EFFECTS OF HUMAN DISTURBANCE ON THE DISTRIBUTION OF NATIVE AND EXOTIC SPECIES: A STUDY BASED ON EVIDENCE FROM THREE SITES IN ZIMBABWE

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Abstract

The understanding of factors driving plant invasions in African Savannas which is pivotal for their management is currently poor. Therefore, this study tested several hypotheses that link human disturbance to species invasions. Firstly, human disturbance facilitates the invasion of introduced plant species into savanna ecosystem. Secondly, species in human disturbed environments, should exhibit traits that are associated with quick regeneration giving advantage to invasive species. The third hypothesis tested was that, human factors when used in conjunction with natural factors should produce habitat prediction models with high accuracy for invasive species. The data for testing the first two hypotheses were collected from 227 sampling plots in three sites in Zimbabwe; Kyle Game reserve and the adjacent Mutirikwi communal lands, Tuli and Mazunga safari areas and Bubiana conservancy and the surrounding Shake and Gwanda communal lands. Vegetation data, including species richness, abundance and frequency of occurrence of introduced plant species were collected. We tested whether plant species richness differed significantly between the human dominated landscape and the adjacent protected areas. In addition, the Z-test was run to determine whether the proportion of introduced exotic plant species was significantly higher in the human-disturbed landscape. The X^2 test was performed to check whether introduced exotic species were significantly associated with human disturbance. To test the third hypothesis, predicting the preferred location on invasive *Xanthium strumarium*, 105 Presence and absence plots were selected from Gonarezhou National Park and the adjacent Malipati communal lands. Ten modeling techniques were employed within the BIOMOD2 environment; thereafter building an ensemble model. For the first two hypotheses, our results indicate that the proportion of introduced exotic plant species was significantly higher in the communal land compared to the adjacent protected site ($Z \geq 2.89$, $P < 0.05$). Introduced exotic plant species were dominated by the ruderal strategy (annual lifespan and forb growth form). They were also significantly associated with human disturbance at two of the three sites assessed ($X^2 \geq 3.4$, $P < 0.05$). Results also indicate that combining human and natural factors as predictors provided good models for predicting the suitable habitat of *X. strumarium* Machine learning based techniques performed well (ROC 0.8) at predicting the occurrence of *X. Strumarium*, although the ensemble prediction outperformed all the individual models (ROC 0.9). *X. strumarium* was predicted to occur in areas that receive direct radiation from the sun, thus, aspect was identified as a critical factor in habitat selection for *X. strumarium.* Conclusions drawn from this multi-site study suggest that human disturbance may favor the success of introduced species.

Dedication

For Atheneum my love and Taylor our son.

Declaration 1: Originality

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

Chikuruwo Charon

Declaration Statement: Publication in Preparation

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

Publication 1: Chikuruwo Charon[1], Mhosisi Masocha[2], Murwira Amom[3], and Ndaimani Henry[4]. (Published in Applied Ecology and Environmental Research). *Predicting the suitable habitat of the invasive Xanthium strumarium L. in south-eastern Zimbabwe.*

This work was done by the first author, under the guidance and supervision of the second, third and fourth author.

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Publication submitted for review 2: Chikuruwo Charon[1], Mhosisi Masocha[2] and Murwira Amon[3]. (Submitted to JASSA). *Assessing the role of disturbance in the invasion of African savannas by introduced alien plant species: evidence from multiple sites.*

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List of Acronyms

GIS	Geographic Information systems
NDVI	Normalized Difference Vegetation Index
SRTM	Shuttle Radar Topography Mission
DEM	Demographic elevation model
GLM	General linear model
GAM	Generalized additive model
MARS	Multivariate additive regression splines
ANN	Artificial neural networks
RF	Random forests
MaxEnt	Maximum entropy
CTA	Classification tree analysis
SRE	Surface range envelope
EM	Ensemble model
TSS	True kill statistic
ROC	Relative operating characteristic
KAPPA	Cohen's Kappa
FAR	False alarm ratio
SR	Success ratio
POD	Probability of detection
CSI	Critical success index
ETS	Equitable threat score

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Chapter 1: General introduction

1.1 Background

1.1.1 An overview of invasive species; success of invasive species

Invasive species are non-native organisms that become self-perpetuating in locations outside of their natural geographical range. (Naiman and Decamps 1997, Richardson et al. 2000). These species have the potential to cause environmental, social or economic detriment to the environment and its surroundings. Not all species that cross geographic boundaries become well established and not all of the ones that establish become invasive. It has been suggested that the species that become invasive may possess features (traits) related to their functioning that enable them to become dominant (Grotkopp and Rejmánek 2007, Gassó et al. 2009, Godoy et al. 2010). These plant functional traits include a shorter lifespan, a lower seed mass and disturbance avoidance traits such as poisonous chemicals or rosette growth habits. Thus identifying the traits of species that make them invasive is important for their management.

Two commonly adopted hypotheses explaining plant invasion are biotic resistance hypothesis and the fluctuating resources hypothesis (Kuebbing et al. 2013). According to the biotic resistance hypothesis, diverse communities are more resistant to invasive species as more space is occupied, more biomass is produced and more resources are used. Within a diverse community, it is implied that resource supply is matched by resource uptake, thus there are no vacant niches hence ecosystem resistance. The fluctuating resources hypothesis stresses that a sudden increase in resources leaves a community vulnerable to plant invasions. The common factor between these hypotheses is that they predict that disturbance may increase the vulnerability of communities to invasion. Hence, human disturbance has been correlated to species invasions.

Human disturbance has been cited as a driving factor for invasive species in various studies (Huston 2004, Chown et al. 2005, Hansen and Clevenger 2005, Kalwij et al. 2008, Diego 2009, Jauni and Hyvanen 2011, Burkitt and Wootton 2012). The transportation of organisms by humans through global trade and globalization has led to the breaking of natural bio-geographic barriers for plants (Clout and Williams 2009). Humans clear land for agriculture, fuel or for shelter which according to the biotic resistance hypothesis and the fluctuating resources hypothesis creates both geographical and ecological niches in an otherwise intact plant community. Removal of biomass also reduces competition between resident and introduced species (Davis et al. 2000), thus, improving the chances of success for introduced species. It has also been suggested that selective grazing of palatable resident species leads to invasion by unpalatable invasive species (Kurokawa et al. 2011). To this end, human disturbed environments are known to be more susceptible to species invasions.

1.1.2 Why study biological invasions

Accurate assessments of location abundance as well as drivers of invasive species are important for managing them (Clout and Williams 2009). Modeling the potential habitats of invasive species using species distribution models is a good method to obtain accurate locations of invasive species. Species distribution models (SDMs) are models that relates species distribution data (occurrence or abundance at known locations) with information on the environmental and/or spatial characteristics of those location (Elith and Leathwick 2009). SDMs provide insight not only into the mechanisms but also potential hotspots for invasion. They explore the species-environment relationship further and thus provide useful information for protecting environments against invasive species. If species distribution models are to be used for early detection and management of invasive species their accuracy and correct interpretation is crucial to minimize the ecological impact and economic cost of biological invasions (Václavík and Meentemeyer 2009). Thus, employing SDMs to predict potential hotspots for invasion may improve the quality of information available that can be used to combat invasive species.

Although studies date back to the 1950's, most studies, have however been geographically biased (Pysek et al. 2008) towards regions in Britain, the Americas and South Africa. Compared with other biomes, there are relatively fewer studies that tackle the subject of invasive species in African savannas (Pysek et al. 2008). Overall, our understanding of the patterns and mechanisms of invasion operating savannas is limited. The few studies that have been conducted in African savannas, (Masocha and Skidmore 2011, Beauséjour et al. 2015, Perkins et al. 2015) have suggested the availability of propagule, herbivore density and the origin of potential invasive species as potential factors explaining invasion. However, more still needs to be explored on the nature of plant invasions in African savannas.

1.1.3 Current known management options

Managing invasive species is a priority for all plant communities, whether they are protected or not. In protected areas, invasive species cause loss of biological diversity and even extinction of native flora and fauna(Foxcroft et al. 2011b). In agricultural ecosystems, invasive species may lead to economic losses amounting to billions (Tracy and Sanderson 2004). In this regard several methods have been proposed for managing invasive species. These fall into three main classes; eradication, control and prevention. Eradication methods aim to eliminate the entire population of the invader(Downey 2012). Elimination includes all life stages of the invasive species, from the seed bank to the adult plant to ensure that no more propagation occurs. Control methods aim to reduce or suppress the density and abundance of invasive species to a pre-set threshold (Clout and Williams 2009). The third class of managing invasive species is prevention. Prevention involves procedures that inhibit the establishment of invasive species in areas that they did not previously inhabit.

Within these classes there are several techniques that could be adopted to control invasive species. These techniques are biological, physical or chemical. Biological methods of control include releasing natural enemies of the invasive species, introducing a natural competitor or introducing a natural predator (Gordon and Fourie , Cilliers and Neser 1991, Baider and Florens 2011). These mainly help with reducing and suppressing the spread of an invasive species. Physical methods include hand pulling, fire, mowing and mulching and solarization. Again these techniques mainly fall under the control of invasive species class. The last technique is the chemical control methods whereby chemicals are used to kill the invader. This technique can be used both in regulation and in elimination of invasive species. Information on the nature and extent of spread of an invasive species is vital for managers to employ the appropriate measures for managing the invader. Hence this study was conducted with the aim of informing management in the south-eastern lowvield of Zimbabwe.

1.2 Thesis objectives

Plant invasion is the introduction and spread of a plant species outside of its native range, causing disruption in its new environment(Chisholm 2012). Thus, the main objective of this thesis is to seek understanding on the role played by human disturbance in the invasion of African savannas. It is dependent upon the invasibility of the ecosystem as well as the nature of the invader (Lavorel et al. 1999, Alpert et al. 2000, Dukes 2001, Tilman 2004, 2009), the first specific objective is to determine whether human disturbance enhanced invasibility. The second specific objective is to determine whether exotic species possess traits that enable them to thrive in disturbed environments. The last objective is to predict the suitable habitat of an exotic invasive species as a function of human and natural factors.

1.3 Organization of the thesis

This thesis consists of five chapters contributing to the understanding whether and in what way human disturbance affects plant species invasions in African savannas

Chapter 1: Gives a background of the role played by African savannas in supporting human and mammalian livelihoods. This chapter provides an explanation of how plant invasions may hinder African savannas from providing these essential services. This background leads to why information on the mechanisms behind plant invasions is important for managing biodiversity in African savannas and explains the gap in knowledge. This chapter concludes with a definition of the thesis objectives.

Chapter 2: Investigates the role played by anthropogenic disturbance in facilitating invasive species. In this chapter, we test whether human disturbance enhances the invasibility of ecosystems using three methods of scientific enquiry. The first method was to test whether anthropogenic disturbance creates niches for introduced species by reducing native species richness. Then, we tested whether exotic species were significantly associated with human disturbed environments. Lastly, we tested whether the proportion of exotic species was significantly higher in human disturbed communities.

This chapter also investigates whether exotic species possess traits that enable them to adjust to human disturbance. We tested for differences in the life traits of native and exotic species to determine whether they were significantly different, thus determining whether exotic species have a ruderal strategy. The results for these two objectives are presented and discussed. Conclusions were also drawn from the results and discussions.

Chapter 3: Presents work on the third objective, spatial prediction of the suitable habitat of *Xanthium strumarium*. In this chapter, we present the importance of including human variables in predicting suitable habitats for invasive species. The advantage of using multiple algorithms in suitable habitat prediction studies was also presented. Using ten modeling algorithms and four predictor variables the suitable habitat of invasive *Xanthium strumarium* was predicted using BIOMOD2. The predictions as well as factors associated with the occurrence of the species were discussed, also conclusions were drawn.

Chapter 4: Provides a synthesis of the findings from the first and the second objectives in the perspective of the main objective of the study. Herein we discuss the contribution of this study to invasive species science with regards to the effect of human disturbance and also what other factors may be important. Finally, as a way of concluding we discuss how future studies may improve upon the work presented in this thesis.

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Chapter 2: Assessing the effect of human disturbance on exotic species invasion in southern African savannas; evidence from three sites.

This chapter is based on Chikuruwo Charon[1], Mhosisi Masocha[2] and Murwira Amon[3]. *Assessing the role of disturbance in the invasion of African savannas by introduced exotic plant species: Evidence from multiple sites.* Submitted to **Journal of Applied Science in Southern Africa.**

Abstract

Introduced invasive exotic species undermine the ability of ecosystems to deliver goods and services to society. Current understanding of the factors driving the invasion of African savannas by introduced plant species is poor yet these ecosystems support the livelihoods of millions of people. This study tested the hypothesis that anthropogenic disturbance aids the invasion of introduced plant species into African savanna ecosystems. Vegetation data were obtained from a total of 204 plots in Kyle Game Reserve and the adjacent Mutirikwi communal land, Tuli Safari Area and the adjacent Machucha and Maramani communal land as well as Gonarezhou National Park (GNP) and Malipati communal land. The Mann-Whitney U-test was used to assess whether plant species richness differed significantly between the communal land and the adjacent protected area. The Z-test was also performed to determine whether the proportion of introduced exotic plant species in the human-disturbed landscape was significantly higher compared to legally protected landscapes adjacent to it. The association between exotic plant and human disturbed landscapes was tested using the X^2 test. Results show that at all the three study sites, the proportion of introduced exotic plant species was significantly higher in the communal land compared to the adjacent protected site ($Z \geq 2.89$, $P < 0.05$). Introduced exotic plant species dominated by the ruderal strategy, were significantly associated with human disturbance at two of the three sites assessed ($X^2 \geq 3.4$, $P < 0.05$). The results from this multi-site study provide empirical support to the hypothesis that human disturbance facilitates invasion African savannas by introduced exotic plant species. This implies that managing human disturbance may be the key to controlling the spread of introduced exotic species in savanna ecosystems.

Keywords: exotic, plant invasion, protected area, anthropogenic.

2.1 Introduction

The invasion of ecosystems by species originating from other regions is associated with loss of biological diversity and diminished service provision (Grice 2006, Olden et al. 2008, Hejda et al. 2009). Invasive species may also affect the distribution of resources among plants which in turn may affect food chains and the larger ecological community (D'Antonio et al. 1999). In Africa, the effect of invasive species may be more pronounced since almost half of the human population in the continent depend directly on forests and forest products for their livelihoods (Sharkey and Raschke 1981). The capacity of African governments to tackle the problem of invasive species is limited due to lack of resources including information of the factors influencing invasion. Therefore, understanding the ecological factors promoting or hindering plant invasions is a research priority, which is critical to the development of successful strategies for controlling invasive species and maintaining ecosystem functioning (Masocha 2009).

A number of human mediated disturbance factors including land use, habitat fragmentation and land mismanagement are associated with invasive species spread (Forrestel et al. 2015). Among these factors, human disturbance has received the most attention from researchers (Zhang et al. 2006, Addo-Fordjour et al. 2009b). For example, in temperate systems in the Americas, comparisons between the proportion of introduced exotic species in human-disturbed and protected habitats generally found that the former contained a higher proportion of established exotic species compared to the latter (Stohlgren et al. 2011). Human disturbance, defined here as the removal of biomass through processes such as human-lit fires, cultivation or livestock grazing, may enhance invasions by reducing resource use by native species thus creating niche opportunities for exotic species to establish (Godefroid et al. 2005, Zhang et al. 2006, Addo-Fordjour et al. 2009b, Polce et al. 2012). In addition, disturbance factors may increase propagule pressure leading to the spread of exotic species (Lockwood et al. 2005). However, there is little information on the effect of human disturbance on invasibility of African savannas in landscapes with a different mosaic of land use. Little is also known about the key traits of exotic plant species that allow them to thrive in disturbed environments better than their native counterparts. Therefore, the main objective of this study is to test whether human disturbance facilitates exotic plant invasions of African savannas. Specifically the study also sought to determine whether exotic species possess physiological traits that allow them to thrive in landscapes with high frequency of disturbance.

