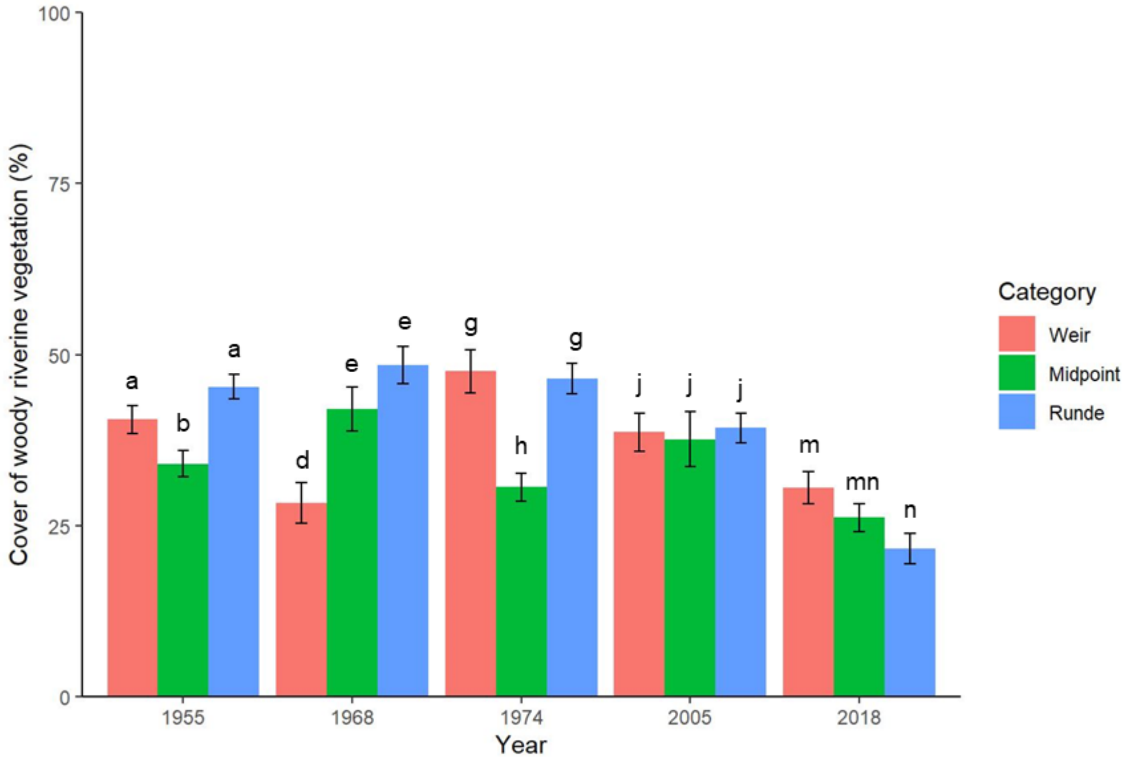

Figure 14. Mean percentage cover (± standard error) of woody riverine vegetation for three sections of the Benji tributary in each year (Benji weir, the Midpoint between the weir and the confluence with the Runde River, and the confluence with the Runde River). Letters correspond to Tukey's post hoc significance; full results are presented in Table 8.

Table 7. Results of one-way analysis of variance for mean percentage woody cover of the three sections of the Benji tributary (Weir, Midpoint and Runde) for each year

Year	F-statistic	df	p-value
1955	8.6200	2,108	0.0003
1968	12.2000	2,108	0.0000
1974	13.9000	2,108	0.0000
2005	0.3000	2,108	0.7400
2016/18	4.4200	2,108	0.0140

Table 8. Results of a Tukey's Post Hoc analysis of variance between percentage of woody riverine vegetation cover between the three sections of the Benji tributary (Weir, Midpoint and Runde) for each year.

Location	difference between means	Lower CI	Upper CI	p-value
1955				
Runde-Midpoint	0.1207	0.0513	0.1901	0.0000
Weir-Midpoint	0.0697	0.0003	0.1391	0.0490
Weir-Runde	-0.0511	-0.1205	0.0183	0.1920
1968				
Runde-Midpoint	0.0695	-0.0395	0.1785	0.2880
Weir-Midpoint	-0.1519	-0.2609	-0.0429	0.0040
Weir-Runde	-0.2214	-0.3304	-0.1124	0.0000
1974				
Runde-Midpoint	0.1787	0.0830	0.2740	0.0000
Weir-Midpoint	0.1886	0.0929	0.2840	0.0000
Weir-Runde	0.0099	-0.0858	0.1060	0.9670
2005				
Runde-Midpoint	0.0365	-0.0809	0.1540	0.7410
Weir-Midpoint	0.0290	-0.0884	0.1460	0.8270
Weir-Runde	-0.0075	-0.1249	0.1100	0.9870
2016/18				
Runde-Midpoint	-0.0615	-0.1481	0.0250	0.2140
Weir-Midpoint	0.0464	-0.0401	0.1330	0.4130
Weir-Runde	0.1079	0.0214	0.1940	0.0100

3.6. Availability of alternative forage

Alternative forage was discernible at the junction of the Runde and Save rivers (see 'reedbed' category in figures 3-8). Plotting woody riverine vegetation cover from the junction to 48 km upstream where the Benji meets the Runde yielded variable results (Figure 15). 2005 shows the greatest variation, as indeed it did for the Benji above. Data from 2018 supports consistently lower woody riverine vegetation cover, while 1968 and 1974 sit between these values (Figure 15).

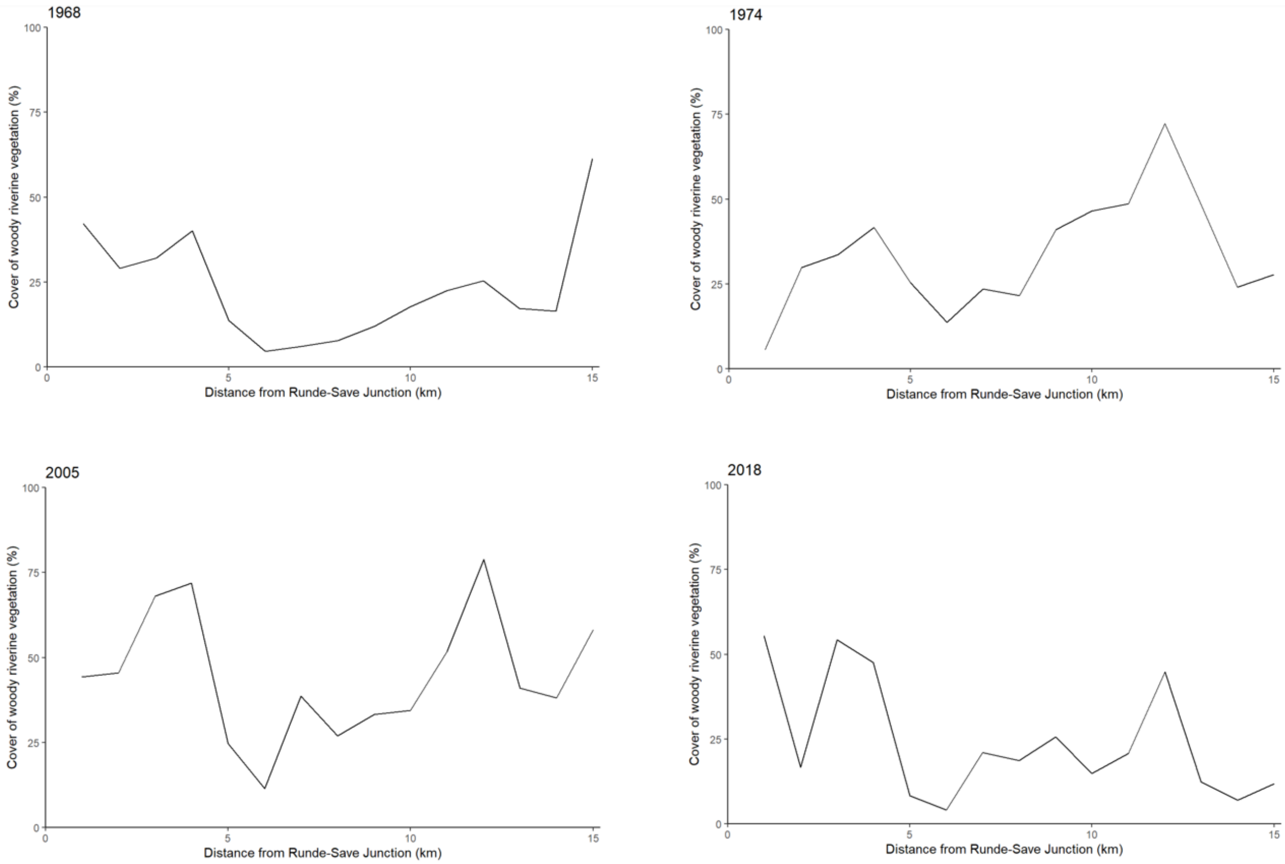

Figure 15. Distance plot showing the percentage of woody riverine vegetation cover in transects at increasing distance upstream of the Runde – Save Junction for each year

Aggregating the transects into two groups the junction area and areas away from the junction allows for a more useful analysis of whether alternative forage at the junction influences woody riverine vegetation or not (Figure 16). There was no significant effect of distance from the junction on woody riverine vegetation cover for all years except for 2018 where the junction had a significantly higher percentage of woody cover (Table 9). In 2018 it is therefore possible that availability of alternative forage in the junction area had reduced the impact of browsing on woody riverine vegetation at the junction relative to the non-junction area.

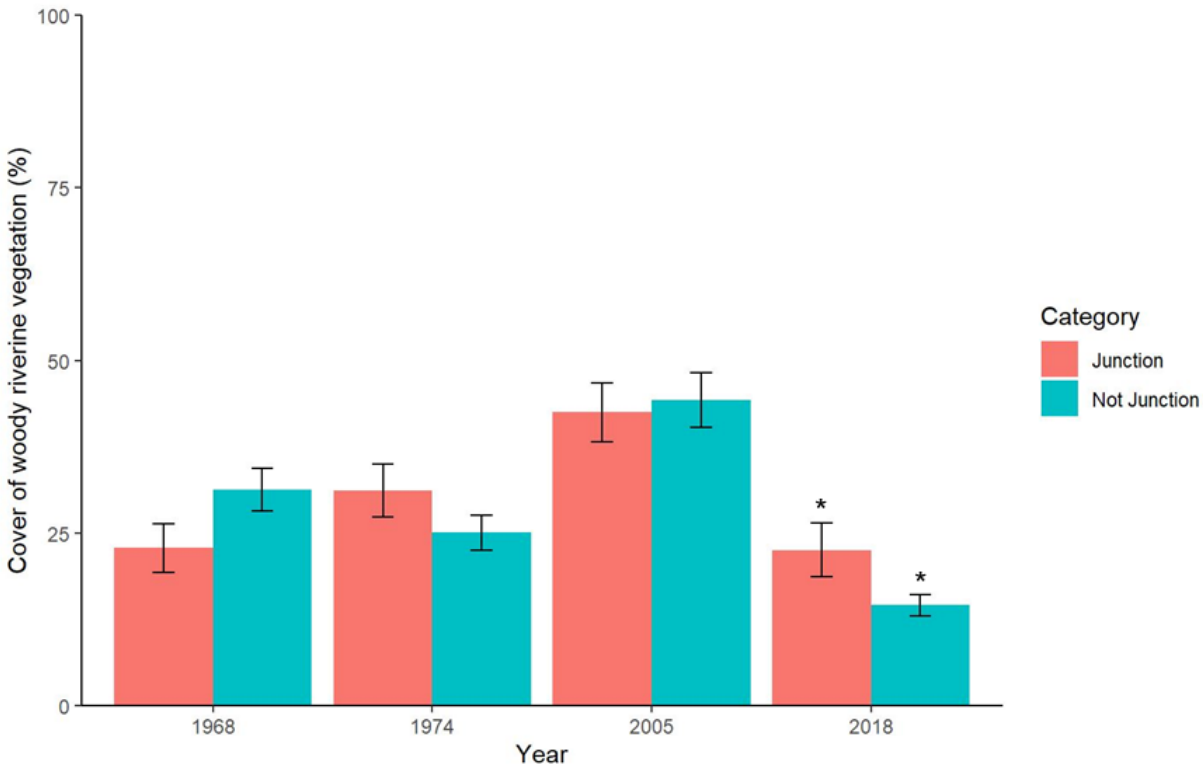

Figure 16. Mean percentage cover (± standard error) of woody riverine vegetation for two sections of the Runde (the Runde-Save Junction and areas upstream of the Junction) in each year. * indicates a significant difference.

Table 9. Result of unpaired t-test with equal variance around the mean for percentage of woody riverine vegetation cover at the Save-Runde junction and areas upstream of the junction for each year

Year	**T-statistic**	**df**	**p-value**	**95%CI**
1968	-1.9135	43	0.0624	-0.2121, 0.0056
1974	1.3529	43	0.1832	-0.0342, 0.1734
2005	-0.2180	43	0.8285	-0.1454, 0.1171
2016/18	2.0534	43	0.0461	0.0018, 0.1993

4. DISCUSSION

The results above allow us to make some clear statements around cover of woody riverine vegetation in Gonarezhou with respect to different drivers of change. Overall cover of woody riverine vegetation shows no net loss of vegetation cover since 1948, however recent declines (from 2005 onwards) appear severe and therefore drivers of change warrant further exploration. The discussion below first considers the human impacts which have historically driven change in riverine woody vegetation cover in the park. It then explores how weather patterns may have affected results before moving on to draw conclusions around more recent elephant impacts on cover of woody riverine vegetation in Gonarezhou. Discussion of the limitations of the classification approach for the analysis of historical imagery and complexity follows, together with an assessment of whether woody cover is in fact a good proxy through which to understand change in woody riverine vegetation. Finally, management implications of the research thus far are explored while making recommendations for further research.

4.1. Human legacy effects on woody riverine vegetation cover

Anthropogenic drivers of vegetation change in Gonarezhou include cultivation and clearing for the control of tsetse fly, the impacts of which should be differentiated from elephant impact to avoid false attribution of change in woody riverine vegetation cover.

Areas affected by historical cultivation represented less than 5% of the total extent of woody riverine vegetation. These areas showed lower woody riverine vegetation cover than uncultivated areas. This difference however was not statistically significant and does not support the expectation that cultivation has a long-term impact on woodland recovery. A study with a similar cultivation history shows prolonged impacts of cultivation on floodplain vegetation recovery. People were forcibly removed from Makuleke Contractual Park (the northern most section of Kruger National Park in South Africa) in the early 1970s and recovery is apparent by 2005 in satellite and aerial imagery, a timescale similar to the present study (Turner, 2021).

Woody cover may not represent the most suitable indication of vegetation recovery as it overlooks elements of structure and composition. McNicol et al (2015) explored the resilience of African woodlands to shifting cultivation. Tree species diversity appeared to recover to that of mature woodland within 10 years of ceasing cultivation. However composition recovery takes much longer, between 60 – 80 years (McNicol et al., 2015). Studies of woodland recovery indicate further measures, such as the assessment of structure and composition, are required to disentangle complexity. They tend to account for factors such as stem diameter, height, canopy structure and presence of successional species to determine recovery (Gonçalves et al., 2017; Mwampamba and Schwartz, 2011). A study on the recovery of Miombo woodland highlighted the challenges associated with accurate monitoring of recovery through mapping of woodland cover alone due to the influence of structure and composition of the woodland, which is also apparent in the present study (Ribeiro et al., 2015).

There is a wide knowledge and literature base concerning the impacts of mesobrowsers on the recovery of woody riverine vegetation. Mesobrowsers, especially impala, have been associated with reduced recovery of woody riverine vegetation as they consume the seedlings of woody riverine species, reducing recruitment (Coetsee and Wigley, 2016; Moe et al., 2009; O'Kane et al., 2012). In Gonarezhou, impala were abundant on previously cultivated areas in the early 1980s (O'Connor and Campbell, 1986a) and surveys conducted by Dunham (2012) indicate that impala remain abundant in the park. O'Connor considers that the degraded state of the old fields studied in 1986 has not improved over the last 40 years, and that impala are still abundant on previously cultivated fields (pers. comm., T. O'Connor). Therefore, delayed recovery of cultivated fields should be apparent in Gonarezhou. Impacts of cultivation therefore require closer investigation and a perspective on vegetation structure and composition to assess the impacts.

Ground measures of woody vegetation recovery regarding historical cultivation in Gonarezhou are not easily procured, as more than 50 years have passed since areas of the park were cultivated. However, resampling of areas studied in 1986 may be possible and could provide further information on structure and complexity of recovery of woody riverine vegetation (O'Connor and Campbell, 1986a). In addition, the use of paired plots on imagery could warrant further investigation. Pairing areas which were cleared with those of a similar size and characteristic could give a more precise measure of change in woody vegetation cover to complement resampling approaches.

Clearing for tsetse fly in Gonarezhou, cleared around 20% of the riverine woody vegetation between the Broken Bridge and Chivelila Falls covering an area of 0.4 km^2. Despite the small sample size, statistical significance is apparent, suggesting that tsetse clearing has had a long-term impact on woody riverine vegetation cover. Although frequent reference to bush clearing of woodland for tsetse control in the 1960s, 1970s and 1980s is apparent in the literature, such studies have not quantified the effect of clearing for tsetse or determined it's long lasting impact on woodland vegetation (Chidumayo, 2002; Cumming et al., 1997; Douthwaite, 1985; Pilossof, 2016; Ribeiro et al., 2020). Long term impacts of tsetse fly clearing on woodland cover have not been uncovered before and warrant further research.

In Gonarezhou, clearing for tsetse fly excluded the dense woody riverine vegetation directly adjacent to the river. Therefore, when compared with areas which were not cleared, the results could also indicate that woody riverine vegetation which was less dense in the first place was cleared. In addition, when clearing occurred, some large woody riverine trees were left behind which may explain why results are only significant in some time steps, depending on growth or loss of leaves under low rainfall conditions. The 1948 imagery for the Broken Bridge to Chipinda pools area was of lower quality which may have posed additional challenges for accurate classification of this imagery. Therefore, this area would benefit from visual reassessment to confirm the effect observed.

Overall, it is apparent that human driven changes in woody riverine vegetation cover have long term and distinguishable impact. Despite the short comings of woody vegetation cover as a proxy for woodland recovery from cultivation, impacts of tsetse clearing cannot be ignored. Therefore, it is essential to consider these when understanding macro changes in vegetation cover in Gonarezhou.