Since human activities such as defined above remove native biomass, competition between native and exotic flora would be lower in communal lands compared to protected landscapes. Consequently, the proportion of introduced exotic plant species is predicted be to higher in the communal agricultural landscapes. Also if human-mediated disturbance is the driving factor behind invasion, exotic species will possess traits enabling them to cope with frequent disturbance such as a small reproductive cycle and a life form that diverges from the dominant native species so as to avoid competition.

2.2 Methods

2.2.1 Study sites

Data for this study were collected from three sites located in the southern Zimbabwe (fig. 2.1). The sites were stratified according to land-use.

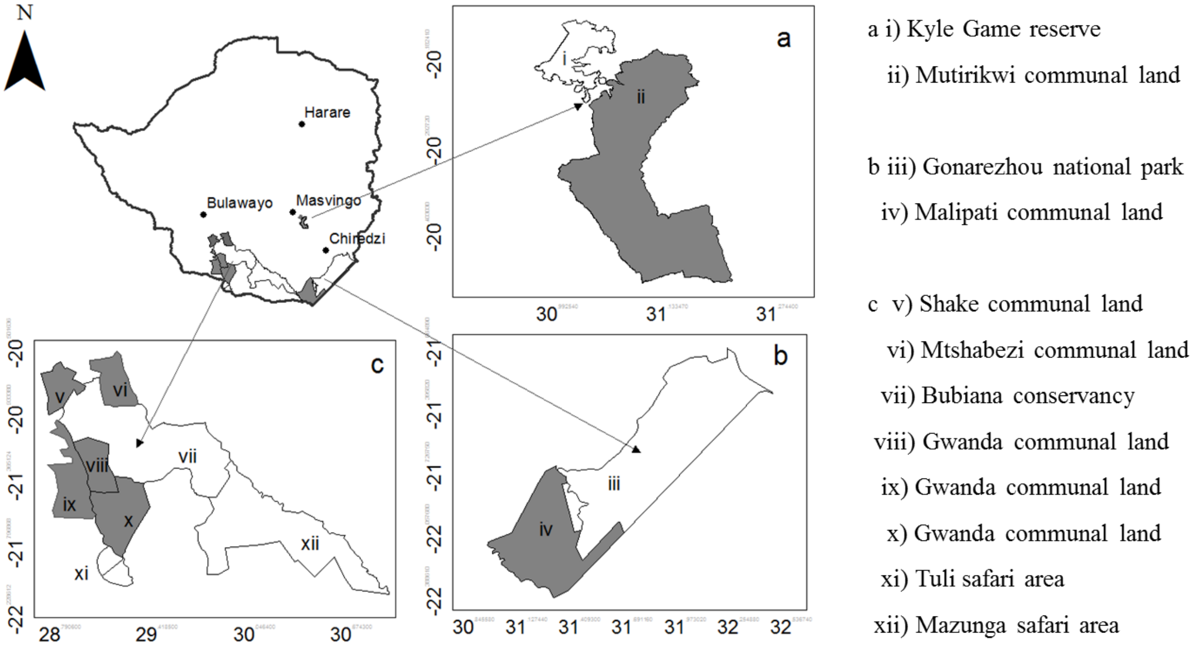

Figure 0-1: Distribution of the three study sites south of Zimbabwe.

The first site (a) is located near the town of Masvingo between at latitude 20° 06´ and longitude 30° 58. This site consists of Kyle Game Reserve and the surrounding Mutirikwi communal land. The Kyle game reserve covers 44 km^2. It receives a mean annual rainfall of 638 mm. The dominant vegetation is Miombo woodland with *Brachystegia spiciformis and Jubernardia globiflora as* the most common tree species. Kyle Game Reserve has been protected since 1961 (Masocha 2009) and the main land use in Kyle Game Reserve is wildlife conservation. By contrast subsistence farming is the main land use in the adjacent Mutirikwi communal land. Mutirikwi's climate and vegetation type are similar to that of Kyle Game Area.

The second site (b) is located in south-west Zimbabwe at latitude 22°00´ and longitude 29°12´ (fig 2.1). It comprises Tuli, Bubiana and Mazunga Safari Areas and the surrounding Shake, Mtshabezi and Gwanda communal land. Tuli safari area covers 416 km^2. The average total annual rainfall at the second site is 332.9 mm (Timberlake et al. 2002). The vegetation is mainly comprised of *Colophospermum mopane* and *Terminalia prunoides* woodlands (Timberlake et al. 2002). Bubiana conservancy and Mazunga safari are community operated wildlife sanctuaries which are protected from human disturbances except for regulated trophy hunting. Taula safari has been a hunting area since 1958 under the Zimbabwe Parks and Wildlife authority (Groom et al. 2014). The main economic activity in the safari areas is trophy hunting and game viewing. Other human activities are prohibited (Darkey and Alexander 2014). In contrast the surrounding Shake, Mtshabezi and Gwanda communal land are characterized by subsistence farming and heavy grazing by livestock especially cattle.

The third site (c) is located at latitude 21° 00´ and longitude 22° 15´. It comprises the protected Gonarezhou National Park and the surrounding Malipati communal land. Gonarezhou National Park covers 5,053-km^2. The mean total annual rainfall in Gonarezhou is 466.5 mm per annum (Tafangenyasha 2001). The dominant vegetation is *Colophospermum mopane* woodland, with associated species that include *Trichilia emetica, Afzelia quansensis, Androstachys johnsonii* and *Faidherbia albida* (Tafangenyasha 2001). Gonarezhou National Park was formally gazetted in 1975 and its boundary is a veterinary buffalo fence erected in 1974 to control foot and mouth transmission between buffalo and cattle (Mombeshora and Bel 2009). The Gonarezhou National Park was set aside for the conservation and protection of natural flora and fauna and efforts were made to exclude human influence. In this study protected landscapes are the reference sites to be compared to the adjacent communal land, which represents human-disturbed landscapes. If the hypothesis proposed in the introduction holds, introduced exotic plant species must comprise a significantly higher proportion of the species pool in the communal land compared to the adjacent protected landscapes.

2.2.2 Data Collection

Following stratification of each site by land tenure type, 204 sample plots were randomly selected in a Geographic Information System (GIS). Table 2.1 indicates the number of plots that data were sampled from. Data were collected in March 2008, May 2010 and April 2012 at Kyle, Gwanda and Gonarezhou sites, respectively.

Table 0.1: Distribution of sample plots at Kyle, Gonarezhou and in Gwanda.

Site Name	Number of plots (Protected landscape)	Number of plots (Communal landscape)	Total
Kyle	41	40	81
Gonarezhou	26	22	48
Gwanda	34	41	75

Due to logistical difficulties Gonarezhou national park has the least number of samples yet it is the largest compared to the other two protected areas in this study. Each sampled plot measured 900m^2 in area. We selected 900m^2 as the standard size of our sampling plot in order to obtain a true representation of the vegetation in that plot. Considering that the study was conducted in 3 sites which lie in different agro-ecological regions. 900m^2 was standardised as the area at which we obtained the maximum in the variation of species in a plot for the three sites. Within each plot, all plants present were identified to species level with the aid of vegetation checklists and recorded. For each plant species, the cover, origin, invasive status, and categorical traits such as life form were determined with the help of botanist from the National Herbarium and Botanic Garden as well as online vegetation checklists such as www.zimbabweflora.co.zw. Native species richness was calculated as the total number of plant species indigenous to Africa that were present in a given plot. Likewise, exotic plant species richness was calculated as the total number of introduced exotic (exotic) plant species present in a given plot.

2.2.3 Data analysis

To determine the appropriate statistical methods for analysis, the data were tested for normality using the Shapiro-Wilk's test and found not follow a normal distribution. Therefore, non-parametric methods were employed for all statistical analyses.

Competition from co-existing native species reduces the likelihood of a system to be invaded by exotic species (Huston 2004, Suding et al. 2004, Schamp et al. 2008, Van Auken 2009, Radford et al. 2011), suggesting that plant communities with high a higher diversity and richness of native species are less likely invaded. Thus, in order to determine whether disturbance reduces native species richness, the Mann-Whitney U was used to compare whether native species richness between plots located in protected landscapes and those located in the human-disturbed communal landscapes. Native species richness was calculated as the total number of native species in each plot, inclusive of woody herbaceous and grass species. We also used Pearson's chi-square method to test whether exotic plant species were significantly associated with the human disturbed savanna. Again, comparisons were made on the proportion of exotic species between plots located in the protected area and the adjacent communal land for each study site.

Exotic species may possess traits that allow them to diversify their needs from native species consequently avoiding competition with native species (Smith et al. 2001). This study, therefore, tested whether there were differences in the proportion of native and exotic species with ruderal traits such as short growth habit and short life span that enable them to adapt to frequent disturbance using the Z test for differences in proportions. These traits were adopted for this study for the reason that although they are relatively easy to determine, they provide sufficient evidence of the plant's strategy (Díaz et al. 2009).

2.3 Results

The most common introduced species found in the three study sites include *Lantana camara* at Kyle-Mutirikwi, *Achyranthes aspera* at Tuli-Gwanda site and *Xanthium strumarium* at Gonarezhou-Malipati. The respective native species dominating in the study sites were *Diospyros lycioides* and *Colophospermum mopane.* See appendix 1 for a detailed list of the exotic and native species that were present in the three sites.

The results from statistical analyses indicate variations in the pattern of species richness within the three sites. In the first site, representing wetter savanna compared to the other two sites, native species richness was significantly higher in the protected area compared to the adjacent communal land at Kyle and Gwanda sites. The Mann-Whitney-U value was 3.84365, and the p value was less than 0.05. In direct contrast, the second site, which represents an intermediate moisture regime, had higher species richness in the human disturbed environment compared to the protected environment. At the third site, which is drier savanna, native species was also higher in the communal land than the protected areas, the difference was not significant (see fig 2.2) U=2190.0, p>0.05.

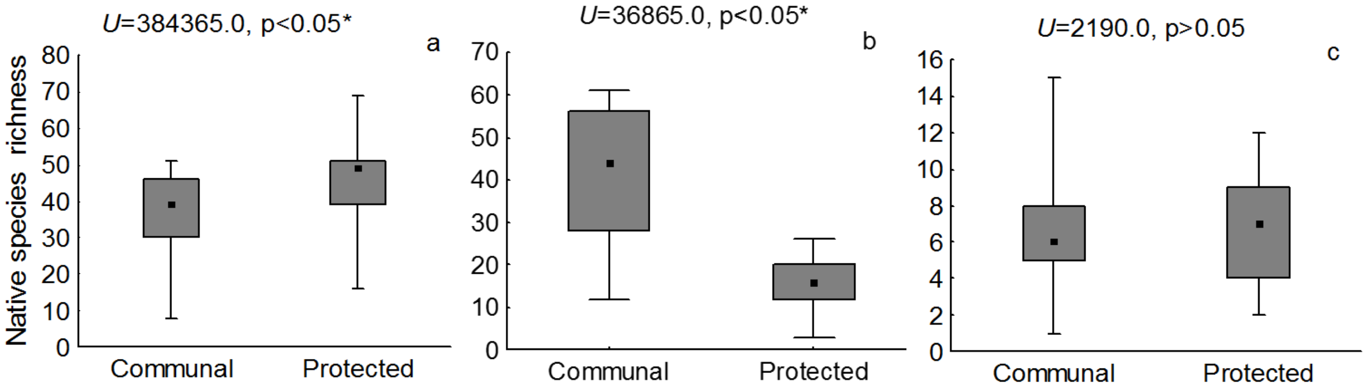

Figure 0-2: Comparison of native plant species richness in communal and the adjacent protected areas at (a) Kyle-Mutirikwi, (b) Tuli-Gwanda and (c) Gonarezhou-Malipati.

It can be observed that exotic plant species were positively associated with communal land. The X^2 values for the three sites are 4.88, 3.4 and 5.7 whilst the respective p-values are 0.021, 0.03 and 0.027 as shown in table 2.2 below. The association between exotic species and human disturbed sites is thus considered significant.

Table 0.2: Association of exotic species to human disturbance, results from X^2 test.

Site Name	X^2 value	p-value
Kyle	$X^2=4.88$	0.021
Gonarezhou	$X^2=3.4$	0.03
Gwanda	$X^2=5.7$	0.027

Figure 2.3 illustrates the differences that were found in the proportion of exotic plant species between plots located in the communal land and those that were located in the adjacent protected area. Irrespective of the moisture regime, at all the three study sites, the proportion of exotic plant species was significantly higher in the human disturbed environment. The proportion of exotic species in the third human disturbed landscapes ranged from 0.6 in the first site to 0.4 in the second site and 0.1 in the third site. On the other hand the proportion of exotic species in protected landscapes ranged from 0.3, in the first two sites and 0.04 in the third site. A Z test for proportion shows that these differences were statistically significant.

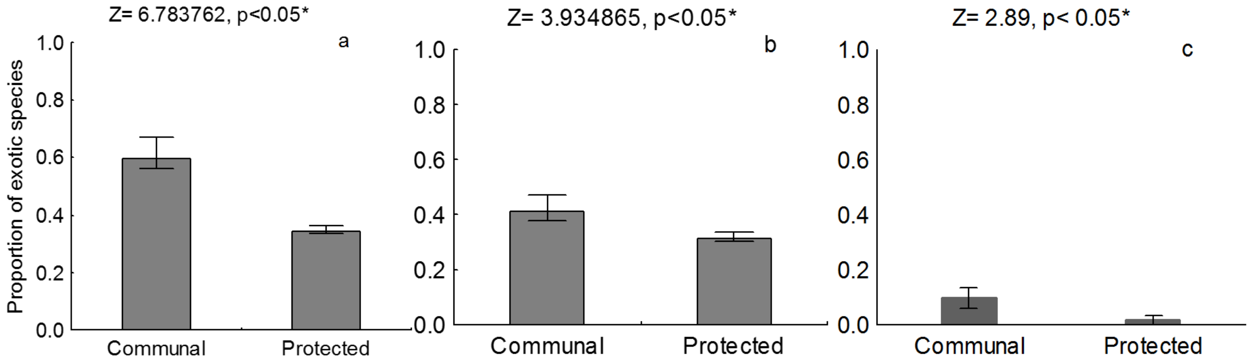

Figure 0-3: Comparison of the proportion of exotic plant species between the protected and the communal land at (a) Kyle-Mutirikwi, (b) Tuli-Gwanda and (c) Gonarezhou-Malipati. The asterisk (*) represents statistically significant differences in the proportions.

Native and exotic species in the three study sites had divergent traits. In all the three sites, exotic species are predominantly forbs with a short life span. The proportion of plant species that were forbs was significantly higher among exotic plant species compared to native species. P values of <0.05 shown in figure 2.4 and 2.5 show that the differences between the predominant growth habits and lifespan of native and exotic species are significantly different.