4.2. Weather patterns and hydrology

Weather patterns can impact woody riverine vegetation cover. In years where rainfall is higher, woody riverine vegetation experiences increased growth and trees retain more leaves for longer periods thus increasing the percentage cover of woody vegetation (Masia et al., 2018; Whitecross et al., 2017). This can also influence the extent of woody cover present in imagery, if it was taken in a particularly wet year, hence rainfall quantities for imagery years are presented in results.

Where rainfall records do not align with observed trends in woody riverine vegetation cover, (whjch is the case for all years except 2016.18 in this study), it is likely that other drivers of change are influencing woody riverine vegetation cover, such as use by elephant populations. It is possible that rainfall in years between those for which imagery is available could also contribute to a different trend in woody cover however intervals in the present data are too wide (sometimes decades apart) to make an informed judgement on this. There are however possible interactions between rainfall and behaviour of elephants which could drive changes in vegetation cover (De Beer et al., 2006). In 2018, the park experienced one of the lowest rainfall years on record. It is likely that lack of rainfall may enhance elephant impact of woody riverine vegetation and well as reducing cover through drought (O'Connor et al., 2007). Elephants congregate at the remaining perennial water sources like the Runde River and lack alternative food sources which may have perished in drought thus enhancing their impact on woody riverine species, which may contribute to reduced cover in imagery (Janecke, 2020; O'Connor et al., 2007; Viljoen et al., 2013).

Gonarezhou is also periodically affected by cyclones from the Indian Ocean, which penetrate into the park from Mozambique (Kupika et al., 2021). Notable cyclones leading to flooding and destruction of woody riverine vegetation by stripping trees along banks of the Runde in Gonarezhou are; cyclone Eline in 2000, cyclone Jokwe in 2008, Dineo in 2017, Idai in 2019 and Mavhura in 2020 (Mavhura, 2020). Cyclone Dineo in 2017 may have contributed to the decline in woody riverine vegetation cover observed in the 2016/18 data. Increased input of water from cyclones and flooding can also temporarily improve growing conditions for vegetation, but this benefit is unlikely to persist beyond one season. However, the classification approach in this study was not designed to investigate detail such as potential loss of banks and the trees thereon. The time frame over which imagery is investigated is not of a temporal resolution high enough to address the impact of flooding between seasons or cyclones and non-cyclone years. As a result of climate change, the frequency and intensity of cyclones is likely to increase in future, therefore their contribution to driving changes in woody riverine vegetation cover may increase and warrants further exploration (Romero-Calcerrada et al., 2022).

Rivers change their courses in response to flow rates, geology, erosion, and deposition of sediments, thus influencing vegetation growth in the surrounding area. Both the Runde and its tributaries have changed course over time (McCartney et al., 1998). Mapping the changes (losses and increases of land) resulting from river changes would have added valuable insight. However, due to the time-sensitive nature of this study, this was not undertaken. Casual observation of the Runde River suggests that its path does change over time, and this could have some influence on woody riverine vegetation cover which should be explored in future.

4.3. Savanna elephant impacts on woody riverine vegetation cover

Having examined the influence of human impacts and weather patterns on woody riverine vegetation it is possible to isolate impacts which are driven by elephants. This study verifies that high densities of elephant have a detrimental impact on woody riverine vegetation cover in Gonarezhou. Elephant activities such as foraging, toppling, ring barking and uprooting have influenced woody riverine vegetation cover. The number of elephants in Gonarezhou has risen since 1995, increasing the intensity of such activities (Dunham, 2012). Woody riverine vegetation inside the park, when compared with a plot outside (experiencing lower densities of elephant) has decreased as the elephant population in Gonarezhou increased. These differences have become more pronounced since 1995. This finding mirrors that of many studies of elephant impact on woody vegetation (Asner et al., 2016; Cumming et al., 1997; Du Toit et al., 2003; Ferry et al., 2021; Leuthold et al., 1977; O'Connor, 2010; Tafangenyasha, 1997). It is possible that the proximity of both the plots to perennial water sources exaggerate the overall impact of elephants on vegetation in Gonarezhou as riverine environments experience a greater intensity of use. However, this pattern is consistent for riverine woody vegetation in the park.

To validate this trend for Gonarezhou further, it would be beneficial to increase the sample size. However, locating paired plots within and outside the park boundary is difficult because of the differences in land use which occur directly beyond the park boundary. On its eastern edge Gonarezhou is unfenced, elephants move freely across the park boundary therefore it is difficult to contrast densities of elephant. The further the paired plot from the park boundary the more likely it is that conditions will differ between plots due to localised hydrological or weather conditions, vegetation cover type or historical land use. The observed difference between the two plots chosen for the study is derived from otherwise very similar environments.

Investigation of woody riverine vegetation cover patterns provide further evidence for the impact of a high density of elephants on vegetation cover. It was predicted that along seasonal tributaries there would be an increase in woody riverine vegetation cover with distance from a perennial water source. Water dependent species like elephants will remain close to water when foraging and seasonal tributaries will, therefore, only experience elephant impacts on woody riverine vegetation when water is present (O'Connor et al., 2007; Skarpe et al., 2004). The Benji river, a seasonal tributary with a weir at one end and confluence with the Runde River at the other, expressed a consistent decline in woody cover at the confluence with the Runde River after 1974. This decline is consistent with elephant impacts. Several studies suggest that during the dry season in particular perennial water sources experience greater use intensity by elephant (Skarpe et al., 2004). In Hluhluwe-iMfolozi Park in South Africa elephant damage reduced with distances of up to 5 km from water (Boundja and Midgley, 2010). One study investigating Zambezian *Baikiaea* woodland in Zimbabwe suggests impact is detectable within 5 km of the permanent water source (Wilson et al., 2021). Where the seasonal Benji meets the perennial Runde river in the present study, we see increased elephant impact on woody riverine vegetation for the 5km closest to the Runde.

In Hwange National Park in Zimbabwe the dry season constrained the entire parks' population of elephants to perennial and artificial water points (Chamaillé-Jammes et al., 2007). The Runde is the largest perennial water source in Gonarezhou, likely supporting a high density of elephants along its banks. As densities of elephants have increased in recent years, damage to the riverine vegetation at the Runde River is exacerbated as elephants congregate where water is reliably available (Gandiwa et al., 2012; O'Connor et al., 2007).

In earlier years the Benji Weir showed greater variability in vegetation cover than the Runde. Water levels at the Weir are affected by drought and flood years and the seasonal nature of the tributary. In addition, the Weir supports less suitable forage for elephants as immediately adjacent to the weir there is very little woody riverine vegetation. In contrast, flow of the Runde is not halted by drought, the water source is larger and supports a continuous and high-volume water supply. It therefore follows that elephants, particularly in cow-and-calf groups, requiring forage close to perennial water, may show preference for forage at the Runde River. This pattern was also observed by Gandiwa et al (2012). In drought years this may be further exaggerated. Elephant impact has been observed to extend to distances further from perennial water sources when available surface water decreases in drought years. This may explain the decrease in woody riverine vegetation cover at the Runde River in 2018, which was a drought year in Gonarezhou (Gaugris and van Rooyen, 2010).

The remote sensing approach taken, accounts for macro changes in woodland cover but may have been on too large a scale to identify trends in distance from water and elephant impact. Interestingly one other such study, using remote sensing techniques, does not find that distance from water influences elephant distribution (Chamaillé-Jammes et al., 2009). An alternative approach would be to sample woody vegetation cover and structure on the ground. One study suggested that overall elephant impact did not severely affect species composition but high densities did affect structure of vegetation (Ferry et al., 2021). A complementary study (J.B. Cragg, unpublished data) has investigated the gradient in the structure and composition of the riverine woody vegetation between the Benji weir and the Runde River in Gonarezhou using 35 ground-based plots. Preliminary results suggest that that there was a clear influence of distance from permanent water from the Runde River toward the weir on vegetation structure and composition. The mid-section can be described as still supporting relatively intact riverine woodland (J.B. Cragg, in preparation). This suggests that investigations of woody cover alone do not provide an adequate description of the complexity of elephant impact on woody riverine vegetation. Further studies of woody riverine vegetation structure in Gonarezhou show variability which can be attributed to elephants and anthropogenic disturbance, further highlighting that woody riverine vegetation cover may not reflect the full range or complexities of elephant impacts (Zisadza-Gandiwa et al., 2013).

Although the present investigation into distance from perennial water sources along the Benji does not allow for conclusions to be drawn regarding the possibility that seasonal tributaries provide a refuge for woody riverine vegetation, it does support the prediction that high densities of elephants are impacting woody riverine vegetation particularly at perennial water sources.