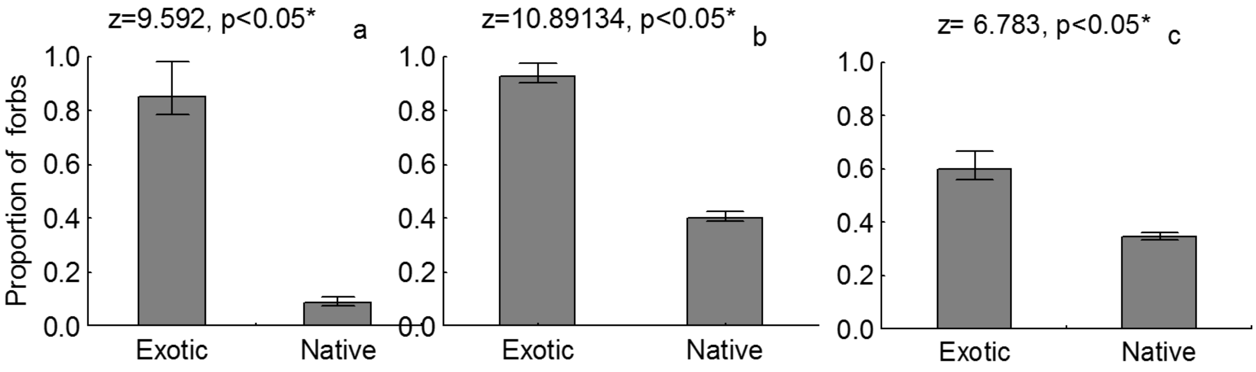

Figure 0-4: Differences in the proportion of native and exotic plant forbs at (a) Kyle-Mutirikwi, (b) Tuli-Gwanda and (c) Gonarezhou-Malipati. Bars represent the proportions whilst the error bars represent the confidence intervals. Z-values with an asterisk (*) are statistically significant at P<0.05.

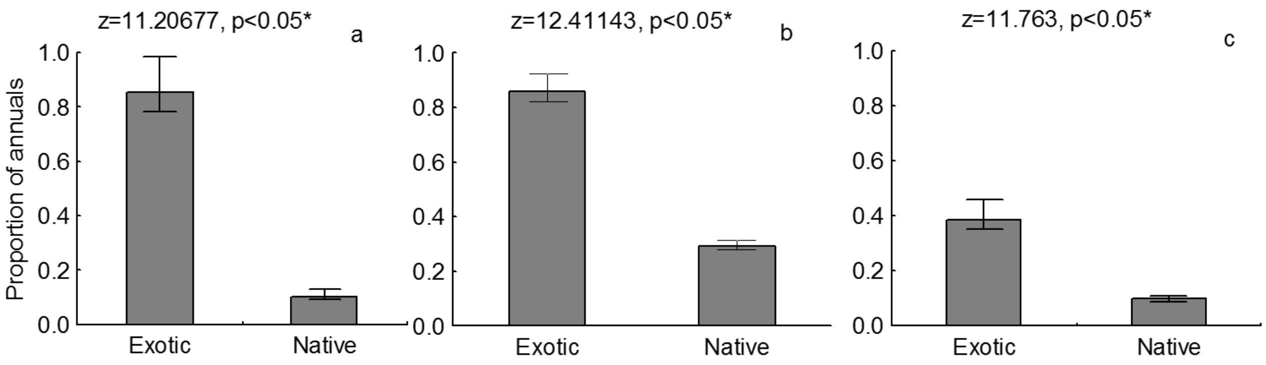

Figure 0-5: A comparison of exotic and native species that follow an annual lifespan in sites (a) Kyle-Mutirikwi, (b) Tuli-Gwanda and (c) Gonarezhou-Malipati. The bars represent the proportions whilst the error bars represent the confidence intervals. The asterisk (*) represents statistically significant differences in the comparisons.

2.4 Discussion

The evidence we gathered to determine whether human disturbance reduces native species richness varied among the three sites. Results from the two drier savanna sites provided results that seem to be in direct contradiction, results from the Kyle-Mutirikwi site suggest that in the more human disturbed communal land, disturbance seems to be creating niches as the native species richness was lower in comparison with the protected area. This may indicate other factors that may contribute to the resultant species richness patterns that were not tested in this study.

Again the results from this study show that within the three study sites, the proportion of exotic species was higher in the communal area compared to the protected savanna. The study also found that exotic plant species were dominated by the ruderal strategy whereas native plant species were dominated by a competitive strategy. These results imply that frequent disturbance regimes prevalent in human-disturbed communities may favor exotic species with a ruderal strategy.

Similar patterns have been suggested in previous studies that were also investigating the relationship between exotic species and human disturbance. (Mack et al. 2000, Foster and Tilman 2003, Kalwij et al. 2008, Foxcroft et al. 2009). In fact, in most terrestrial ecosystems, humans have been implicated in aiding the invasion by increasing the source of propagule and by eliminating competition. Human disturbance acts as an 'environmental filter' (Diaz et al. 1998), eliminating species which are not adapted to it at the same time promoting those species that are adapted to human disturbances. The results of this study show that exotic species are more adapted to human disturbance. Hence humans promote the establishment and spread of invasive exotic species.

Within a plant community with finite resources, introduced plants should have traits that are divergent from the resident native species to gain competitive ability (Müller-Schärer et al. 2004). This study tested whether the life history and growth habit of native and exotic species in the three sites were significantly different. The life history of a plant shows its space holding capabilities, which is a competitive trait. Also, it indicates plant longevity and disturbance tolerance. The growth habit of a plant indicates its adaptability to prevalent disturbance regimes. The results show that there are significantly different. Exotic species depict a ruderal strategy, with short life-spans and predominantly forb growth forms. This result confirms that exotic species possess traits that are associated with high competitive ability, which could be the reason why they may become invasive, (Pyšek and Richardson 2008). It also indicates that exotic species are adapted to frequent disturbance hence they thrive in human-disturbed communities.

Where this study differs with previous studies is that we herein provide insight into the traits of exotic species that may be allowing them to become invasive in Southern African Savannas. We have also confirmed that disturbed habitats are more prone to invasions thus they targeted allocation of resources may improve efforts against invasive species. Results from this study provide important implications for the management of protected areas against invasive species; however, future endeavors may explore the relationship between human disturbance and plant species invasion using controlled experiments. This might improve the quality of information available for managing invasive species. In addition, increasing the geographic extent of the studies may provide improve the quantity of information available, given that the continent is lagging behind in terms of information on invasive species (Pysek et al. 2008).

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Chapter 3: Spatial prediction of the suitable habitat for invasive *Xanthium strumarium*

This chapter is based on Chikuruwo Charon[1], Mhosisi Masocha[2], Murwira Amom[3], and Ndaimani Henry[4]. Predicting the suitable habitat of the invasive *Xanthium strumarium L*. in south-eastern Zimbabwe. Published at **Applied Ecology and Environmental Research**.

Abstract

Biological invasions have negatively affected virtually all ecosystems on earth. Thus, the reduction of spread is important. A few broad strategies are available on how to reduce the spread of invasive species, making the identification of suitable habitat key in the effective control of invasive species. Thus, this study aims to predict the suitable habitat of the invasive species *Xanthium strumarium* and to identify the factors associated with its spread. Presence (53 plots) and absence (52 plots) data for building the prediction model were collected from Gonarezhou National Park and the adjacent Malipati communal lands in April 2013. Ten modeling techniques were employed namely; Generalized linear model, General additive model, Classification tree analysis, Surface range envelope, Multivariate adaptive regression splines, Random Forest, Gradient boosting machines, Maximum entropy, Artificial neural networks, and an ensemble model. Environmental factors related to the establishment success of *X.strumarium* were also identified. Results of this study indicate that machine learning based techniques performed better at predicting the occurrence of *X.strumarium*, although the ensemble prediction outperformed all the individual models. *X.strumarium* was predicted to occur in areas that receive direct radiation from the sun, thus, aspect was identified as a critical factor in habitat selection for *X.strumarium.*

Keywords: exotic, modeling, location

3.1 Introduction

Rough cocklebur (*Xanthium strumarium*), is a broadleaved, tap rooted forb whose stems are erect, ridged, rough and hairy (Hare 1980). The species belongs to the Asteraceae family and it reproduces annually (Venodha 2016). Rough cocklebur often appears in thick mono-specific stands usually in low-lying riparian areas and in agricultural fields (Marwat et al. 2010). The native habitat of *X. strumarium* is North America and Argentina (Nel et al. 2004, Henderson and Henderson 2011). Several studies have identified *X. strumarium* to be invasive in southern African savannas, (Ekeleme et al. 2000, Holmes et al. 2008, Sithole et al. 2012). The success of *X. strumarium* as an invasive species has been attributed to competitive genetic makeup (Gray et al. 1986) among other adaptive capabilities that the species possesses. However, the extent of *X. strumarium* invasion in south eastern Zimbabwe is yet to be established.

The process of invasion depends on both the invasive capabilities of the species and the invasibility of the ecosystem. Hence it is important to consider the factors which are associated with habitat invasibility when predicting the occurrence of an invasive species. According to the ecological niche theory, the preferred habitat of a plant is that which gives positive feedbacks from interactions with both biotic and abiotic factors (Austin 2002). Given the fact that introduced species are more successful in disturbed ecosystems where competition has either been reduced or totally eliminated (Dukes 2001, Eppstein and Molofsky 2007, Seastedt and Suding 2007, Radford et al. 2011) it is vital to consider the natural and human factors that are associated with the occurrence of *X. strumarium*.

Information on the potential distribution of invasive species is essential as it may improve the quality of control efforts against invasion. Single model species distribution models are often affected by bias (Araújo and New 2007b). Thus, researchers have ventured into multi-model approaches and ensemble forecasting (Ochoa-Ochoa et al. 2016). The use of several models could remove model-based bias and improve the chances of model suitability. Although multi algorithm species distribution modeling has gained popularity among spatial geographers, more work still needs to be done in Southern African savannas, especially for invasive species. This is especially important given that savannas play a vital role in human welfare and economic development since half of the biome's human population is directly dependent on it for their sustenance (Sankraan et al. 2005).

Currently, there are a limited number of studies that attempt to identify the potential distribution of invasive species, *X. strumarium* included. Given that in the south eastern low-veld of Zimbabwe cattle farming is the main economic activity supporting livelihoods (Zengeya et al. 2011, Chigwenhese et al. 2016), and the area hosts a considerable number of wild mammals in the Gonarezhou national park, information on the suitable habitat of the invasive species is critical. That is especially true because this exotic weed is unpalatable to both livestock and wildlife, thus, if left unmanaged the invasive species could cause major economic and biological losses. In that regard, this study aims to predict the occurrence of this invasive species in south eastern Zimbabwe. This prediction will be made by using an ensemble model which will incorporate the best performing algorithm among: Gradient boosting machines (GBM), Artificial neural networks (ANN), Maximum entropy (MaxEnt), Random forests (RF), General linear model (GLM), General additive machines (GAM), Multivariate adaptive regression splines (MARS) Surface range envelope (SRE) and Classification tree analysis (CTA). In this study, the ensemble model was also used to identify the environmental factors that are associated with the distribution of *X. strumarium.*

3.2 Methods

3.2.1Study site

This study was conducted in the Gonarezhou National park (GNP) and the adjacent Malipati communal land (MCL). The study area is located in the south-eastern low veld region of Zimbabwe between latitudes 21° 00´ and 22° 15´ south and longitudes 32° 30´ and 33° 15´ east (Fig. 3.1). The south-eastern low veld is semi-arid, with average monthly maximum temperatures of 25.9 C in July and 36 C in January and average monthly minimum temperatures range between 9 C in June and 24 C in January (Gandiwa 2014). Characteristic vegetation in the area is Savanna woodland dominated by *Colophospermum mopane*, interspersed with *Androstachys johnsonii* and *Combretum apiculatum* on ridges and in riverine areas.

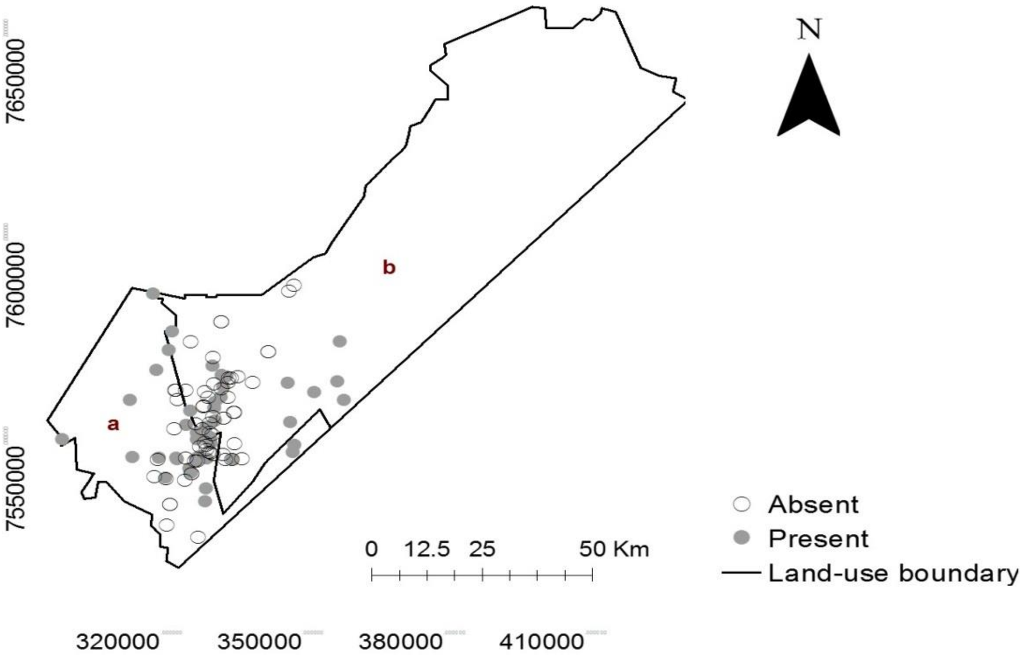

Figure 0-6: Distribution of presence and absence data points in (a) Malipati communal land and (b) Gonarezhou National Park.

The study was conducted in these separate but adjacent sites so as to account for the effect of land use on the distribution of *X. strumarium*. The sites, GNP and MCL have similar biophysical characteristics (Mombeshora and Bel 2009) albeit they differ in their main land uses and, therefore, disturbance regimes. GNP is a protected area where wildlife conservation is the main land use activity while MCL is a communal land where cropping and livestock grazing are the main economic activities.

3.2.2 Data collection

Species presence and absence data were collected in April 2013 from Gonarezhou national park and Malipati communal land. First, the study site was stratified according to land-use, Gonarezhou being protected and Malipati being communal. Thereafter; sampling units were randomized in the sites within a GIS environment. Vegetation surveys were conducted in 105 randomized plots. Each plot measured 900m^2. In each plot, we recorded all present rooted plant species. Out of the total sample of 105 plots, *X. strumarium* was present in 53 and in 52 plots it was absent. Thus we had 53 plots as presence data and 52 plots as absence data.

3.2.3 Environmental variable selection

Figure 3.2 presents maps of four environmental variables namely distance from homesteads, distance from roads, normalized difference vegetation index (NDVI), and aspect selected to predict the distribution of *X. strumarium.* The selection of these variables was based on the ecological niche theory and the invasive species' dependency on disturbance regimes.

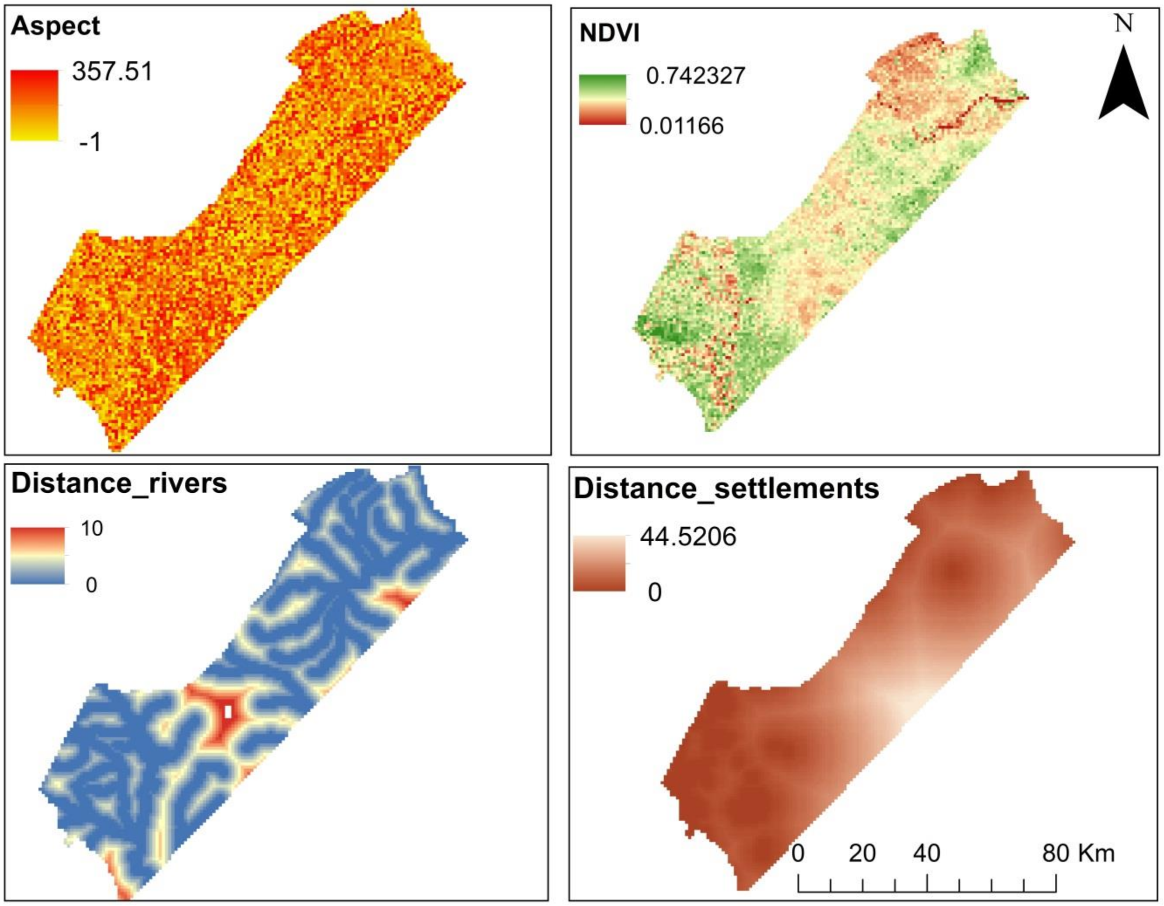

Figure 0-7: Environmental variables used in model building

To represent the potential role of human and livestock disturbance in the distribution of *X. strumarium*, we used the inverse the distance from settlements as a proxy of disturbance. Many studies identify anthropogenic disturbance as one of the major drivers of invasive species establishments in most ecosystems (Hobbs and Huenneke 1992, Larson et al. 2001, Huston 2004, Godefroid et al. 2005, Marini et al. 2012). The use of distance from settlements as a proxy of anthropogenic disturbance was justified on the basis that human-mediated disturbance activities such as crop production and livestock production occur in close proximity to where people live and keep their livestock. A point map of all settlements (that is dwelling units) in the study area was created by digitizing these as point features using a Landsat 8 image for April 2013 made available via Google Earth (www.googleearth.com) as the base layer. Next, the Euclidean distance from each dwelling unit was calculated using the Spatial Analyst tool in ArcGIS 9.2 (Wang et al. 2001). Then, an inverse distance map was derived from the Euclidean distance map using the in-built inverse distance Algorithm in Spatial Analyst tool. The weighted map of distance from homesteads was used as a proxy for human and livestock disturbance.

Distance from rivers was used as a proxy for moisture availability, which is crucial to the establishment of *X. strumarium* given that the study site is a semi-arid Savanna hence moisture availability is a limiting factor. Distance from rivers also served as a surrogate for propagule dispersal since it is known that the burs that carry the seeds of *X. strumarium* are buoyant and can, therefore, be transported in flowing water, (Davies and Johnson 2012). Also, considering the fact that the burs of *X. strumarium* can be dispersed by animals via attachment it makes ecological sense to assume that the propagules of *X. strumarium* are more likely to be dispersed more efficiently along riparian areas as animals both domestic and wildlife come to drink water. We extracted the river network of Gonarezhou national park and the adjacent Malipati communal lands from a Demographic Elevation Model of the area using the Hydrology tool in ArcGIS 9.2. The inverse distance from rivers was calculated from the rasterized poly-lines of the river network using the standard Euclidean distance tool in ESRI ArcGIS 9.2 (Wang et al. 2001). The resultant raster map was then used as a proxy for the effect of rivers.

Previous studies have highlighted a negative relationship between competition and invasion (Kauffman et al. 1983, Mortensen et al. 1993). The third environmental predictor used for modeling the distribution of *X. strumarium* is NDVI (Normalized Difference Vegetation Index), which is a widely used proxy for primary production, which in turn represents the competitive ability of species already established in the study site (Hobbs and Huenneke 1992). To calculate NDVI, we downloaded a Landsat TM 4-5 (30m resolution) image of Gonarezhou National Park and the adjacent Malipati communal area for April 2013 from the United States Geological surveys website (http://earthexplorer.usgs.gov/). The image was processed for atmospheric corrections and calibrated in ENVI 5.1 using the Quick atmospheric correction tool (QUAC) which provides accurate calibrations. Formally, NDVI was calculated as:

$$NDVI = \frac{(NIR - R)}{(NIR + R)} \qquad \textbf{Equation 1}$$

Where NIR is the Near Infrared band and R is the red band of the Landsat TM image.

Aspect was included because previous studies have highlighted that *X. strumarium* establishes more successfully in areas where there is light, (especially the red band of light), as opposed to shaded areas (Sharkey and Raschke 1981). Thus, the aspect was included as a proxy for light availability. Aspect was derived from a 30 m Shuttle Radar Topography Mission (SRTM) digital elevation model with the Spatial Analyst-surface tool in ArcGIS 9.2 (Wang et al. 2001). The DEM was downloaded from (www. usgs.gov).

3.2.4 Spatial prediction of the suitable habitat of invasive *X. strumarium*.

The study used a range of machine learning based, classification based, regression based and surface range envelope techniques to predict the distribution of *X. strumarium* based on the presence/absence data and four environmental factors described earlier. Three regression-based modeling techniques were used in this study, namely, the General linear model (GLM), generalized additive model (GAM) and the Multivariate additive regression splines (MARS). GLM predicts from the linear relationship of a given variable to a set of explanatory variables. GAM is almost similar to GLM except it adopts a smoothing effect. MARS derives its predictions from recursive partitioning to derive a good set of basic functions. Thus, each of these techniques was included for their individual competences.

Also, four machine learning techniques were used in this study. These were: Artificial neural networks (ANN) which were developed from the mathematical models of the human nervous system. Prediction is accomplished by adjusting to cause the overall network to output appropriate results (Sithole et al. 2012). The Random forests (RF) which operate with a set of trees called ‘forests’. To make a classification each tree gives a classification and the ‘forest’ votes on the classification. Random forests choose the classification which received the most votes (Cutler et al. 2007). Maximum entropy (MaxEnt) which uses the maximum entropy theory to estimates the maximized probability distribution given a set of constraints (Phillips et al. 2006).

The above-mentioned regression-based and machine-learning techniques were complemented by a classification based technique, Classification tree analysis (CTA). Classification methods consist of recursive partitions of dimensional space defined by predictions into groups that are as homogeneous as possible, as such classification have their strengths. The ninth modeling technique used was the surface range envelope modeling technique (SRE). It involved the use of interpolation of various climatic parameters to produce a model of the best fit of those parameters (Chown et al. 2005).

Using Biomod 2 within the R statistical software, we implemented the above-mentioned models using the default settings for each model. Adjusting the settings for algorithms would give some algorithms advantage thus we used the default settings since we intended to make comparisons of the prediction provided by each model. We used 80% of our dataset to make the predictions and the remaining 20% for evaluating the predictions. We set the models to use give equal weight to the presence and the absence data. Variable importance was calculated from three permutations. The True Skills Statistic (TSS) and Relative Operating Characteristics (ROC) were used as the model evaluation techniques and we ran the evaluation only once.

A consensus or ensemble model (EM) which incorporated results from the best performing models was then executed, the results from which were regarded as the final prediction. This was done within the Ensemble Modeling environment in the R statistical computing software. The total consensus model (Ekeleme et al. 2000) uses the datasets used in building individual models, as well as the individual models. A True Skills Statistic (TSS) threshold of 0.6 was used to determine models that were included in building the ensemble model. To this end, models that had TSS of <0.6 were not included in the EM, ensuring that the consensus was robust. The weighted mean of probabilities algorithm which gives more weight to individual models with better TSS scores was adopted as the final prediction of the location of *X. strumarium* in this study.

Ten model evaluation metrics, namely; the Receiver operating curve (ROC), Cohen's Kappa (KAPPA), True Skills statistic (TSS), False alarm ratio, (FAR) Success ratio (SR), Accuracy (fraction correct), Bias score (frequency bias), Probability of detection (POD), Critical success index (CSI), and Equitable threat score (ETS) are available in BIOMOD2 and can be used to determine the models that provided accurate predictions, given that a species distribution model is only useful if it is robust (Václavík and Meentemeyer 2009). However, to strike a balance between the need for multiple test statistics which improves the robustness of assessments (Elith and Graham 2009) and to avoid redundancy by using all of them, two of the commonly used model evaluation metrics namely ROC and TSS were used. ROC measures the ability of a model to discriminate between presence and absent points. Values of the ROC statistic range from 0 to 1, where < 0.5 represent predictions which are not better than random. The TSS statistic ranges from random (−1) to perfect agreement (+1) (Guisan and Thuiller 2005). The advantage of using TSS is that it has all the good properties of KAPPA yet it is not sensitive to prevalence (Allouche et al. 2006).

The relative importance of each predictor variable used in building the ensemble model was also calculated using the BIOMOD2 package (Ekeleme et al. 2000). In the evaluation procedure, BIOMOD first created a standard prediction by using all the four environmental variables. Thereafter, it generated other predictions, with one independent variable randomized. Thus, each variable was evaluated using the correlation scores of the standard prediction and each of the random predictions (Capinha and Anastácio 2011). If the standard and random predictions are highly correlated, then the variable's relative importance is low (Capinha and Anastácio 2011). The relative importance values ranged from 0 (lowest importance) to 1 (highest importance).

Curves representing the predictive ability of each environmental variable were also used to assess the response of the model to the variable. The BIOMOD2 response.plot2 function (Ekeleme et al. 2000), was used to plot the response curves. To build the response curves, all other variables except the target variable were set constant to a fixed value (the mean) while the target variable for which the curve was being plotted was the only one that was allowed to vary. Thus, the variations and the curve attained showed how the model was sensitive to that specific predictor variable.

3.3 Results

Model performance varied among the nine individual modeling techniques used as shown in figure 3.3. The random forest (RF) and GBM, performed well in predicting the occurrence of *X. strumarium* in Gonarezhou National Park. These two modeling techniques had high TSS and ROC values exceeding 0.6. Consequently, these algorithms were selected for building the ensemble projection, which is shown in Figure 3.3 performed best with a TSS score of 0.87. The predictions made by MARS, MaxEnt, GLM, and SRE, were not better than outcomes of random predictions, given their TSS scores were less than 0.5.

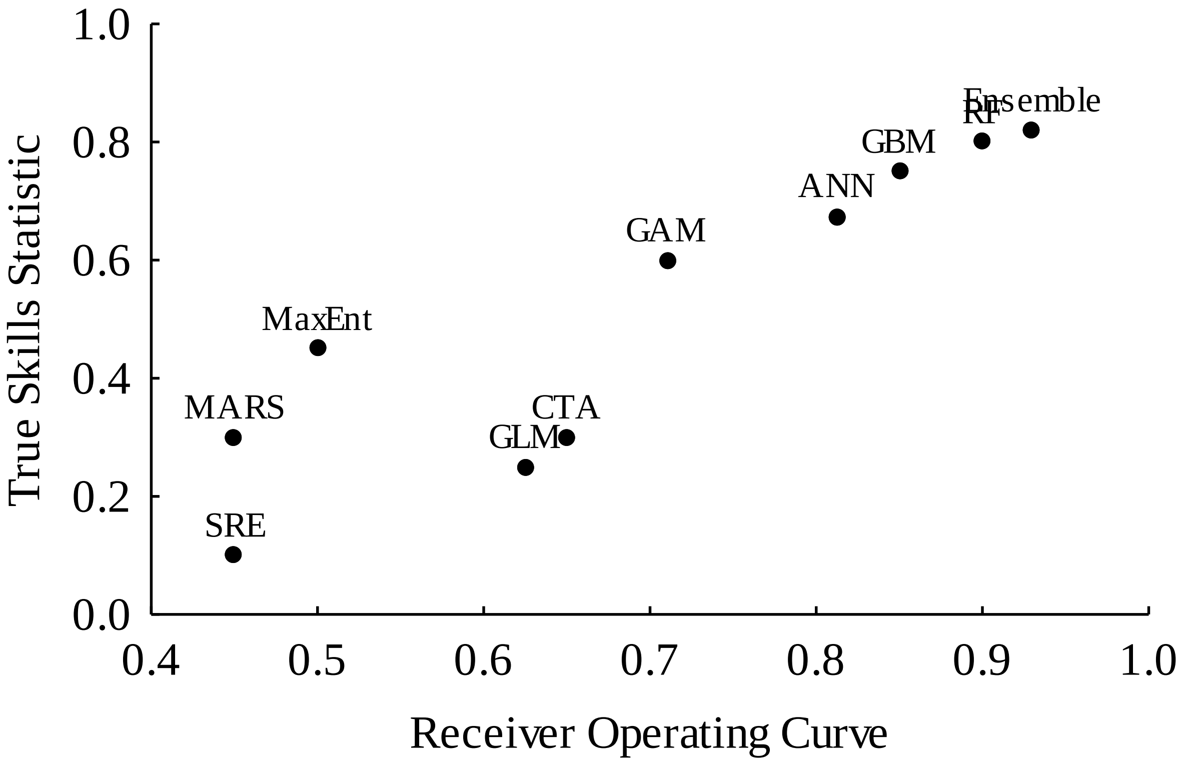

Figure 0.8: Scatter plot showing the performance of ten modeling techniques used to predict the occurrence of the invasive species *X. strumarium* in Gonarezhou National Park and Malipati communal land. The x-axis represents True skills statistic (TSS) and the y-axis shows Receiver operating curve (ROC).