I investigated how the availability of alternative forage may impact the use of woody riverine vegetation (Clegg, 2010; O'Connor et al., 2007). Woody riverine vegetation cover was expected to decline less in areas where alternative forage was available. The junction where the Runde River meets the Save is distinct from the areas of woody riverine vegetation upstream. As water is readily available at the confluence, the area supports green grasses and hygrophilous vegetation alongside woody riverine vegetation throughout wet and dry seasons. Bulls show a preference for grazing on grasses thus reducing their impact on woody riverine vegetation when alternative forage is available (Clegg, 2010; Clegg and O'Connor, 2016). In the present study, a reduction in the decline of woody riverine vegetation at the junction was not initially apparent when compared with areas upstream. However, existing evidence based on models would suggest that elephant impact on woody species Is reduced when the abundance of grasses increases (Baxter and Getz, 2005; Jeltsch et al., 2000). *Faidberbia albida* is abundant at the Runde Save junction, and its presence also typically reduces impact on other woody riverine species as it is attractive to elephants (Moe et al., 2009). Preferential browse of *F. albida* however, reduces their abundance over time and their seedlings are susceptible to consumption by mesobrowsers and elephants. This suggests that over time, and in the presence of high densities of elephants and impala such as in Gonarezhou, these species may become less abundant and the impact of browsers on woody vegetation could increase (Dunham, 2012; Gope et al., 2015; Moe et al., 2009). It is possible that additional available forage and water at the junction means that the area experiences a higher use intensity by elephants, particularly bulls due to their preference for grasses, thus resulting in increased impact on woody riverine vegetation overall compared with areas upstream (Clegg and O'Connor, 2016; Macfadyen et al., 2019).

In 2016/18, however, the expected trend for higher woody riverine vegetation cover at the junction is evident. In this dataset 2016 imagery is used for the areas upstream of the junction while the junction area uses imagery from 2018. However, it is unlikely that a 10% difference in woody riverine vegetation cover at and away from the junction can be accounted for by 2 years difference between the images alone. Elephant populations have increased since 1995. Ecological responses often lag behind change in landscape use and therefore changes in vegetation cover at the macro-scale may only be emerging now (Lira et al., 2019). Further monitoring of these areas in future would confirm if these differences reflected an emerging trend.

A useful extension of this analysis would be to quantify the extent of alternative forage to ensure this is in fact higher at the junction area. The classification in use, grouped together alternative forage as 'reedbeds' in the classification schema. A complementary study (J.B. Cragg, in preparation) currently in preparation has sampled woodland structure and composition along the gradient from the Junction upstream using 70 plots on the ground. The expected pattern of a higher woody cover of riverine vegetation at the junction was present, but not conspicuous, owing to the relatively diverse array of vegetation types in the Junction area, including palmveld, *Faidherbia albida* woodland, and gallery forest, among others. This confirms that the woody riverine vegetation classification for this study may not have been at a high enough resolution to delineate this complexity. To investigate this further it may be more useful to conduct a visual assessment as the vegetation complexity at the junction is high. Hydromorphic grasslands around the pans at the junction, for example, are extensive and easily identified and mapped. There are also extensive *Faidherbia* woodlands which are not as easily mapped but visual assessment of imagery may be able to discern these (Cunliffe et al., 2012). Such analysis would confirm the impact of alternative forage on woody riverine vegetation cover at the junction and further support Cragg's findings.

Overall, the impact of elephants on woody riverine vegetation in Gonarezhou is considered significant. However, the extent to which seasonal tributaries and alternative forage provide a refuge for woody riverine vegetation cannot be confirmed from this study alone, although indicative patterns of impact do emerge in 2018. Further investigation and closer analysis of macro changes in woody riverine vegetation cover would be required to confirm the importance of such areas for woody riverine vegetation conservation in Gonarezhou.

4.4. Limitations of the woodland cover and classification approach

Supervised object-based classification is the state of the art regarding image processing and analysis for land cover. Typically, multi-spectral satellite imagery is used, and the classification can, when trained, attribute values to each spectral band to use as criteria for classification into various land cover classes. Increasingly the use of supervised classification approaches on satellite or aerial imagery is being explored as an alternative to manually digitising and visually classifying vegetation communities (Liu et al., 2002; Ma et al., 2017; Mohd Hasmadi et al., 2009). The greatest advantage of supervised classification approaches is that once running, the approach is repeatable. A classification schema, training samples and classification definition file can be read into programmes such as Python and reused. If run again on the same imagery, the same result will be returned (Liu et al., 2002; Ma et al., 2017). Visual approaches are more subjective, and even though subjectivity can be reduced through use of calibration tools and multiple estimators looking at the same image, overall, it is not as likely that the same result will be returned if the approach was attempted again on the same set of imagery.

When using historical imagery, however, there are further considerations which may in fact favour a more subjective approach. Because the aerial photographs used in this study were taken decades apart with different cameras and at different scales there is considerable variation in the quality of the images. Early imagery appears to have been taken with a silver nitrate lens (different resolution) and is greyscale. Their quality in print also varies between print runs of different areas of the park. Older imagery (1948-1974) was also received as hard copy prints and had to be rephotographed for digital use. In contrast, later imagery (2005-2016/18) is supplemented by satellite images from Google Earth which are colour images downloaded directly from the provider. Object-based supervised classification advocates that the object under consideration shows a consistent range in shape and colour over space and time (Ma et al., 2017; Mohd Hasmadi et al., 2009). These differences were accounted for by setting up separate classifications with separate training samples for each year while using the same learning classifier and classification schema for all analyses. Because of this the resulting classifications are therefore difficult to compare between years as they are trained on different data. Older greyscale imagery is also not truly multispectral, and the classification can only rely on reflectance and pixel aggregations to identify objects hence the accuracy achieved is limited.

The study tried to identify macro changes in woody riverine vegetation cover, and a simplistic classification schema was used, therefore, to classify imagery into only seven categories. In reality, however, the complexity of the land cover in Gonarezhou is much higher than this. The junction where the Runde meets the Save for example supports reedbeds, grasses and hygrophilous vegetation which in the classification schema are grouped into one category, despite the physical qualities of these vegetation types being visibly distinct in the imagery. This divergence may have reduced the accuracy with which the classifier was able to classify these types of vegetation. The results of this study also reflect a possible mismatch between the complexity identified in the classification and that which is required to identify patterns of vegetation change (Liu et al., 2002; Rwanga and Ndambuki, 2017). The classified outputs clearly show macro changes in vegetation cover over time for the entire woody riverine vegetation area, tsetse clearing and cultivation. It is less accurate when trying to identify fine scale patterns of land use by elephants such as distance from perennial water and use of alternative forage. With further iterations of the classification and a finer scale segmentation of the imagery, it is possible that the classification approach could identify and respond to this level of complexity, however, the time-limited nature of and computational capacity available for this study did not allow for further iterations of the classification.

Aerial and satellite imagery includes shadows, which in my approach and for simplicity, were included in the vegetation type which casts the shadow. However, shadows vary in length based on time of day and time of year, which could not always be accounted for, given that relatively little information is available regarding the timing of historical imagery. It is possible therefore that changes in woody riverine vegetation cover may have been artificially inflated as there is a non-linear relationship between the amount of vegetation cover and the shadow cast. Shadows are larger than the objects casting them at certain time of day so that, therefore, there is a greater decrease in shadow for extent of canopy cover lost. This could explain why the decrease between 2005 and 2016/18 is so dramatic, together with other drivers of change. An improved approach to classification would separate shadows from the vegetation to ensure this effect was not experienced. Shadow has long represented a challenge to accurate classification of land cover and although some efforts to automate its identification in imagery have been proposed, they remain in their infancy (De Agirre and Malpica, 2012).

Historical imagery is rarely uniform and the nature of technological enhancements and improvements over time mean that it is difficult to make comparisons between the time steps. However, a detailed analysis of the changes in vegetation cover at different periods is important in understanding the drivers of historical change over time. Many of the limitations expressed in this section are simply a manifestation of differences in the original information source. The classification approach, although repeatable and standardised, is limited by the quality and uniformity of the data presented to it. Given these conditions it is possible that the use of a manual classification may be more helpful in understanding true change over time. Manual visual assessment is better able to compensate for changes and variability in imagery quality and is the most likely next step in the continuation of this study.

Woody cover is ultimately comprised of very large trees, medium-sized and small trees, shrubs, and copses of thicket. An assessment of vegetation cover on its own, does not distinguish the underlying structure of the vegetation which can lead to confounding results. The loss of large trees, for example, is expected to register a loss of canopy cover, but the extent of this loss can be partially masked by the remains of a dead standing tree and the shrubs which continue to occur below it. It is possible that the cover of shrubs and thickets will often provide a reasonable woody cover due to thickets such as *Capparis tomentosa*, *Capparis sepiaria*, and *Salvadora persica*, in the total absence of any tree cover (Cunliffe et al., 2012; O'Connor and Campbell, 1986b). Therefore, cover is a very conservative measure of woody vegetation because no account is made of structural diversity. Large trees can have been lost with little indication that cover is changing which may explain why some expected patterns discussed above have not emerged. However, where significant differences are observed they are likely to indicate a very important influence on vegetation due to the crude nature of this measure.

In addition, the classification approach does not distinguish between evergreen and deciduous vegetation. Unlike temperate species, many of the deciduous species are facultatively deciduous, only losing their leaves once available soil water declines to a certain level. Therefore, the nature of the preceding wet season may influence the level of cover recorded which determines the proportion of plants which are deciduous or evergreen (Masia et al., 2018; Whitecross et al., 2017). If it were possible to use only evergreen trees as an indication of cover this could improve accuracy. In satellite imagery it may be possible to identify evergreens or correct for the influence of counting deciduous trees by using many different years of imagery. However, more imagery for time periods before satellite data became available does not exist for Gonarezhou therefore correcting for the influence of deciduous trees in this imagery is challenging. It is apparent that classification would require continuous accuracy assessment against visual classification to ascertain if it could distinguish between deciduous and evergreen trees although there is some evidence that this has been achieved with Landsat imagery (Chastain and Townsend, 2007).