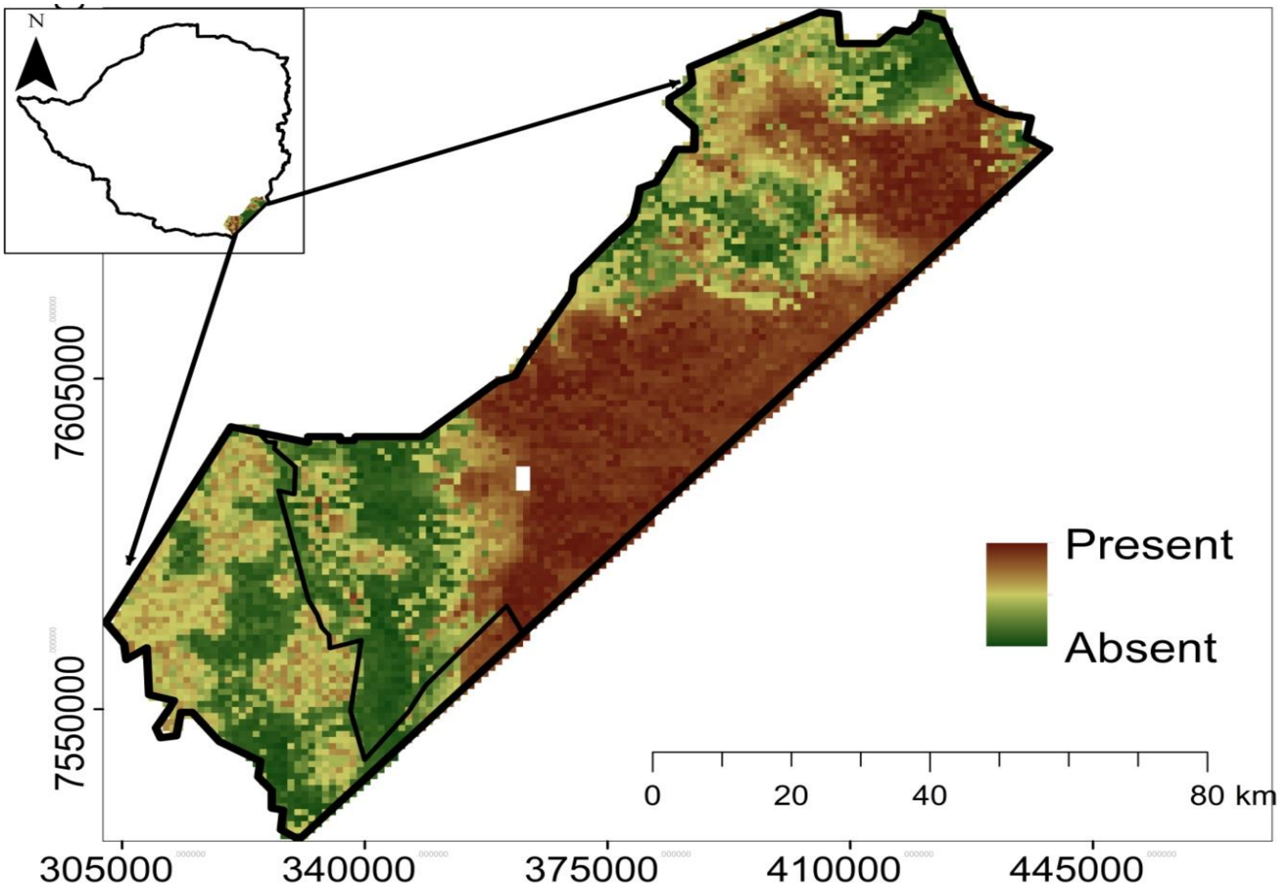

Figure 0.9: The predicted suitable habitat for *X. strumarium* in Malipati Communal lands and Gonarezhou National Park derived from the Ensemble model. Whilst the green represents a high probability of absence, the probability of presence increases through the color yellow and the highest probability of presence is represented by red.

Results show that aspect, with a relative importance of 0.486 was the most important variable influencing the results of the ensemble prediction, followed by NDVI and distance from settlements with relative importance values of 0.303 and 0.277, respectively. The predictor variable with the lowest relative importance of 0.021 was the distance from rivers.

Results shown in figure 3.5 illustrate the response curves of *X. strumarium* to the four factors considered important in predicting the species' probability of occurrence in Gonarezhou National Park. It can be observed that in general, the probability of occurrence of *X. strumarium* increases with aspect and there is a local maximum centered on 100˚. The response curves for the distance from settlements indicates that the highest peak in the probability of *X. strumarium* occurred within a distance of 2-km from settlements. After this distance, the probability of *X. strumarium* fluctuates but an increasing trend is discernible up to a distance of 15 km from settlements. With regard to NDVI, results in figure 3.5 illustrate that the probability of occurrence of *X. strumarium* decreases with increasing NDVI.

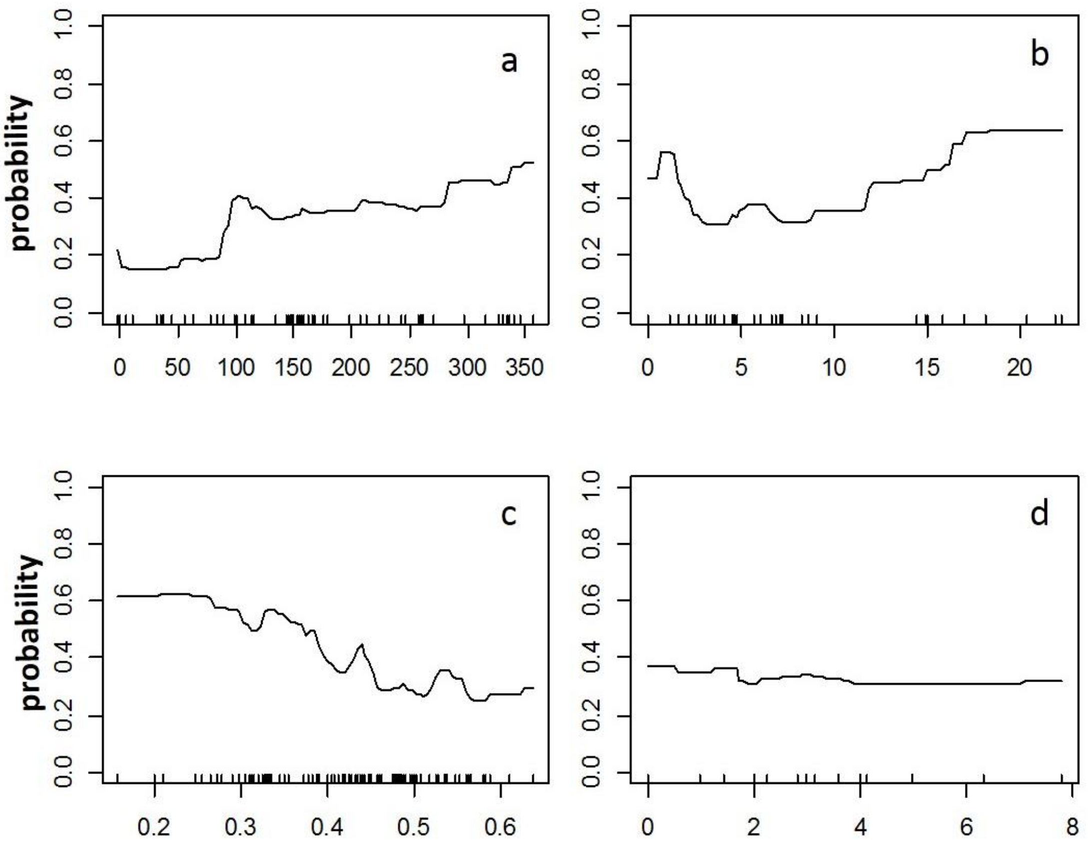

Figure 0-10: Curves showing the response of *X. strumarium* to (a) aspect (b) distance from settlements (c) NDVI (d) Distance from rivers**.**

3.4 Discussion

Since human disturbance is known to promote invasion (Chown et al. 2005, Addo-Fordjour et al. 2009a, Holland et al. 2011), factors associated with human disturbance in conjunction with biotic factors improve the performance of models in predicting the occurrence of exotic species. The prediction produced by the ensemble model was fairly accurate with both the TSS and ROC more than 0.8 (Figure 3.3). The prediction suggested that areas within the protected area have a higher probability of *X. strumarium* occurrence than those in the communal area. This result implies the need for improved efforts in managing the spread of *X. strumarium* inside the protected area since conditions inside the national park is conducive to the growth of the species.

The study also intended to make a comparison of the performance of modeling techniques when predicting the location of *X. strumarium* in and around a protected area in south Eastern Zimbabwe. In line with our hypotheses, the ensemble model provided a superior prediction to all the other algorithms in this study. The superior performance of the consensus model could be attributed to the fact that it combines the outcomes of several good predictions to come up with one that has better accuracy (Mestre et al. 2015, Ochoa-Ochoa et al. 2016). According to the accuracy assessment parameters employed in this study, RF performed better than the other algorithms. In fact, the top two algorithms RF and GBM are machine learning techniques. The success of machine learning algorithms could be attributed to the fact that learning based models learn from the existing data thus, they do not require a priori model (Kasabov 1996). Hence their predictions are unbiased and mostly turn out to represent nature more accurately.

The success of machine learning techniques in this study is not unique. Other studies, (Austin 2002, Austin et al. 2006, Guisan et al. 2006) which also made comparisons of species distribution modeling techniques have also cited the strength of machine-based algorithms. Some of the algorithms, however, produced poor predictions regardless of the fact that similar variables were used for all the models. The differences in the predictions of the ensemble model and the SRE model illustrates the importance of accurate species distribution modeling of invasive species. Accurate predictions of invasive species locations allow for the targeted application of limited resources; especially in African savannas where resources are constrained.

Therefore, from the results, it is deductible that the use of appropriate algorithms may improve efficiency in invasive species management. The poor performance of these algorithms in this study regardless of previous success in other studies proves that no single model works best for all species, in all areas, at all spatial scales, and over time (Jarnevich et al. 2015). Thus, from these results, we deduce that a multi-model approach is important for eliminating problems associated with model bias in species distribution modeling.

Another objective of this study was to investigate the environmental variables that were most influential in predicting the occurrence of *X. strumarium*. The results suggest that the aspect was the most important factor in building the predicted location of *X. strumarium*. This finding implies that among the factors that were considered, the direction in which the slope is facing is most critical for the success of *X. strumarium*. Several studies have established that quality of light reaching an *X. strumarium* plant is important for its growth (Austin 2002). Since it is an annual herb which grows in mono-specific thickets of only about 1m in height (Burkart 2001), which means it could be affected by the availability of taller species which shades them from sunlight. Thus competition for light is identified as a limiting factor for the growth of the species. Therefore, management strategies could prioritize surfaces that have direct access to sunlight to reduce the survival rate of new introductions.

X. strumarium responded negatively to competition just as previous studies (Stachowicz et al. 1999, MacDougall and Turkington 2005, Foxcroft et al. 2011a) have established the competition avoidance nature of most invasive species. Studies on ecosystem invasibility have established that invasive species generally avoid competitive patches as a competition avoiding strategy

(Stachowicz et al. 1999, Bartomeus et al. 2012). As such, the response of *X. strumarium* to NDVI may imply that the weed’s strength is its capability to utilize niche left over by disturbance events such as tilling or trampling and livestock grazing. This is evident in the fact that the species follows an annual lifecycle (Venodha 2016) and also one plant can produce up to several hundreds of propagules. Thus, it can regenerate quickly and invade communities in very short amounts of time. To that end, it is important to acknowledge the role that disturbance plays in the establishment of invasive *X. strumarium* in order to improve efforts of managing the spread of this invasive species.

The results also suggest that distance from homesteads has a relatively substantial contribution in building the model for predicting the occurrence of *X. strumarium* with a relative importance value of 0.277. In fact, the response curve for the distance from homesteads shows a rise of probability within 1-2 km of homesteads. Other studies on invasive species have identified humans as a source of propagules (Mack and Lonsdale 2001, Farji-Brener and Ghermandi 2008, Simberloff 2009, Wichmann et al. 2009) thus; the human environment acts as the epicenter for the spread of invasive species. Again, *X. strumarium* is an agricultural weed (Masocha and Skidmore 2011), land tillage activities that occur in the communal area adjacent to Gonarezhou systematically creates niches for the establishment of the weed.

Given that the South Eastern Low Vield of Zimbabwe is dry Savanna, and animal husbandry is the main economic activity, the livestock numbers in the area may promote the establishment of the invader in two ways. The first way is through overgrazing which may disturb the natural vegetation and create niches for potential establishment of the invasive weed. Secondly, is through propagule dispersal. *X. strumarium* seeds are dispersed by water and by attaching to animal fur. Thus, large amounts of livestock improve the transport of the plant's seeds hence it spreads over large areas quickly. It is thus critical to consider the critical role that

humans are playing in facilitating the establishment of invasive *X. strumarium*.

Although rivers had the least influence in building the ensemble model, the response curve shows that the highest probability of occurrence is observed with close proximity to rivers. This area contains the riparian zone. Riparian zones are plant communities on or near the banks of river channels. A variety of natural disturbances usually creates a unique mosaic of vegetation in riparian zones, which may be parallel to vegetation in the larger landscape (Didham et al. 2007). Adding to that, rivers play a second significant role of propagule transportation to terrestrial plants. The riparian zone mostly consists of palatable forbs, thus there is the effective transport of the invader to and from riparian zones when animals come for food and water. Therefore, it is important to target these riparian areas when implementing management strategies of *X. strumarium*, given the role riparian areas play in the species' establishment.

This study differs from other spatial modeling studies in the southern African Savanna (Colgan et al. 2012, Baldeck et al. 2014, Stevens et al. 2014) in that it adopted a consensus approach to species modeling targeting an invasive species. In fact, previous studies in the biome have only been limited to single models (Stevens et al. 2014). Using the consensus modeling framework, robust predictions were made to aid pinpointing of potential hotspots *X. strumarium* invasion in Gonarezhou national park and the adjacent communal landscapes.

More study sites could be necessary to further test the validity of the results obtained in this study. Also, this study focused on only one invasive species which may have unique characteristics. Focus on more than one species could lead to more generalized conclusions. In this regard, it is recommended, that future studies focus on more than one study species and also include more bio-physical factors that may be essential in explaining invasion. Multiple study sites may also help in providing comprehensive predictions which yield useful information for managing invasive species.

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Chapter 4: Functional traits of native and alien species; a synthesis

4.1 Introduction

4.1.1 The need to understand plant species invasion in African Savannas.

Invasive species homogenize plant communities and are a leading cause of losses in biodiversity worldwide (Sax and Gaines 2003). An invaded ecosystem receives negative feedbacks from plant productivity, soil fertility, water quality, atmospheric chemistry, and many other local and global environmental conditions that ultimately affect human welfare(Shackleton et al. 2006). Invasive species also interfere with food and cash crop production in agricultural systems (Cilliers and Neser 1991, Pimentel et al. 2000), costing millions of dollars worldwide. Other than having negative impacts on biodiversity and human welfare, invasive species also reduce the quantity and quality of graze and browse available for both wildlife and livestock. Most exotic species that eventually become invasive possess herbivore avoidance traits such as poisons or thorns; hence they do not provide feed for wildlife and livestock (Jogesh et al. 2008). Therefore, invasive species pose an imminent threat to the sustainability of natural ecosystems, human and wildlife welfare.