4.5. Management implications and recommendations

This study demonstrates that woody riverine vegetation cover in Gonarezhou is declining in part due to increasing elephant populations which degrade the woody riverine vegetation. Park management could consider ways in which to reduce the impact of elephants on vegetation in the park. However, further research is required to look more specifically at the extent of damage by elephants to understand how effective targeted management of elephant impact would be in restoring or preventing further degradation of woody riverine vegetation. Understanding elephant use patterns of the riverine woodland environment by elephants would also support decision making regarding areas where the vegetation may experience more damage (O'Connor et al., 2007).

Further investigation of possible refugia for woody riverine vegetation is required. Although this study did appear to find that woody riverine vegetation closest to the Runde River experienced a greater decrease in cover than woody riverine vegetation further away. This did not yield significant results specifically for areas furthest from water. Therefore, conclusions that distance from permanent water sources can be a refuge for woody riverine vegetation cannot be reached based on this study alone. Similarly, the presence of alternative forage for elephants did not appear to significantly alter riverine woody vegetation cover until 2018. The classification approach taken may not have been able to distinguish trends at this scale. Despite this, literature suggests that management of water and vegetation could reduce the impacts of large elephant populations (O'Connor et al., 2007; Owen-Smith et al., 2006). However, it is recommended that this analysis is repeated with visual estimation of woody riverine vegetation cover before management recommendations are made. Continuous monitoring could also help to disentangle if the emerging trend for presence of alternative forage and degradation of woody cover at the Benji confluence with the Runde in 2018 is consistent in future.

Analysis of the impacts of human drivers of vegetation change including clearing for control of tsetse fly result in long term reduction of riverine woody vegetation cover. In areas where reduction in cover is identified due to these drivers, management of elephant impact will be less effective in improving the condition of woody riverine vegetation. Possible exclusion of mesobrowsers could improve regeneration of woody riverine vegetation in these areas, zoning for management of woodland and browsers has been recommended to encourage woodland recovery in other studies (Owen-Smith et al., 2006; Ribeiro et al., 2020).

Future management of woody riverine vegetation should also account for hydrology and weather patterns (Whitecross et al., 2017). The impacts of rainfall and hazard events on woody riverine vegetation could be explored by reviewing satellite imagery from recent cyclone or rainfall events to assess damage and through gathering information from on-the-ground reports around these times. There is possible combined effect of drought and elephant impact on vegetation (De Beer et al., 2006; O'Connor et al., 2007). Nevertheless, identifying and separating impacts of weather events from elephant impact could inform management of woody riverine vegetation loss in future.

Given international pressure to protect elephant populations, further consolidation and confirmation of results is required before management recommendations regarding elephant populations can be made (Cumming et al., 1997; Dickson and Adams, 2009; Owen-Smith et al., 2006).

5. CONCLUSION

This study demonstrates the importance of considering all possible influences on vegetation change. Evidence that elephants reduce woody vegetation cover over time is presented. However, the longer-term influences of cultivation and clearing of woody vegetation for control of tsetse fly, as well as the availability of refugia for woody riverine vegetation or alternative forage for elephant, cannot be disregarded as drivers or modifiers of change in woody riverine vegetation cover.

Monitoring of woody cover alone overlooks critical indicators of recovery such as the structure, composition and diversity of woodland which are required to detect if change in woody riverine vegetation is occurring. Woodland cover is a crude measure and the complexity of the woody riverine vegetation in Gonarezhou warrants a hybrid approach, combining both cover classification with delineation of structure on the ground. On-the-ground observations would support this research in detection of structural and compositional changes indicative of human legacy and elephant impacts on woody riverine vegetation along the Runde River in Gonarezhou.

Overall, an assiduous approach is required to measure changes in woody riverine vegetation and understand their drivers to ensure impacts are not falsely attributed. This has particular relevance when considering elephant impact, the management of which is highly sensitive in the context of conservation. Protected areas have an ultimate responsibility to conserve biodiversity within park boundaries. Where conflict arises between the protection of species such as elephant at the global level and impact on local biodiversity, as is evidenced by the decline in woody riverine vegetation cover in Gonarezhou, a comprehensive understanding of the drivers of change is critical to ensure that management actions are appropriate and can stand up to critical scrutiny.

REFERENCES

Asner, G.P., Vaughn, N., Smit, I.P.J., Levick, S., 2016. Ecosystem-scale effects of megafauna in African savannas. Ecography (Cop.). 39, 240–252. https://doi.org/10.1111/ECOG.01640

Barnes, R.F.W., 1983. Effects of Elephant Browsing on Woodlands in a Tanzanian National Park: Measurements, Models and Management. J. Appl. Ecol. 20, 521. https://doi.org/10.2307/2403524

Baxter, P.W.J., Getz, W.M., 2005. A model-framed evaluation of elephant effects on tree and fire dynamics in African savannas. Ecol. Appl. 15, 1331–1341. https://doi.org/10.1890/02-5382

Beller, E., McClenachan, L., Trant, A., Sanderson, E.W., Rhemtulla, J., Guerrini, A., Grossinger, R., Higgs, E., 2017. Toward principles of historical ecology. Am. J. Bot. 104, 645–648. https://doi.org/10.3732/ajb.1700070

Beuchner, H.K., Dawkins, H.C., 1961. Vegetation Change Induced by Elephants and Fire in Murchison Falls National Park, Uganda. Ecology 42, 752–766. https://doi.org/10.2307/1933504

Boundja, R.P., Midgley, J.J., 2010. Patterns of elephant impact on woody plants in the Hluhluwe-Imfolozi park, Kwazulu-Natal, South Africa. Afr. J. Ecol. 48, 206–214. https://doi.org/10.1111/J.1365-2028.2009.01104.X

Challender, D.W.S., Brockington, D., Hinsley, A., Hoffmann, M., Kolby, J.E., Massé, F., Natusch, D.J.D., Oldfield, T.E.E., Outhwaite, W., ’t Sas-Rolfes, M., Milner-Gulland, E.J., 2022. Mischaracterizing wildlife trade and its impacts may mislead policy processes. Conserv. Lett. 15, e12832. https://doi.org/10.1111/CONL.12832

Chamaillé-Jammes, S., Fritz, H., Madzikanda, H., 2009. Piosphere contribution to landscape heterogeneity: a case study of remote-sensed woody cover in a high elephant density landscape. Ecography (Cop.). 32, 871–880. https://doi.org/10.1111/J.1600-0587.2009.05785.X

Chamaillé-Jammes, S., Valeix, M., Fritz, H., 2007. Managing heterogeneity in elephant distribution: Interactions between elephant population density and surface-water availability. J. Appl. Ecol. 44, 625–633. https://doi.org/10.1111/j.1365-2664.2007.01300.x

Chastain, R.A., Townsend, P.A., 2007. Use of Landsat ETM and Topographic Data to Characterize Evergreen Understory Communities in Appalachian Deciduous Forests. Photogramm. Eng. Remote Sensing 73, 563–575. https://doi.org/10.14358/PERS.73.5.563

Chidumayo, E.N., 2002. Changes in miombo woodland structure under different land tenure and use systems in central Zambia. J. Biogeogr. 29, 1619–1626. https://doi.org/10.1046/j.1365-

2699.2002.00794.x

Clegg, B., 2010. Habitat and diet selection by the African elephant at the landscape level: a functional integration of multi-scale foraging processes: : a functional integration of multi-scale foraging processes. University of the Witwatersrand, South Africa.

Clegg, B.W., O'Connor, T.G., 2016. Harvesting and chewing as constraints to forage consumption by the African savanna elephant (Loxodonta africana). PeerJ 2016. https://doi.org/10.7717/peerj.2469

Coetsee, C., Wigley, B.J., 2016. Browser impacts in mapungubwe national park, South Africa: Should we be worried? Koedoe 58. https://doi.org/10.4102/koedoe.v58i1.1347

Crain, C.M., Bertness, M.D., 2006. Ecosystem engineering across environmental gradients: Implications for conservation and management. Bioscience. https://doi.org/10.1641/0006-3568(2006)056[0211:EEAEGI]2.0.CO;2

Cumming, D.H.M., Fenton, M.B., Rautenbach, I.L., Taylor, R.D., Cumming, G.S., Cumming, M.S., Dunlop, J.M., Ford, A.G., Hovorka, M.D., Johnston, D.S., Kalcounis, M., Mahlangu, Z., Portfors, C.V.R., 1997. Elephants, woodlands and biodiversity in Southern Africa. S. Afr. J. Sci. 93, 231–236.

Cunliffe, R., Muller, T., Mapaura, A., 2012. Vegetation survey of Gonarezhou National Park, Zimbabwe.