Humans play an important role in facilitating the introduction and spread of exotic species. Humans provide transport for the propagules of invasive species intentionally as ornamental plants or accidentally by attaching themselves to vehicles or clothing of people in transit (Hulme 1998). Human-related activities such as livestock production, crop production, and deforestation also eliminate competition for these propagules to become established by removing native biomass (Chown et al. 2005, Jack 2009, Jauni and Hyvanen 2011, Bartomeus et al. 2012).

Hence, this thesis investigates the relationship between humans and invasive species in African Savannas.

In order for introduces species to become invasive, they have to possess traits that enable them to perpetuate without human assistance (Alpert et al. 2000, Beckstead and Parker 2009). This is referred to as invasiveness in invasion ecology; the capability of a species to achieve close to mono-specific status in a community, disrupting ecosystem balance and service provision (Grotkopp et al. 2002, Hamilton et al. 2005). Invasiveness could be attributed to the ability to acquire resources better than co-existing species (Price et al. 2011), better competitive abilities, or prevention of predation. Hence understanding trait diversity between native and exotic species may lead to a better understanding of species invasion.

The aim of this study is to determine whether human disturbance facilitates invasion in African savannas. The study has three specific objectives. The first objective is to determine whether human disturbed landscapes contain more exotic species than adjacent protected areas. The second objective is to determine whether the physiognomic traits of co-occurring native and exotic species differ. The second objective also seeks to establish whether the difference in physiognomic traits equips exotic species to thrive in frequently disturbed environments. The third objective of this study is to spatially predict the suitable habitat of the invasive species *Xanthium strumarium* in a Savanna ecosystem using a combination of human and ecological factors. In combinations, these objectives seek to improve the quality of information available on the role that human disturbance plays in the invasion of southern African savannas.

4.2 Human disturbance enhances invasion in Southern African savannas

This thesis investigated the effect of human disturbance on native and exotic species by contrasting plant community assemblages inside and outside of protected areas. Anthropogenic factors such as livestock farming may lead to overgrazing and trampling of native plants hence the results indicate that human disturbance significantly lowers native species richness. Humans also remove native species with intentions of clearing land for farming, for roads or for building houses. This study also confirmed that exotic species are significantly associated with human disturbed environments and there is a higher proportion of exotic species in the human disturbed environment compared to protected environments. These activities affect the native biodiversity directly and indirectly by creating niches in the ecological community that can be occupied by introduced species. The results from this study are consistent with similar studies conducted within and outside of Savanna ecosystems. A wealth of literature is available on the subject of invasion in most ecosystems except for the African savanna(Pysek et al. 2008). Most of these studies highlight the importance of human disturbance as a driver for invasion. However, African savannas are unique in that their natural balance is governed by disturbance (fire and herbivory). This study, therefore, provides empirical evidence, from multiple sites, that human disturbance enhances invasion despite the disturbance-dependent nature of the savanna ecosystems.

4.3 Physiognomic traits of co-existing exotic and native species differ significantly

Invasive species are known to possess a set of traits that allow them to be adapted to be competitive and to withstand disturbance (MacDougall and Turkington 2005, Küster et al. 2008, Gassó et al. 2009, Arianoutsou and Bazos 2010, Martin and Murray 2011). This study investigated the competitive ability of the exotic species that were found in the three sites by contrasting their physiognomic traits to those of co-occurring native species. The results indicate that exotic species are divergent from the grasses and woody species that are native to the study sites, a larger proportion of the exotics are forbs which follow an annual life-cycle. This result implies that exotic species are competitive and it holds a lot of implications for the threat of invasion. This is an important finding, especially for African savannas where there is meager information as it allows potential invaders to be identified and managed before they cause a lot of ecological and economic harm (Pyšek and Richardson 2008).

4.4 The predicted habitat of invasive Xanthium *strumarium L.* in south eastern Zimbabwe

After realizing the potential effect of human disturbance on invasive species, the thesis went on to build a model to predict the habitat of an invasive species *Xanthium strumarium*. Unlike conventional models which mostly consider biotic factors alone, this study included distance from settlements as a parameter accounting for human influence. Again, unlike conventional spatial prediction studies, this study employed the use of several modeling algorithms in its final output using an ensemble modeling technique. From the results, it is evident that both the environmental variables and the ensemble modeling technique used in this study provide good prediction (ROC > 0.8). This finding is consistent with the work of (Araújo and New 2007a) which discusses the advantages of employing multiple modeling techniques.

The results from this objective also indicate that aspect, which determines the angle at which a *Xanthium strumarium* plant receives sunlight, was the most important factor determining its suitable habitat. NDVI was used in this study as a proxy for competition. The results from this study indicate that competition is important in building the prediction of the suitable habitat for *X. strumarium*. This result implies that the weed avoids areas that are already populated with other species and targets areas that have undergone disturbance and are therefore less populated which is in line with the literature of the invasive species (Dukes 2001, Eppstein and Molofsky 2007, Garcia-Serrano et al. 2007). These findings also provide support to the study hypothesis that human disturbance facilitates invasive species as the distance from homesteads was had a considerable contribution in building the model to the predicted habitat of *Xanthium strumarium*. Distance implies human disturbance thus it can be translated to mean that human disturbance contributes positively to habitat selection by the invasive weed. Distance from rivers had the least contribution; however, it was still important in building the prediction. X. strumarium is dispersed exozoochory also by water, thus river networks provide the species with propagule transport thus they are important for its regeneration. Overall this objective provides evidence that in combination with ecological factors, human factors influence the establishment and spread of invasive species.

4.5 Summary of findings

This thesis employed several methods of investigation in order to determine the role that disturbance plays in the invasion of southern African Savannas. The results indicate that human disturbance enhances the establishment and spread of invasive species. Native species richness was lower in communal areas. Exotic species were significantly associated with communal areas as opposed to adjacent protected areas. The proportion of exotic species was significantly higher in communal areas as opposed to protected areas. The results also suggest that co-occurring native and exotic species have divergent traits. Unlike the native species which are predominantly biennial or perennial trees and grasses, exotic species are predominantly annual forbs which are more competitive. Hence their ability to cope with frequent disturbances. Another important finding made in this study is that since human disturbance is an important factor in species invasions; combining human and ecological factors in predicting the suitable habitat of invasive species may improve the accuracy of the models produced.

4.6 The future

This thesis has established that anthropogenic disturbance enhances the establishment and spread of invasive species by analyzing data from three savanna sites in Zimbabwe. We have also established that the majority of species threatening invasion in the three study sites are competitive annual forbs. These findings hold important implications for the management of invasive species in this ecosystem, given that there is very little information available in the geographic area and about the taxons that affect the area (Pysek et al. 2008). In the case of *X. strumarium* in the Gonarezhou National Park and Malipati communal area, this study provided a prediction model which is the requisite information for targeted management. Chemical and physical control of the invader is recommended for *X. strumarium* and the quick regenerating exotic species in the other sites.

Studies that are based on survey data alone such as this one are important for providing the basic information and the underlying trends. However, more information is still required that addresses the problem of invasive species in Southern African Savannas. Experimental studies may provide more in-depth knowledge of the mechanisms behind the invasion. Also, savannas cover a large area of the African continent, information derived from a larger geographic range may also improve the quality of information available for the management of invasive species in African Savannas. In terms of predicting the suitable habitat of invasive species, this study has opened an important avenue with ensemble modeling which improves the accuracy of the prediction. In the future, studies could involve several species while making predictions over larger geographical areas. Fine tuning individual models and including more variables in the models could further improve the quality of models produced.

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Appendix

Appendix A: Gonarezhou Malipati data

Species Name	**Life form**	**Status**
Acacia karoo	Woody	Native
Acacia nigrescence	Woody	Native
Acacia tortilis	Woody	Native
Acacia xanthophloea	Woody	Native
Acanthospermum hispidium	Herb	Exotic
Aerva leucura	Herb	Native
Androstachys johnsonii	Woody	Native
Argemone mexicana	Herb	Exotic
Aristida conjesta	Grass	Native
Barleria senensis	Grass	Native
Berchemia discolor	Woody	Native
Bidens pilosa	Herb	Exotic
Bidens schimperi	Herb	Exotic
Boscia albitrunca	Woody	Native
Bridelia micrantha	Woody	Native
Colophorspermum mopane	Woody	Native
Combretum apiculatum	Woody	Native
Combretum hereroens	Woody	Native
Combretum imbebe	Woody	Native

Combretum mole	Woody	Native
Combretum molle	woody	native
Combretum mosambicensis	woody	native
Corchorus confusus	Herb	Native
Cordia grandicalyx	woody	native
Cyathula cylindrica	Herb	Exotic
Cynodon dactylon	Grass	Native
Dalbergia melanoxylon	Woody	Native
Dichrostachys cineria	Woody	Native
Diospyros mespliphormis	Woody	Native
Dyschoriste alba	Herb	Native
Elytraria acaulis	Herb	Native
Eragrostis nindensis	Grass	Native
Eragrostis tenuifolia	Grass	Native
Euclea crispa	Woody	Native
Euclea divinorium	Woody	Native
Euneapogon cencroides	Grass	Native
Eurphorbia ingens	Herb	Native
Evolvulusalsinoides	Herb	Native
Ficus cordata	woody	native
Fiscus sycomorus	Woody	Native

Flueggea virosa	Woody	Native
Gibortia jugata	Woody	Native
Gomphrena celosiodes	Herb	Exotic
Grewia amoena	woody	native
Grewia flavescens	Woody	Native
Hackelochloa granularis	Grass	Native
Hisbiscus canabinus	Woody	Native
Ipomoea purpurea	Woody	Exotic
Jatrofa curcas L.	Woody	Exotic
Justicia glabra	Herb	Native
Kigelia pinnata	Woody	Native
Kirkia acuminata	Woody	Native
Leucus martinicensis	Herb	Exotic
Lipia javanca	Woody	Native
Loncacarpus capassa	Woody	Native
Magaritaria discoidea	woody	native
Marsilea ephippiocarpa	Herb	Native
Mimusops zeyheri	Woody	Native
Mundulea sericea	Woody	Native
Ocimum incanum	Herb	Exotic
Opuntia fulgida	Herb	Exotic

Panicum maximum	Grass	Native
Peltophorum africanum	woody	native
Phragmites mauritanius	Grass	Native
Phyllanthus mederaspatensis	Grass	Native
Phyllanthus reticulatus	woody	native
Pseudolachnostylis maprouneifolia	Woody	Native
Pterocarpus angolensis	Woody	Native
Richardia scabra	Herb	Exotic
Rubus rigidus	Herb	Native
Schkuhria pinnata	Herb	Exotic
Senna petersianna	Woody	Native
Silver terminalia	Woody	Native
Spercoce senensis	Woody	Native
Spirostachys africana	woody	native
Stipagrostis uniplumis	Grass	Native
Tacca leontopetaloides	Herb	Native
Tagetes minuta	Herb	Exotic
Tephrosia purpurea	Herb	Native
Toddalia asiatica	Woody	Native
Trichelia emertica	Woody	Native
Xanthium strumarium	Herb	Exotic

Ximenia americana	woody	native
Ximenia caffra	Woody	Native
Zantedeschia tropicalis	Herb	Native
Ziziphus mucronata	Woody	Native

Appendix B: Kyle Mtirikwi data

Species Name	**Life form**	**Status**
Abrus precatorius L.	Herb	Native
Acacia karroo Hayne	Woody	Native
Acacia nilotica (L.) Willd. ex Delile	Woody	Native
Acacia rehmanniana Schinz	Woody	Native
Acacia sieberiana DC.	Woody	Native
Acalypha indica L.	Grass	Native
Acanthospermum australe (Loefl.) Kuntze	Herb	Exotic
Acanthospermum hispidum DC.	Herb	Exotic
Achyranthes aspera L.	Herb	Exotic
Adenia gummifera (Harv.) Harms	Herb	Native
Agathisanthemum bojeri Klotzsch	Grass	Native
Agave sisalana Perr. ex. Engelm	Woody	Exotic
Albizia amara (Roxb.) Boivin	Woody	Native
Albizia antunesiana Harms	Woody	Native
Albizia gummifera (J.F. Gmel.) C.A. Sm.	Woody	Native
Albizia tanganyicensis Baker f.	Woody	Native
Albizia versicolor Welw. ex Oliv.	Woody	Native
Aloe chabaudii Schönland	Grass	Native
Aloe excelsa A. Berger	Woody	Native

Aloe zebrina Baker	Grass	Native
Amaranthus hybridus L.	Herb	Exotic
Ampelocissus obtusata (Welw. ex Baker) Planch.	Grass	Native
Aneilema hockii De Wild.	Grass	Native
Annona senegalensis Pers.	Woody	Native
Annona stenophylla Engl. & Diels	Woody	Native
Antidesma venosum E. Mey. ex Tul.	Woody	Native
Aristida barbicollis Trin. & Rupr.	Grass	Native
Aristida junciformis Trin. & Rupr.	Grass	Native
Aristida stipitata Hack.	Grass	Native
Artabotrys brachypetalus Benth.	Herb	Native
Asparagus africanus Lam.	Herb	Native
Asparagus asparagoides (L.) Wight	Herb	Native
Asparagus falcatus L.	Herb	Native
Asparagus laricinus Burch.	Herb	Native
Asparagus plumosus Baker	Herb	Native
Azanza garckeana (F. Hoffm.) Exell & Hillc.	Woody	Native
Balanites aegyptiaca (L.) Delile	Woody	Native
Barleria crassa C.B. Clarke	Woody	Native
Barleria kirkii T. Anderson	Grass	Native
Berkheya zeyheri (Sond. & Harv.) Oliv. & Hiern	Grass	Native

Bidens bipinnata L.	Herb	Exotic
Bidens pilosa L.	Herb	Exotic
Blepharis maderaspatensis (L.) Roth	Grass	Native
Boophone disticha (L.f.) Herb.	Grass	Native
Bothriochloa insculpta (A. Rich.) A. Camus	Grass	Native
Brachiaria brizantha (A. Rich.) Stapf	Grass	Native
Brachiaria eruciformis (J.E. Sm.) Griseb.	Grass	Native
Brachylaena discolor DC.	Woody	Native
Brachystegia glaucescens Burtt Davy & Hutch.	Woody	Native
Brachystegia spiciformis Benth.	Woody	Native
Brachystelma plocamoides Oliv.	Grass	Native
Bridelia cathartica G. Bertol.	Woody	Native
Bridelia micrantha (Hochst.) Baill.	Woody	Native
Bridelia mollis Hutch.	Woody	Native
Bulbostylis burchellii (Ficalho & Hiern) C.B. Clarke	Herb	Native
Burkea africana Hook.	Woody	Native
Carissa bispinosa (L.) Desf. ex Brenan	Woody	Native
Catha edulis (Vahl) Forssk. ex Endl.	Woody	Native
Catunaregam swynnertonii (S. Moore) Bridson (S. Moore) Bridson	Woody	Native
Celosia trigyna L.	Grass	Native