De Agirre, A.M., Malpica, J.A., 2012. Detecting shadows in a segmented Land Use Land Cover image with LIDAR data. Int. Geosci. Remote Sens. Symp. 5458–5461. https://doi.org/10.1109/IGARSS.2012.6352371

De Beer, Y., Kilian, W., Versfeld, W., Van Aarde, R.J., 2006. Elephants and low rainfall alter woody vegetation in Etosha National Park, Namibia. J. Arid Environ. 64, 412–421. https://doi.org/10.1016/j.jaridenv.2005.06.015

DeFries, R., Hansen, A., Turner, B.L., Reid, R., Liu, J., 2007. Land use change around protected areas: Management to balance human needs and ecological function. Ecol. Appl. https://doi.org/10.1890/05-1111

Dickson, P., Adams, W.M., 2009. Science and uncertainty in South Africa's elephant culling debate. Environ. Plan. C Gov. Policy 27, 110–123. https://doi.org/10.1068/C0792J

Douthwaite, B., 1985. The Impact of Tsetse Fly Control Campaigns on African Wildlife. Oryx 19, 202–209. https://doi.org/10.1017/S003060530002562X

Du Toit, J.T., Biggs, H., Rogers, K.H., 2003. Large herbivores and savanna heterogeneity, in: The Kruger Experience: Ecology and Management of Savanna Heterogeneity. Island Press, p. 519.

Dudley, J.P., 2000. Seed dispersal by elephants in semiarid woodland habitats of Hwange National Park, Zimbabwe. Biotropica. https://doi.org/10.1111/j.1744-7429.2000.tb00503.x

Dunham, K.M., 2012. Trends in populations of elephant and other large herbivores in Gonarezhou National Park, Zimbabwe, as revealed by sample aerial surveys. Afr. J. Ecol. 476–488.

Dunham, K.M., 1990. Fruit Production by Acacia Albida Trees in Zambezi Riverine Woodlands. J. Trop. Ecol. 6, 445–457. https://doi.org/10.1017/S0266467400004843

Farrell, J.A.K., 1960. A report on the vegetation of the south Lundi area - Unpublished report for the Department of Tsetse and Trypanosomiasis Control and Reclamation, Southern Rhodesia.

Ferry, N., Dray, S., Fritz, H., Ipavec, A., Wigley, B.J., Charles-Dominique, T., Bourgarel, M., Sebele, L., Valeix, M., 2021. Long-term high densities of African elephants clear the understorey and promote a new stable savanna woodland community. J. Veg. Sci. 32, e13101. https://doi.org/10.1111/JVS.13101

Ford, A.T., Ali, A.H., Colla, S.R., Cooke, S.J., Lamb, C.T., Pittman, J., Shiffman, D.S., Singh, N.J., 2021. Understanding and avoiding misplaced efforts in conservation. Facets. https://doi.org/10.1139/FACETS-2020-0058

Fritz, H., Duncan, P., Gordon, I., Oecologia, A.I.-, 2002, U., 2002. Megaherbivores influence trophic guilds structure in African ungulate communities. Oecologia 131, 620–625. https://doi.org/10.1007/s00442-002-0919-3

Gandiwa, E., Tupulu, N., Zisadza-Gandiwa, P., Muvengwi, J., 2012. Structure and composition of woody vegetation around permanent artificial and ephemeral-natural water points in northern Gonarezhou National Park, Zimbabwe. Trop. Ecol. 53, 169–175.

Gaugris, J.Y., van Rooyen, M.W., 2010. Effects of water dependence on the utilization pattern of woody vegetation by elephants in the Tembe Elephant Park, Maputaland, South Africa. Afr. J. Ecol. 48, 126–134. https://doi.org/10.1111/J.1365-2028.2009.01095.X

Gillson, L., Ekblom, A., 2009. Untangling anthropogenic and climatic influence on riverine forest in the Kruger National Park, South Africa. Veg. Hist. Archaeobot. 18, 171–185. https://doi.org/https://doi.org/10.1007/s00334-008-0202-6

Gobush, K.S., Edwards, C.T.T., Balfour, D., Wittemyer, G., Maisels, F., Taylor, R.D., 2021. Loxodonta africana (amended version of 2021 assessment) [WWW Document]. IUCN Red List

Threat. Species.

Gonçalves, F.M.P., Revermann, R., Gomes, A.L., Aidar, M.P.M., Finckh, M., Juergens, N., 2017. Tree Species Diversity and Composition of Miombo Woodlands in South-Central Angola: A Chronosequence of Forest Recovery after Shifting Cultivation. Int. J. For. Res. 2017. https://doi.org/10.1155/2017/6202093

Gope, E.T., Sass-Klaassen, U.G.W., Irvine, K., Beevers, L., Hes, E.M.A., 2015. Effects of flow alteration on Apple-ring Acacia (Faidherbia albida) stands, Middle Zambezi floodplains, Zimbabwe. Ecohydrology 8, 922–934. https://doi.org/10.1002/eco.1541

Guldemond, R., Van Aarde, R., 2008. A Meta-Analysis of the Impact of African Elephants on Savanna Vegetation. J. Wildl. Manage. 72, 892–899. https://doi.org/10.2193/2007-072

Guldemond, R.A.R., Purdon, A., Van Aarde, R.J., 2017. A systematic review of elephant impact across Africa. PLoS One. https://doi.org/10.1371/journal.pone.0178935

He, W.M., Callaway, R.M., 2009. The potential for misleading correlations in single-factor analysis of complex gradients. Web Ecol. 9, 77–81. https://doi.org/10.5194/WE-9-77-2009

IPBES, 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany.

Janecke, B.B., 2020. Vegetation structure and spatial heterogeneity in the granite supersite, Kruger National Park. Koedoe 62, 1–12. https://doi.org/10.4102/koedoe.v62i2.1591

Jeltsch, F., Weber, G.E., Grimm, V., 2000. Ecological buffering mechanisms in savannas: A unifying theory of long-term tree-grass coexistence. Plant Ecol. 161, 161–171.

Jones, A., 2018. A wilderness called Nuanetsi, 1st ed. Allan Jones Dp Printmedia, Bulawayo, Zimbabwe.

Jones, C.G., Gutiérrez, J.L., Byers, J.E., Crooks, J.A., Lambrinos, J.G., Talley, T.S., 2010. A framework for understanding physical ecosystem engineering by organisms. Oikos 119, 1862–1869. https://doi.org/10.1111/j.1600-0706.2010.18782.x

Jones, C.G., Lawron, J.H., Shachak, M., 1997. Positive and negative effects of organisms as physical ecosystem engineers. Ecology. https://doi.org/10.1890/0012-9658(1997)078[1946:PANEOO]2.0.CO;2

Kabii, T., 1996. An overview of African wetlands, Ramsar Report.

Kelly, R.D., Walker, B.H., 1976. The Effects of Different Forms of Land Use on the Ecology of a

Semi-Arid Region in South-Eastern Rhodesia. J. Ecol. 64, 553. https://doi.org/10.2307/2258773

Kupika, O.L., Gandiwa, E., Ayuk, J., Bandeira, S., Kunedzimwe, F., 2021. Evidence of the Impact of Cyclones and Floods on Biodiversity and Wildlife Resources in Southern Africa 265–278. https://doi.org/10.1007/978-3-030-74303-1_17

Landman, M., 2007. Chapter 3 Effects of elephants on ecosystems and biodiversity, in: Assessment of South African Elephant Management.

Laws, R.M., 1970. Elephants as Agents of Habitat and Landscape Change in East Africa. Oikos 21, 1. https://doi.org/10.2307/3543832

Le Saout, S., Hoffmann, M., Shi, Y., Hughes, A., Bernard, C., Brooks, T.M., Bertzky, B., Butchart, S.H.M., Stuart, S.N., Badman, T., Rodrigues, A.S.L., 2013. Protected areas and effective biodiversity conservation. Science (80-.). https://doi.org/10.1126/science.1239268

Leuthold, W., Laws, R.M., Parker, I.S.C., Johnstone, R.C.B., 1977. Elephants and Their Habitats: The Ecology of Elephants in North Bunyoro, Uganda. J. Wildl. Manage. 41, 804. https://doi.org/10.2307/3800017

Lira, P.K., de Souza Leite, M., Metzger, J.P., 2019. Temporal Lag in Ecological Responses to Landscape Change: Where Are We Now? Curr. Landsc. Ecol. Reports 4, 70–82. https://doi.org/10.1007/S40823-019-00040-W

Liu, X.H., Skidmore, A.K., Van Oosten, H., 2002. Integration of classification methods for improvement of land-cover map accuracy. ISPRS J. Photogramm. Remote Sens. 56, 257–268. https://doi.org/10.1016/S0924-2716(02)00061-8

Ma, L., Li, M., Ma, X., Cheng, L., Du, P., Liu, Y., 2017. A review of supervised object-based land-cover image classification. ISPRS J. Photogramm. Remote Sens. https://doi.org/10.1016/j.isprsjprs.2017.06.001

Macfadyen, S., Hui, C., Verburg, P.H., Van Teeffelen, A.J.A., 2019. Spatiotemporal distribution dynamics of elephants in response to density, rainfall, rivers and fire in Kruger National Park, South Africa. Divers. Distrib. https://doi.org/10.1111/ddi.12907

Maciejewski, K., De Vos, A., Cumming, G.S., Moore, C., Biggs, D., 2015. Cross-scale feedbacks and scale mismatches as influences on cultural services and the resilience of protected areas. Ecol. Appl. 25, 11–23. https://doi.org/10.1890/13-2240.1

Masia, N.D., Stevens, N., Archibald, S., 2018. Identifying phenological functional types in savanna trees. African J. Range Forage Sci. 35, 81–88. https://doi.org/10.2989/10220119.2018.1442367

Mavhunga, C., 2002. ‘If they are as thirsty as all that, let them come down to the pool’: unearthing ‘Wildlife’ history and reconstructing ‘Heritage’ in Gonarezhou National Park, from the late nineteenth century to the 1930s. Historia Santiago. 47, 531–558.