Celtis africana Burm. f.	Woody	Native
Centella asiatica (L.) Urb.	Grass	Native
Ceratotheca triloba (Bernh.) Hook. f.	Grass	Native
Chamaecrista fenarolii (Mendonça & Torre) Lock	Grass	Native
Cheilanthes involuta (Sw.) Schelpe & N.C. Anthony	Grass	Native
Cheilanthes viridis (Forssk.) Sw.	Grass	Native
Chlorophytum brachystachyum Baker	Grass	Native
Chrysanthemoides monilifera (L.) Norl.	Woody	Native
Cissampelos mucronata A. Rich.	Herb	Native
Clematis brachiata Thunb.	Herb	Native
Cleome monophylla L.	Grass	Native
Clerodendrum eriophyllum Gürke	Woody	Native
Clerodendrum ternatum Schinz	Grass	Native
Coleochloa setifera (Ridl.) Gilly	Herb	Native
Combretum apiculatum Sond.	Woody	Native
Combretum collinum Fresen.	Woody	Native
Combretum erythrophyllum (Burch.) Sond.	Woody	Native
Combretum hereroense Schinz	Woody	Native
Combretum imberbe Wawra	Woody	Native
Combretum molle R.Br ex G. Don	Woody	Native
Combretum platypetalum Welw. ex M.A. Lawson	Woody	Native

Combretum zeyheri Sond.	Woody	Native
Commelina africana L.	Grass	Native
Commelina welwitschii C.B.Clarke	Grass	Native
Commiphora marlothii Engl.	Woody	Native
Commiphora mollis (Oliv.) Engl.	Woody	Native
Commiphora pyracanthoides Engl.	Woody	Native
Convolvulus arvensis L.	Herb	Exotic
Convolvulus arvensis L.	Herb	Exotic
Convolvulus sagittatus Thunb.	Grass	Native
Conyza sumatrensis (Retz.) E. Walker	Herb	Exotic
Coptosperma neurophyllum (S. Moore) Degreef	Woody	Native
Coptosperma zygoon (Bridson) Degreef	Woody	Native
Corchorus tridens L.	Grass	Native
Crabbea velutina S. Moore	Grass	Native
Crotalaria anisophylla (Hiern) Welw. ex Baker f.	Grass	Native
Crotalaria laburnifolia L.	Woody	Native
Cryptolepis cryptolepidioides (Schltr.) Bullock	Herb	Native
Cryptolepis oblongifolia Schltr.	Woody	Native
Cucumis anguria L.	Grass	Native
Cussonia arborea Hochst. ex A. Rich.	Woody	Native
Cussonia spicata Thunb.	Woody	Native

Cyanotis speciosa (L.f.) Hassk.	Grass	Native
Cycnium tubulosum (L.f.) Engl.	Grass	Native
Cynodon dactylon (L.) Pers.	Grass	Native
Cyperus esculentus L.	Herb	Native
Cyperus involucratus Rottb.	Herb	Native
Cyperus tenax Boeck.	Herb	Native
Cyphostemma junceum (Webb) Desc. ex Wild & R.B. Drumm.	Grass	Native
Cyphostemma rhodesiae (Gilg & Brandt) Desc. ex Wild & R.B. Drumm	Grass	Native
Dalbergiella nyasae Baker f.	Woody	Native
Danthoniopsis pruinosa C.E. Hubb.	Grass	Native
Dicerocaryum senecioides (Klotzsch) Abels	Grass	Native
Dichrostachys cinerea (L.) Wight & Arn.	Woody	Native
Dicoma gerrardii Harv. ex F.C. Wilson	Grass	Native
Dicoma kirkii Harv.	Grass	Native
Digitaria eriantha Steud.	Grass	Native
Digitaria ternata (A. Rich.) Stapf	Grass	Native
Diheteropogon amplectens (Nees) Clayton	Grass	Native
Diospyros lycioides Desf.	Woody	Native
Diospyros mespiliformis Hochst. ex A. DC.	Woody	Native

Diospyros natalensis Desf.	Woody	Native
Diplorhynchus condylocarpon (Müll. Arg.) Pichon	Woody	Native
Dodonaea viscosa Jacq.	Woody	Native
Dolichos kilimandscharicus Harms ex Taub.	Grass	Native
Dombeya rotundifolia (Hochst.) Planch.	Woody	Native
Dovyalis longispina (Harv.) Warb.	Woody	Native
Dovyalis zeyheri (Sond.) Warb.	Woody	Native
Duranta erecta L.	Woody	Exotic
Dyschoriste alba S. Moore	Grass	Native
Ehretia amoena Klotzsch	Woody	Native
Ekebergia benguelensis Welw. ex C.DC.	Woody	Native
Ekebergia capensis Sparrm.	Woody	Native
Elaeodendron matabelicum Loes.	Woody	Native
Elaeodendron schlechterianum Loes.	Woody	Native
Elaeodendron transvaalense (Burtt Davy) R.H. Archer	Woody	Native
Elephantorrhiza elephantina (Burch.) Skeels	Grass	Native
Elephantorrhiza goetzei (Harms) Harms	Woody	Native
Eleusine africana Kenn.-O'Byrne	Grass	Native
Emilia discifolia (Oliv.) C. Jeffrey	Grass	Native
Englerophytum magalismontanum (Sond.) T.D. Penn.	Woody	Native
Epaltes gariepina (DC.) Steetz	Grass	Native

Eragrostis cylindriflora Hochst.	Grass	Native
Eragrostis heteromera Stapf	Grass	Native
Eragrostis inamoena K. Schum.	Grass	Native
Eragrostis patens Oliv.	Grass	Native
Eragrostis racemosa (Thunb.) Steud.	Grass	Native
Eragrostis superba Peyr.	Grass	Native
Eragrostis tenuifolia (A. Rich.) Hochst. ex Steud.	Grass	Native
Eragrostis viscosa (Retz.) Trin.	Grass	Native
Eriosema pauciflorum Klotzsch	Grass	Native
Erythrina abyssinica Lam. ex DC.	Woody	Native
Euclea crispa (Thunb.) Sond. ex Gürke	Woody	Native
Euclea divinorum Hiern	Woody	Native
Euclea natalensis A. DC.	Woody	Native
Eugenia malangensis (O. Hoffm.) Nied.	Woody	Native
Euphorbia heterophylla L.	Herb	Exotic
Euphorbia ingens E. Mey. ex Boiss.	Woody	Native
Fadogia ancylantha Hiern	Grass	Native
Faurea saligna Harv.	Woody	Native
Felicia muricata (Thunb.) Nees	Grass	Native
Ficus glumosa Delile	Woody	Native
Ficus ingens (Miq.) Miq.	Woody	Native

Ficus natalensis Hochst.	Woody	Native
Ficus sur Forssk.	Woody	Native
Ficus sycomorus L.	Woody	Native
Flacourtia indica (Burm. f.) Merr.	Woody	Native
Flemingia grahamiana Wight & Arn.	Grass	Native
Flueggea virosa (Roxb. ex Willd.) Voigt	Woody	Native
Fuirena pachyrrhiza Ridl.	Herb	Native
Garcinia livingstonei T. Anderson	Woody	Native
Gardenia ternifolia Schumach. & Thonn.	Woody	Native
Gerbera viridifolia (DC.) Sch. Bip.	Grass	Native
Gladiolus melleri Baker	Grass	Native
Gloriosa superba L.	Grass	Native
Gnidia kraussiana Meisn.	Grass	Native
Grewia flavescens Juss.	Woody	Native
Grewia monticola Sond.	Woody	Native
Gymnosporia buxifolia (L.) Szyszyl.	Woody	Native
Gymnosporia senegalensis (Lam.) Loes.	Woody	Native
Haplocarpha scaposa Harv.	Grass	Native
Helichrysum kraussii Sch. Bip.	Woody	Native
Hemizygia bracteosa (Benth.) Briq.	Grass	Native
Herb	Grass	Native

Hermannia glanduligera K. Schum.	Grass	Native
Hermannia quartiniana A. Rich.	Grass	Native
Heteropogon contortus (L.) P. Beauv. ex Roem. & Schult.	Grass	Native
Heteropyxis natalensis Harv.	Woody	Native
Hibiscus kirkii Mast.	Grass	Native
Hibiscus meeusei Exell	Grass	Native
Hippocratea parviflora N.E. Br.	Grass	Native
Holarrhena pubescens (Buch. - Ham.) Wall. ex G. Don	Woody	Native
Hoslundia opposita Vahl	Grass	Native
Huernia hislopii Turrill	Grass	Native
Hyparrhenia filipendula (Hochst.) Stapf	Grass	Native
Hyperthelia dissoluta (Steud.) Clayton	Grass	Native
Hypoxis obtusa Burch. ex Ker Gawl.	Grass	Native
Hypoxis rigidula Baker	Grass	Native
Indigofera astragalina DC.	Grass	Native
Indigofera emarginella Steud. ex A. Rich.	Woody	Native
Indigofera setiflora Baker	Grass	Native
Indigofera tinctoria L.	Woody	Native
Indigofera wildiana J.B. Gillett	Grass	Native
Inula glomerata Oliv. & Hiern	Grass	Native
Ipomoea cairica (L.) Sweet	Grass	Native

Ipomoea hochstetteri House	Grass	Native
Ipomoea obscura (L.) Ker Gawl.	Grass	Native
Ipomoea papilio Hallier f.	Grass	Native
Jasminum multipartitum Hochst.	Woody	Native
Julbernardia globiflora (Benth.) Troupin	Woody	Native
Justicia protracta (Nees) T. Anderson	Grass	Native
Kalanchoe lanceolata (Forssk.) Pers.	Grass	Native
Kalanchoe rotundifolia (Haw.) Haw.	Grass	Native
Kirkia acuminata Oliv.	Woody	Native
Kyllinga alba Nees	Herb	Native
Lannea discolor (Sond.) Engl.	Woody	Native
Lannea edulis (Sond.) Engl.	Grass	Native
Lantana camara L.	Woody	Exotic
Lantana rugosa Thunb.	Woody	Native
Ledebouria zambesiaca (Baker) S. Venter	Grass	Native
Leptactina benguelensis (Welw. ex Benth. & Hook. f.) R. D. Good	Grass	Native
Leucas martinicensis R. Br.	Herb	Exotic
Leucas tettensis Vatke	Grass	Native
Lippia javanica (Burm.f.) Spreng.	Woody	Native
Lippia woodii Moldenke	Grass	Native

Loudetia simplex (Nees) C.E. Hubb.	Grass	Native
Mangifera indica L.	Woody	Exotic
Margaritaria discoidea (Baill.) G.L. Webster	Woody	Native
Mariscus dregeanus Kunth	Herb	Native
Melanthera scandens (Schumach. & Thonn.) Roberty	Grass	Native
Melia azedarach L.	Woody	Exotic
Melinis nerviglumis (Franch.) Zizka	Grass	Native
Melinis repens (Willd.) Zizka	Grass	Native
Microchloa caffra Nees	Grass	Native
Mimusops zeyheri Sond.	Woody	Native
Monotes glaber Sprague	Woody	Native
Mucuna pruriens (L.) DC.	Grass	Native
Mundulea sericea (Willd.) A. Chev.	Woody	Native
Myrothamnus flabellifolius Welw.	Woody	Native
Nidorella resedifolia DC.	Grass	Native
Ochna pulchra Hook.	Woody	Native
Ocimum americanum L.	Grass	Native
Ocimum obovatum Benth.	Grass	Native
Olax dissitiflora Oliv.	Woody	Native
Olea europaea L.	Woody	Native
Opuntia ficus-indica (L.) Mill.	Woody	Exotic

Ormocarpum kirkii S. Moore	Woody	Native
Orthosiphon rubicundus (D. Don) Benth.	Grass	Native
Ozoroa reticulata (Baker f.) R. & A. Fern.	Woody	Native
Panicum maximum Jacq.	Grass	Native
Panicum repens L.	Grass	Native
Parinari curatellifolia Planch. ex Benth.	Woody	Native
Pavetta gardeniifolia Hochst. ex A. Rich.	Woody	Native
Pavetta schumanniana F. Hoffm. ex K. Schum.	Woody	Native
Pellaea calomelanos (Sw.) Link	Grass	Native
Peltophorum africanum Sond.	Woody	Native
Pergularia daemia (Forssk.) Chiov.	Herb	Native
Pericopsis angolensis (Baker) Meeuwen	Woody	Native
Perotis patens Gand.	Grass	Native
Phyllanthus fraternus G.L. Webster	Grass	Native
Phyllanthus maderaspatensis L.	Woody	Native
Phyllanthus reticulatus Poir.	Woody	Native
Piliostigma thonningii (Schumach.) Milne-Redh.	Woody	Native
Pittosporum viridiflorum Sims	Woody	Native
Plumbago zeylanica L.	Grass	Native
Podranea brycei (N.E. Br.) Sprague	Herb	Native
Pogonarthria squarrosa (Roem. & Schult.) Pilg.	Grass	Native

Portulaca oleracea L.	Herb	Exotic
Pouzolzia mixta Solms	Woody	Native
Pseudolachnostylis maprouneifolia Pax	Woody	Native
Psidium guajava L.	Woody	Exotic
Psydrax livida (Hiern) Bridson	Woody	Native
Pterocarpus angolensis DC.	Woody	Native
Pterocarpus rotundifolius (Sond.) Druce	Woody	Native
Pycreus macranthus (Boeck.) C.B.Clarke	Herb	Native
Rauvolfia caffra Sond.	Woody	Native
Rhoicissus revoilii Planch.	Woody	Native
Rhoicissus tridentata (L.f.) Wild & R.B. Drumm.	Herb	Native
Rhus chirindensis Baker f.	Woody	Native
Rhus dentata Thunb.	Woody	Native
Rhus gueinzii Sond.	Woody	Native
Rhus longipes Engl.	Woody	Native
Rhus pyroides Burch.	Woody	Native
Rhynchosia minima (L.) DC.	Grass	Native
Rhynchosia resinosa (Hochst. ex A. Rich.) Baker	Herb	Native
Richardia scabra L.	Herb	Exotic
Ricinus communis L.	Woody	Exotic
Rotheca myricoides (Hochst.) D.A. Steane & Mabb.	Woody	Native

Rothmannia manganjae (Hiern) Keay	Woody	Native
Sansevieria aethiopica Thunb.	Grass	Native
Sarcostemma viminale (L.) R. Br.	Herb	Native
Schistostephium artemisiifolium Baker	Grass	Native
Schkuhria pinnata (Lam.) Thell.	Herb	Exotic
Schotia brachypetala Sond.	Woody	Native
Sclerocarya birrea (A. Rich.) Hochst.	Woody	Native
Securidaca longipedunculata Fresen.	Woody	Native
Senecio coronatus (Thunb.) Harv.	Grass	Native
Senecio latifolius DC.	Grass	Native
Senecio triactinus S. Moore	Grass	Native
Senna singueana (Delile) Lock	Woody	Native
Setaria homonyma (Steud.) Chiov.	Grass	Native
Setaria incrassata (Hochst.) Hack.	Grass	Native
Setaria sphacelata (Schumach.) Moss	Grass	Native
Sida alba L.	Grass	Native
Sida cordifolia L.	Grass	Native
Solanum incanum L.	Herb	Exotic
Solanum nigrum L.	Grass	Native
Sonchus oleraceus L.	Herb	Exotic
Sorghum arundinaceum (Desv.) Stapf	Grass	Native