Mavhunga, C.C., 2008. The Moblie Workshop: mobility, technology and human-animal interaction in Gonarezhou National Park 1850-present.

Mavhura, E., 2020. Learning from the tropical cyclones that ravaged Zimbabwe: policy implications for effective disaster preparedness. Nat. Hazards 104, 2261–2275. https://doi.org/10.1007/s11069-020-04271-7

McCartney, M., Butterworth, J., Moriarty, P., Owen, R., 1998. Comparison of the hydrology of two contrasting headwater catchments in Zimbabwe, in: Hydrology, Water Resources and Ecology in Headwaters. pp. 515–522.

McNicol, I.M., Ryan, C.M., Williams, M., 2015. How resilient are African woodlands to disturbance from shifting cultivation? Ecol. Appl. 25, 2330–2336. https://doi.org/10.1890/14-2165.1

Moe, S.R., Rutina, L.P., Hytteborn, H., Du Toit, J.T., 2009. What controls woodland regeneration after elephants have killed the big trees? J. Appl. Ecol. 46, 223–230. https://doi.org/10.1111/j.1365-2664.2008.01595.x

Mohd Hasmadi, I., Pakhriazad, H.Z., Shahrin, M.F., 2009. Evaluating supervised and unsupervised techniques for land cover mapping using remote sensing data. Malaysian J. Soc. Sp. 5, 1–10.

Mombeshora, S., le Bel, S., 2009. Parks-people conflicts: The case of Gonarezhou National Park and the Chitsa community in south-east zimbabwe. Biodivers. Conserv. 18, 2601–2623. https://doi.org/10.1007/s10531-009-9676-5

Mwampamba, T.H., Schwartz, M.W., 2011. The effects of cultivation history on forest recovery in fallows in the Eastern Arc Mountain, Tanzania. For. Ecol. Manage. 261, 1042–1052. https://doi.org/10.1016/J.FORECO.2010.12.026

O’Connor, T.G., 2010. Transformation of riparian forest to woodland in Mapungubwe National Park, South Africa, between 1990 and 2007. Austral Ecol. 35, 778–786. https://doi.org/10.1111/j.1442-9993.2009.02084.x

O’Connor, T.G., Campbell, B.M., 1986a. Hippopotamus habitat relationships on the Lundi River, Gonarezhou National Park, Zimbabwe. Afr. J. Ecol. 24, 7–26.

O’Connor, T.G., Campbell, B.M., 1986b. Classification and condition of the vegetation types of the Nyahungwe area on the Lundi River, Gonarezhou National Park, Zimbabwe. South African J.

Bot. 52, 117–123. https://doi.org/10.1016/S0254-6299(16)31575-7

O'Connor, T.G., Goodman, P.S., Clegg, B., 2007. A functional hypothesis of the threat of local extirpation of woody plant species by elephant in Africa. Biol. Conserv. 136, 329–345. https://doi.org/10.1016/j.biocon.2006.12.014

O'Kane, C.A.J., Duffy, K.J., Page, B.R., MacDonald, D.W., 2012. Heavy impact on seedlings by the impala suggests a central role in woodland dynamics. J. Trop. Ecol. 28, 291–297. https://doi.org/10.1017/S026646741200017X

Owen-Smith, N., Kerley, G.I.H., Page, B., Slotow, R., Van Aarde, R.J., 2006. A scientific perspective on the management of elephants in the Kruger National Park and elsewhere. S. Afr. J. Sci.

Pilossof, R., 2016. A brief history of tsetse control methods in Zimbabwe and possible effects of climate change on their distribution. Int. J. African Dev. v.4 4, 14.

Pressey, R.L., Cabeza, M., Watts, M.E., Cowling, R.M., Wilson, K.A., 2007. Conservation planning in a changing world. Trends Ecol. Evol. 22, 583–592. https://doi.org/10.1016/j.tree.2007.10.001

Pressey, R.L., Visconti, P., McKinnon, M.C., Gurney, G.G., Barnes, M.D., Glew, L., Maron, M., 2021. The mismeasure of conservation. Trends Ecol. Evol. 36, 808–821. https://doi.org/10.1016/J.TREE.2021.06.008

Prins, H.H.T., van der Jeugd, H.P., 1993. Herbivore Population Crashes and Woodland Structure in East Africa. J. Ecol. 81, 305. https://doi.org/10.2307/2261500

Reason, C.J.C., Keibel, A., 2004. Tropical Cyclone Eline and its unusual penetration and impacts over the Southern Africa mainland. Weather Forecast. 19, 789–805. https://doi.org/10.1175/1520-0434(2004)019<0789:TCEAIU>2.0.CO;2

Ribeiro, N.S., Grundy, I.M., Gonçalves, F.M.P., Moura, I., Santos, M.J., Kamoto, J., Ribeiro-Barros, A.I., Gandiwa, E., 2020. People in the Miombo Woodlands: Socio-Ecological Dynamics, in: Miombo Woodlands in a Changing Environment: Securing the Resilience and Sustainability of People and Woodlands. Springer, Cham, pp. 55–100. https://doi.org/10.1007/978-3-030-50104-4_3

Ribeiro, N.S., Syampungani, S., Matakala, N.M., Nangoma, D., Ribeiro-Barros, A.I., 2015. Miombo Woodlands Research Towards the Sustainable Use of Ecosystem Services in Southern Africa, in: Biodiversity in Ecosystems - Linking Structure and Function. IntechOpen. https://doi.org/10.5772/59288

Robson, A.S., Trimble, M.J., Purdon, A., Young-Overton, K.D., Pimm, S.L., Van Aarde, R.J., 2017.

Savanna elephant numbers are only a quarter of their expected values. PLoS One 12. https://doi.org/10.1371/JOURNAL.PONE.0175942

Romero-Calcerrada, R., Chanza, N., Musakwa, W., 2022. Ecological and Hydrological Indicators of Climate Change Observed by Dryland Communities of Malipati in Chiredzi, Zimbabwe. Diversity 14, 541. https://doi.org/10.3390/D14070541

Rwanga, S.S., Ndambuki, J.M., 2017. Accuracy Assessment of Land Use/Land Cover Classification Using Remote Sensing and GIS. Int. J. Geosci. 08, 611–622. https://doi.org/10.4236/ijg.2017.84033

Salafsky, N., Boshoven, J., Burivalova, Z., Dubois, N.S., Gomez, A., Johnson, A., Lee, A., Margoluis, R., Morrison, J., Muir, M., Pratt, S.C., Pullin, A.S., Salzer, D., Stewart, A., Sutherland, W.J., Wordley, C.F.R., 2019. Defining and using evidence in conservation practice. Conserv. Sci. Pract. 1, e27. https://doi.org/10.1111/csp2.27

Sherry, B.Y., 1970. Vegetation map of Gonarezhou National Park.

Skarpe, C., Aarrestad, P.A., Andreassen, H.P., Dhillion, S.S., Dimakatso, T., Du Toit, J.T., Halley, D.J., Hytteborn, H., Makhabu, S., Mari, M., Marokane, W., Masunga, G., Modise, D., Moe, S.R., Mojaphoko, R., Mosugelo, D., Motsumi, S., Neo-Mahupeleng, G., Ramotadima, M., Rutina, L., Sechele, L., Sejoe, T.B., Stokke, S., Swenson, J.E., Taolo, C., Vandewalle, M., Wegge, P., 2004. The return of the giants: Ecological effects of an increasing elephant population. Ambio 33, 276–282. https://doi.org/10.1579/0044-7447-33.6.276

Skarpe, C., Hester, A.J., 2008. Plant Traits, Browsing and Gazing Herbivores, and Vegetation Dynamics, in: The Ecology of Browsing and Grazing. Springer, Berlin, Heidelberg, pp. 217–261. https://doi.org/10.1007/978-3-540-72422-3_9

Sparrow R., 2018. Lowveld Legend. 1st ed. Ray Sparrow of Lone Star Ranche, Everbest Printing Investment Ltd.Hong Kong.

Stoll-Kleemann, S., Job, H., 2008. The relevance of effective protected areas for biodiversity conservation: An introduction. Gaia 17, 86–89. https://doi.org/10.14512/gaia.17.s1.3

Sutherland, W.J., Pullin, A.S., Dolman, P.M., Knight, T.M., 2004. The need for evidence-based conservation. Trends Ecol. Evol. 19, 305–308. https://doi.org/10.1016/j.tree.2004.03.018

Swetnam, T.W., Allen, C.D., Betancourt, J.L., 1999. Applied historical ecology: Using the past to manage for the future. Ecol. Appl. 9, 1189–1206. https://doi.org/10.1890/1051-0761(1999)009[1189:AHEUTP]2.0.CO;2

Tafangenyasha, C., 1997. Tree loss in the Gonarezhou National Park (Zimbabwe) between 1970 and 1983. J. Environ. Manage. 49, 355–366. https://doi.org/10.1006/jema.1996.9987

Tavuyanago, B., 2017. "Our fathers and grandfathers were born here…" Shangaan eviction experiences from the Gonarezhou National Park, 1957-1968. Hist. (Hist. Assoc. S. Afr). 62, 46–67. https://doi.org/10.17159/2309-8392/2017/v62n2a3

Tavuyanago, B., Makwara, E., 2011. Contested Landscape: the struggle for the control of Gonarezhou since the inception of colonial rule in Zimbabwe. J. Sustain. Dev. Africa 13, 87–107.