Sparrmannia africana L.f.	Woody	Native
Spermacoce arvensis (Hiern) Good	Grass	Native
Sporobolus pyramidalis P. Beauv.	Grass	Native
Steganotaenia araliacea Hochst.	Woody	Native
Stereochlaena cameronii (Stapf) Pilg.	Grass	Native
Strychnos cocculoides Baker	Woody	Native
Strychnos spinosa Lam.	Woody	Native
Stylosanthes fruticosa (Retz.) Alston	Grass	Native
Synaptolepis kirkii Oliv.	Woody	Native
Syzygium guineense (Willd.) DC.	Woody	Native
Tabernaemontana elegans Stapf	Woody	Native
Tagetes minuta L.	Herb	Exotic
Tapiphyllum velutinum (Hiern) Robyns	Woody	Native
Tephrosia longipes Meisn.	Grass	Native
Tephrosia purpurea (L.) Pers.	Woody	Native
Terminalia mollis M.A. Lawson	Woody	Native
Terminalia sericea Burch. ex DC.	Woody	Native
Tetradenia riparia (Hochst.) Codd	Woody	Native
Themeda triandra Forssk.	Grass	Native
Thunbergia natalensis Hook.	Grass	Native
Tragia okanyua Pax	Grass	Native

Tragus berteronianus Schult.	Grass	Native
Trema orientalis (L.) Blume	Woody	Native
Trichodesma zeylanicum (Burm. f.) R. Br.	Grass	Native
Tricliceras longepedunculatum (Mast.) R. Fern.	Grass	Native
Tristachya nodiglumis K. Schum.	Grass	Native
Triumfetta annua L.	Grass	Native
Triumfetta rhomboidea Jacq.	Woody	Native
Triumfetta tomentosa Bojer	Woody	Native
Triumfetta welwitschii Mast.	Woody	Native
Turraea nilotica Kotschy & Peyr.	Woody	Native
Tylosema fassoglense (Schweinf.) Torre & Hillc.	Grass	Native
Uapaca kirkiana Müll. Arg.	Woody	Native
Urginea altissima (L.f.) Baker	Grass	Native
Vangueria infausta Burch.	Woody	Native
Vernonia amygdalina Delile	Woody	Native
Vernonia colorata (Willd.) Drake	Woody	Native
Vernonia glaberrima Welw. ex O.Hoffm.	Woody	Native
Vernonia glabra (Steetz) Vatke	Grass	Native
Vernonia oligocephala (DC.) Sch. Bip. ex Walp.	Grass	Native
Vigna unguiculata (L.) Walp.	Grass	Native
Vitex mombassae Vatke	Woody	Native

Waltheria indica L.	Grass	Native
Xanthocercis zambesiaca (Baker) Dumaz-le-Grand	Woody	Native
Xerophyta equisetoides Baker	Herb	Native
Ximenia americana L.	Woody	Native
Ximenia caffra Sond.	Woody	Native
Xysmalobium undulatum (L.) W.T. Aiton	Grass	Native
Ziziphus mucronata Willd.	Woody	Native
Zornia glochidiata C. Rchb. ex DC.	Grass	Native

Appendix C: Gwanda Beitbridge data

Species Name	**Life form**	**Status**
Acanthospermum hispidum	herb	exotic
Achyranthes aspera	herb	exotic
Ageratum conyzoides	herb	exotic
Alternanthera coracasana	herb	exotic
Alternanthera pungens	herb	exotic
Argemone mexicana	herb	exotic
Bidens pilosa	herb	exotic
Bidens schimperi	herb	exotic
Conyza bonariensis	herb	exotic
Cyathula cylindrica	herb	exotic
Gomphrena celosiodes	herb	exotic
Lantana camara	woody	exotic
Leucus martinicensis	herb	exotic
Ocimum incanum	herb	exotic
Opuntia ficus-indica	woody	exotic
Portulaca kermesina	herb	exotic
Portulacca quadrifida	herb	exotic
Pupalia lappacea	herb	exotic
Richardia scabra	herb	exotic

Schkuhria pinnata	herb	exotic
Sorghum bicolor	Grass	exotic
species	lifeform	status
Tagetes minuta	herb	exotic
Zea mays	Grass	exotic
Aristida barbicorlis	grass	native
Aristida congesta	grass	native
Aristida congesta subsp. barbicollis	grass	native
Aristida rhiniochloa	grass	native
Aristida scabrivalvis	grass	native
Aristida stipitata	grass	native
Brachiaria deflexa	grass	native
Brachiaria eruciformis	grass	native
Cenchrus ciliaris	grass	native
Chloris virgata	grass	native
Cleistachne sorghoides	grass	native
Cynodon dactylon	grass	native
Dichrostachys cinerea	grass	native
Digitaria eriantha	grass	native
Digitaria eruciformis	grass	native
Digitaria milanjiana	grass	native

Digitaria ternata	grass	native
Digitata ternata	grass	native
Elionurus muticus	grass	native
Enneapogon cenchroides	grass	native
Enteropogon macrostachys	grass	native
Enteropogon macrostachyus	grass	native
Eragrostis aspera	grass	native
Eragrostis cylindriflora	grass	native
Eragrostis inamoena	grass	native
Eragrostis patens	grass	native
Eragrostis plana	grass	native
Eragrostis racemosa	grass	native
Eragrostis sclerantha	grass	native
Eragrostis superba	grass	native
Eragrostis ternufolia	grass	native
Eragrostis viscosa	grass	native
Eragrostis volkensii	grass	native
Evolvulus alsinoides	grass	native
Geigeria burkei	grass	native
Heteropogon contortus	grass	native
Hyparrhenia filipendula	grass	native

Hyperthelia dissoluta	grass	native
Imperata cylindrica	grass	native
Melinis kallimorpha	grass	native
Melinis nerviglumis	grass	native
Melinis repens	grass	native
Microchloa caffra	grass	native
Ocimum incanum	grass	native
Panicum maximum	grass	native
Panicum repens	grass	native
Perotis patens	grass	native
Pogonarthria squarrosa	grass	native
Schimidtia pappophoroides	grass	native
Setaria pumila	grass	native
Setaria sphacellata	grass	native
Setaria sphacellata	grass	native
Setaria vericillata	grass	native
Sporobolus festivus	grass	native
Sporobolus pyramidalis	grass	native
Sporobolus stapfii	grass	native
Stipagrostis uniplumis	grass	native
Tetrapogon tennelus	grass	native

Tragus berteronianus	grass	native
Urochloa mosambicensis	grass	native
Urochloa mosambicensis	grass	native
Abutilon angulatum	herb	native
Abutilon fruticosum	herb	native
Abutilon fruticosum	herb	native
Abutilon rehmannii	herb	native
Abutilon rehmannii	herb	native
Acalypha ornata	herb	native
Acanthospermum hispidum	herb	native
Acanthospermum hsipidum	herb	native
Adenia gumifera	herb	native
Agathisanthemum bojeri	herb	native
Aloe chabaudii	herb	native
Aloe zebrina	herb	native
Amaranthus thunberii	herb	native
Ammannia auriculata	herb	native
Ampelocissus africana	herb	native
Aptosimum lineare	herb	native
Aristida congesta subsp. barbicollis	herb	native
Asparagus africanum	herb	native

Asparagus africanus	herb	native
Asparagus laricinus	herb	native
Asparagus plumosus	herb	native
Asparagus suaveolens	herb	native
Blepharis aspera	herb	native
Blepharis diversifolia	herb	native
Blepharis diverspina	herb	native
Blepharis maderaspatensis	herb	native
Ceratotheca triloba	herb	native
Chamaecrista mimosioides	herb	native
Chloris pycnothrix	herb	native
Chlorophytum subpetiolatum	herb	native
Cissus quadrangularis	herb	native
Cleistachne sorghoides	herb	native
Clerodendron ternatum	herb	native
Clerodendrum ternata	herb	native
Commelina africana	herb	native
Commelina benghalensis	herb	native
Commelina eckloniana	herb	native
Corchorus tridens	herb	native
Corchorus olitorius	herb	native

Corchorus tridens	herb	native
Crabbea velutina	herb	native
Cucumis anguria	herb	native
Cyathula cylindrica	herb	native
Dicerocaryon senecioides	herb	native
Dicoma anomala	herb	native
Dicoma gerradii	herb	native
Dyschoriste matopensis	herb	native
Enneapogon cenchroides	herb	native
Eragrostis inamoena	herb	native
Eragrostis nindensis	herb	native
Eragrostis patens	herb	native
Euphorbia glanduligera	herb	native
Euphorbia prostrata	herb	native
Evolvulus alsinoides	herb	native
Geigeria burkei	herb	native
Geigeria filifolia	herb	native
Helichrysum argyrosphaerum	herb	native
Helichrysum nudifolium	herb	native
Hemizygia elliottii	herb	native
Hermannia kirkii	herb	native

Hermbstaedtia fleckii	herb	native
Hibiscus guandensis	herb	native
Hibiscus micranthus	herb	native
Hibiscus praeteritus	herb	native
Hibiscus pusillus	herb	native
Indigofera arrecta	herb	native
Indigofera astragalina	herb	native
Indigofera setifera	herb	native
Indigofera spicata	herb	native
Indigofera wildiana	herb	native
Ipomoea obscura	herb	native
Justicia prostrata	herb	native
Justicia protracta	herb	native
Kahourtia cynanchica	herb	native
Kalanchoe lanceolata	herb	native
Kalanchoe rotundifola	herb	native
Kohautia cynanchica	herb	native
Kyllinga alba	herb	native
Kymphocarpa angustifolia	herb	native
Lantana rugosa	herb	native
Leonotis nepetifolia	herb	native

Leucus neuflizeana	herb	native
Macrotylomma africanum	herb	native
Melhania forbesii	herb	native
Melhania randii	herb	native
Melharnia randii	herb	native
Melinis nerviglumis	herb	native
Monechma debile	herb	native
Mormodica balsamina	herb	native
Myrothamnus flabellifolius	herb	native
Ocimum incanum	herb	native
Oxalis obliquifolia	herb	native
Oxygonum sinuatum	herb	native
Passiflora subpeltata	herb	native
Pavonia burchellii	herb	native
Pavonia burchellii	herb	native
Pellaea calomelanos	herb	native
Persicaria senegalensis	herb	native
Phyllanthus maderaspatensis	herb	native
Plumbago zeyhlanica	herb	native
Polygala sphenoptera	herb	native
Ptycholobium contortum	herb	native

Pupalia lappacea	herb	native
Rhoicissus tridentata	herb	native
Rhynchosia minima	herb	native
Rhynchosia resinosa	herb	native
Scadoxus multiflorus	herb	native
Sida alba	herb	native
Sida cordifolia	herb	native
Solanum catombelensis	herb	native
Solanum delagoense	herb	native
Solanum incanum	herb	native
Spermacoce senensis	herb	native
Tephrosia noctiflora	herb	native
Tephrosia purpurea	herb	native
Tephrosia villosa	herb	native
Tragia okanyua	herb	native
Triumfetta annua	herb	native
Triumfetta rhomboidea	herb	native
Tylosema fassoglense	herb	native
Vernonia poskeana	herb	native
Vigina unguiculata	herb	native
Vigna luteola	herb	native

Vigna unguiculata	herb	native
Waltheria indica	herb	native
Zornia glochidiata	herb	native
Bulbostylis macra	herb	native
Cyperus denudatus	herb	native
Cyperus rotundus	herb	native
Fuirena pachyrrhiza	herb	native
Kyllinga alba	herb	native
Schoenoplectus corymbosus	herb	native
Acacia karroo	woody	native
Acacia melifera	woody	native
Acacia mellifera	woody	native
Acacia nilotica	woody	native
Acacia rehmanniana	woody	native
Acacia senegal	woody	native
Acacia tortilis	woody	native
Acalypha pubiflora	woody	native
Adansonia digitata	woody	native
Afzelia quanzensis	woody	native
Albizia amara	woody	native
Albizia anthlemintica	woody	native

Albizia harveyi	woody	native
Aloe excelsa	woody	native
Azanza garckeana	woody	native
Berchemia discolor	woody	native
Berchemia zeyheri	woody	native
Boscia albitruncata	woody	native
Boscia foetida	woody	native
Boscia salicifolia	woody	native
Bridellia mollis	woody	native
Capparis tomentosa	woody	native
Cassia abbreviata	woody	native
Catophractes alexandri	woody	native
Catunaregum obovata	woody	native
Clerodendron erythrophyllum	woody	native
Clerodendron myricoides	woody	native
Clerodendron ternatum	woody	native
Colophospermum mopane	woody	native
Combretum apiculatum	woody	native
Combretum hereroense	woody	native
Combretum imberbe	woody	native
Combretum molle	woody	native

Combretum mosambicensis	woody	native
Commiphora edulis	woody	native
Commiphora glandulosa	woody	native
Commiphora merkerii	woody	native
Commiphora mollis	woody	native
Commiphora mosambicensis	woody	native
Commiphora mossambicensis	woody	native
Commiphora mossambiscensis	woody	native
Commiphora pyracanthoides	woody	native
Cordia grandicalyx	woody	native
Cordia monoica	woody	native
Dalbergia melanocarpus	woody	native
Dalbergia melanoxylon	woody	native
Dichrostachys cinerea	woody	native
Diospyros lycioides	woody	native
Diospyros mespliformis	woody	native
Dombeya rotundifolia	woody	native
Ehretia amoena	woody	native
Elephantorhiza goetzei	woody	native
Euclea divinorum	woody	native
Euclea natalensis	woody	native

Euphorbia ingens	woody	native
Ficus abutilifolia	woody	native
Ficus cordata	woody	native
Flueggea virosa	woody	native
Gardenia resinosa	woody	native
Gardenia ternifolia	woody	native
Grewia amoena	woody	native
Grewia bicolor	woody	native
Grewia flavescens	woody	native
Grewia villosa	woody	native
Gymnosporia heterophylla	woody	native
Gymnosporia senegalensis	woody	native
Hexalobus monopetalus	woody	native
Kirkia acuminata	woody	native
Lantana rugosa	woody	native
Lippia javanica	woody	native
Magaritaria discoidea	woody	native
Makharmia zanzibarica	woody	native
Margaritaria discoidea	woody	native
Markhamia zanzibarica	woody	native
Melhania forbesii	woody	native

Mimusops zeyheri	woody	native
Mundulea sericea	woody	native
Ormocarpum kirkii	woody	native
Ormorcapum kirkii	woody	native
Ozoroa reticulata	woody	native
Pappea capensis	woody	native
Pavetta gardeniifolia	woody	native
Pavetta schumanniana	woody	native
Peltophorum africanum	woody	native
Philenoptera violacea	woody	native
Phyllanthus reticulatus	woody	native
Poulsolzia mixta	woody	native
Psydrax livida	woody	native
Pterocarpus angolensis	woody	native
Pterocarpus rotundifolia	woody	native
Rhigosum zambesiacum	woody	native
Rhoicissus revolii	woody	native
Rhus lancea	woody	native
Rhus leptodictya	woody	native
Rhygosum zambesiacum	woody	native
Sclerocarya birrea	woody	native

Senna singuena	woody	native
Sericanthe andongensis	woody	native
Spirostachys africana	woody	native
Steganotaenia araliacea	woody	native
Sterculia rogersii	woody	native
Strychnos madagascariensis	woody	native
Strychnos madascarienses	woody	native
Strychnos potatorum	woody	native
Terminalia prunoides	woody	native
Terminalia sericea	woody	native
Tinnea rhodesiana	woody	native
Vangueria infausta	woody	native
Xeminea americana	woody	native
Xeminia americana	woody	native
Xeminia caffra	woody	native
Ximenia americana	woody	native
Zanthoxylum humile	woody	native
Ziziphus mucronata	woody	native