Turner, J., 2021. The dynamics of the Vachellia xanthophloea and Faidherbia albida woodlands in the floodplains of the Makuleke contractual park. MSc thesis,. University of the Witwatersrand, Johannesburg.

Vanak, A.T., Thaker, M., Slotow, R., 2010. Do fences create an edge-effect on the movement patterns of a highly mobile mega-herbivore? Biol. Conserv. 143, 2631–2637. https://doi.org/10.1016/j.biocon.2010.07.005

Viljoen, J.J., Reynecke, H.C., Panagos, M.D., Langbauer, W.R., Ganswindt, A., 2013. Seasonal selection preferences for woody plants by breeding herds of African elephants (Loxodonta africana) in a woodland savanna. Int. J. Ecol. https://doi.org/10.1155/2013/769587

Western, D., Lindsay, W.K., 1984. Seasonal herd dynamics of a savanna elephant population. Afr. J. Ecol. 22, 229–244. https://doi.org/10.1111/j.1365-2028.1984.tb00699.x

Whitecross, M.A., Witkowski, E.T.F., Archibald, S., 2017. Assessing the frequency and drivers of early-greening in broad-leaved woodlands along a latitudinal gradient in southern Africa. Austral Ecol. 42, 341–353. https://doi.org/10.1111/aec.12448

Wilkie, D.S., Morelli, G.A., Demmer, J., Starkey, M., Telfer, P., Steil, M., 2006. Parks and people: Assessing the human welfare effects of establishing protected areas for biodiversity conservation. Conserv. Biol. https://doi.org/10.1111/j.1523-1739.2005.00291.x

Wilson, L.J., Hoffman, M.T., Ferguson, A.J., Cumming, D.H.M., 2021. Elephant browsing impacts in a Zambezian Baikiaea woodland with a high density of pumped waterholes. Glob. Ecol. Conserv. 31, e01854. https://doi.org/10.1016/J.GECCO.2021.E01854

Zisadza-Gandiwa, P., Mango, L., Gandiwa, E., Goza, D., Parakasingwa, C., Chinoitezvi, E., Shimbani, J., Muvengwi, J., 2013. Variation in woody vegetation structure and composition in a semi-arid savanna of Southern Zimbabwe. Int. J. Biodivers. Conserv. 5, 71–77. https://doi.org/10.5897/IJBC12.095

Annex 1 – Rainfall record for Gonarezhou National Park

Rainfall quantity by year for Gonarezhou National Park is described below. Rainfall records were acquired from Gonarezhou park management for the Chipinda pools data. Chipinda pools is a campsite in Gonarezhou which is located on the banks of the Runde River. Malilangwe Conservation Trust is adjacent to Gonarezhou, and their records are used for years when Gonarezhou records were unavailable. No rainfall records are available for prior to 1952.

Table A1 - Rainfall quantity by year for Gonarezhou National Park. Blues indicate high rainfall years while red indicates low rainfall years.

Year	Total annual rainfall (January - December)	Source
1952	731.2	Malilangwe Conservation Trust HQ
1953	453.5	Malilangwe Conservation Trust HQ
1954	641	Malilangwe Conservation Trust HQ
1955	761.8	Malilangwe Conservation Trust HQ
1956	616.5	Malilangwe Conservation Trust HQ
1957	409.7	Malilangwe Conservation Trust HQ
1958	706.2	Malilangwe Conservation Trust HQ
1959	928.9	Malilangwe Conservation Trust HQ
1960	465.5	Malilangwe Conservation Trust HQ
1961	469.2	Malilangwe Conservation Trust HQ
1962	657.1	Malilangwe Conservation Trust HQ
1963	552.3	Malilangwe Conservation Trust HQ
1964	436	Malilangwe Conservation Trust HQ
1965	206.7	Malilangwe Conservation Trust HQ
1966	523.9	Malilangwe Conservation Trust HQ
1967	447.2	Malilangwe Conservation Trust HQ
1968	452.4	Malilangwe Conservation Trust HQ
1969	598.7	Malilangwe Conservation Trust HQ
1970	350.4	Malilangwe Conservation Trust HQ
1971	428.5	Malilangwe Conservation Trust HQ
1972	108	Chipinda Pools, Gonarezhou
1973	359.3	Chipinda Pools, Gonarezhou
1974	619.3	Chipinda Pools, Gonarezhou
1975	666.1	Chipinda Pools, Gonarezhou
1976	738.2	Chipinda Pools, Gonarezhou
1977	877.4	Chipinda Pools, Gonarezhou
1978	788.7	Chipinda Pools, Gonarezhou
1979	498.7	Chipinda Pools, Gonarezhou
1980	342.5	Chipinda Pools, Gonarezhou
1981	588.2	Chipinda Pools, Gonarezhou
1982	378.4	Chipinda Pools, Gonarezhou
1983	378.5	Chipinda Pools, Gonarezhou
1984	457.2	Chipinda Pools, Gonarezhou

1985	552.5	Chipinda Pools, Gonarezhou
1986	551.6	Chipinda Pools, Gonarezhou
1987	284.2	Chipinda Pools, Gonarezhou
1988	422	Malilangwe Conservation Trust HQ
1989	460.5	Malilangwe Conservation Trust HQ
1990	326.7	Malilangwe Conservation Trust HQ
1991	375.2	Chipinda Pools, Gonarezhou
1992	309.4	Chipinda Pools, Gonarezhou
1993	468.2	Chipinda Pools, Gonarezhou
1994	174.9	Chipinda Pools, Gonarezhou
1995	481.2	Chipinda Pools, Gonarezhou
1996	623.5	Chipinda Pools, Gonarezhou
1997	513.5	Chipinda Pools, Gonarezhou
1998	426.3	Chipinda Pools, Gonarezhou
1999	562.7	Chipinda Pools, Gonarezhou
2000	1114.6	Chipinda Pools, Gonarezhou
2001	619.9	Chipinda Pools, Gonarezhou
2002	196.3	Chipinda Pools, Gonarezhou
2003	782.7	Chipinda Pools, Gonarezhou
2004	509.3	Chipinda Pools, Gonarezhou
2005	266.8	Chipinda Pools, Gonarezhou
2006	513.6	Chipinda Pools, Gonarezhou
2007	932.9	Chipinda Pools, Gonarezhou
2008	205.9	Chipinda Pools, Gonarezhou
2009	194.5	Chipinda Pools, Gonarezhou
2010	248.5	Chipinda Pools, Gonarezhou
2011	526.2	Chipinda Pools, Gonarezhou
2012	371	Chipinda Pools, Gonarezhou
2013	460	Chipinda Pools, Gonarezhou
2014	674.5	Chipinda Pools, Gonarezhou
2015	448	Chipinda Pools, Gonarezhou
2016	513	Chipinda Pools, Gonarezhou
2017	529	Chipinda Pools, Gonarezhou
2018	203	Chipinda Pools, Gonarezhou
2019	215.4	Chipinda Pools, Gonarezhou

Appendix A – Class definition file 1948

Description

The accompanying class definition file includes the attribute statistics required for the Supervised object-based classification (Support Vector Machine Classifier) in ArcGISPro carried out on the 1948 imagery.

File Location:

https://doi.org/10.25375/uct.21930747.v1

File name:
Appendix_A_ClassDefinitions_1948.ecd

Appendix B – Class definition file 1955

Description

The accompanying class definition file includes the attribute statistics required for the Supervised object-based classification (Support Vector Machine Classifier) in ArcGISPro carried out on the 1955 imagery.

File Location:
https://doi.org/10.25375/uct.21930747.v1

File name:
Appendix_B_ClassDefinitions_1955.ecd

Appendix C – Class definition file 1968

Description
The accompanying class definition file includes the attribute statistics required for the Supervised object-based classification (Support Vector Machine Classifier) in ArcGISPro carried out on the 1968 imagery.

File Location:
https://doi.org/10.25375/uct.21930747.v1

File name:
Appendix_C_ClassDefinitions_1968.ecd

Appendix D – Class definition file 1974

Description
The accompanying class definition file includes the attribute statistics required for the Supervised object-based classification (Support Vector Machine Classifier) in ArcGISPro carried out on the 1974 imagery.

File Location:
https://doi.org/10.25375/uct.21930747.v1

File name:
Appendix_D_ClassDefinitions_1974.ecd

Appendix E – Class definition file 2005

Description

The accompanying class definition file includes the attribute statistics required for the Supervised object-based classification (Support Vector Machine Classifier) in ArcGISPro carried out on the 2005 imagery.

File Location:

https://doi.org/10.25375/uct.21930747.v1

File name:
Appendix_E_ClassDefinitions_2005.ecd

Appendix F – Class definition file 2016/18

Description

The accompanying class definition file includes the attribute statistics required for the Supervised object-based classification (Support Vector Machine Classifier) in ArcGISPro carried out on the 2016/18 imagery.

File Location:

https://doi.org/10.25375/uct.21930747.v1

File name:

Appendix_F_ClassDefinitions_2016_18.ecd