

**ECOLOGY AND MANAGEMENT OF SAVANNA
VEGETATION IN SARISKA TIGER RESERVE
RAJASTHAN, INDIA**

Thesis submitted to the
Forest Research Institute University
Dehra Dun, Uttarakhand

FOR
THE AWARD OF THE DEGREE OF
DOCTOR OF PHILOSOPHY
IN FORESTRY
(ENVIRONMENT MANAGEMENT)



By

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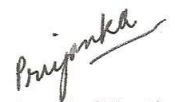
“In the end, our society will be defined not only by what we create, but by what we refuse to destroy” - J. C. Sawhill

DECLARATION


I hereby declare that the thesis entitled "Ecology and Management of Savanna Vegetation in Sariska Tiger Reserve, Rajasthan" submitted to Forest Research Institute (Deemed) University, Dehradun, for the award of the degree of Doctor of Philosophy in Forestry (Environment Management), is a record of original research work done by me under the supervision of Dr. G. S. Rawat, Scientist-G, Wildlife Institute of India, Dehradun and under the co-supervision of Dr. K. Sankar, Scientist-G, Wildlife Institute of India, Dehradun and it does not form the basis for the award of any other degree or diploma.


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CERTIFICATE

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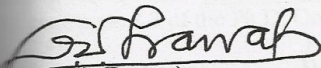

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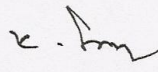
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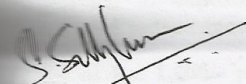
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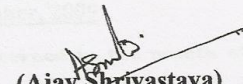
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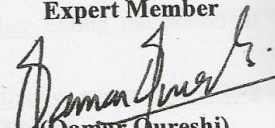

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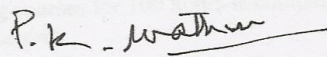

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Finally, the day has come when I am happily writing this page but it doesn't seem that I would be able to do justice in such a short space. So much has happened in these three years that when I look back, it didn't seem achievable when I had started but with the help and guidance of a lot of people it has finally taken shape.

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Concluding this it is needless to say that omissions and errors, if any, are solely mine and I beseech advance apologies for any and all of them.

(Priyanka Bhatt)

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ABBREVIATIONS

PA: Protected Area

PAM: plant available moisture

PAN: plant available nutrients

STR: Sariska Tiger Reserve

GEST: Global Experiments on Savanna Tree seedlings

SH: State Highway

IVI: Importance Value Index

GBH: Girth at Breast Height

MBA: Mean Basal Area

TBA: Total Basal Area

WII: Wildlife Institute of India

NTFP: Non Timber Forest Product

ANOVA: Analysis of Variance

AIP: Alien Invasive plant

NIP: Native Invasive plant

GPS: Global Positioning System

VDC: Village Development Committee

1.1 Background

Until recently Savanna vegetation was assumed to be limited to African sub-continent. The first studies regarding the presence of this type of vegetation in India dates back to the post- independence era (Yadava, 1990; Misra, 1983; Meher-Homji, 1989; Gadgil & Homji, 1985). While savanna vegetation still does not have a universal definition and composition, the scholars continue to describe it in their respective ways (Table 1.1) based on geographical distinction. Savannas are characterized by a continuous herbaceous layer dominated by grasses and a discontinuous cover of shrubs and trees (Huntley & Walker, 1982; Frost *et al.*, 1986). A savanna is a tropical or subtropical grassland containing scattered trees and drought-resistant undergrowth, the term savanna is believed to have originally come from an Arawak word describing "land which is without trees but with much grass either tall or short" (Oviedo y Valdes, 1535) and by the late 1800s it was used to mean "land with both grass and trees". It now refers to land with grass and either scattered trees or an open canopy of trees. Savannas are found on all the habitable continents of the world (Cole, 1986; Sims, 1988; Scholes & Archer, 1997; Eva *et al.*, 1998; Specht & Specht, 1999; Stibig & Beuchle, 2003). Throughout the world savanna vegetation has variable physiognomy and floristic composition, the result of independent evolution of savanna vegetation on different continents from a host of plant genera in response to local environmental conditions. The physiognomy of savanna ranges from open grasslands with few or no trees, through grasslands with scattered trees (low shrub savannas, parklands) to tall woodlands underlain by grass, to thicket and scrub, where little grass remains (Cole, 1986). Savannas have been broadly subdivided based on the stature, canopy cover and arrangements of woody elements. "Savanna grasslands" contain widely scattered trees or shrubs, and these may grade into "tree savanna", "shrub savanna" or "savanna woodland".

The definition of savannas, as communities with trees distributed in a continuous layer of grass, is rather general and can be used to describe vegetation communities from the tropics to the taiga. From a global perspective, there are large changes in the physiognomy of savanna communities, both across and within continents substantially due to differences in the physical environments. Savannas are among the strikingly most important vegetation types where contrasting life forms co-dominate. Tropical savannas

cover about an eighth of the global land surface (Scholes & Hall, 1996), covering over half the area of Africa and Australia, 45% of South America and 10% of India and Southeast Asia (Werner, 1991) and have a net primary production close to that of the equatorial forests, but with only about one tenth of the standing biomass (Hall & Scurlock, 1991). They are geographically extensive and socio-economically important in tropical and temperate regions (Anderson *et al.*, 1997; Burgess, 1995; McPherson, 1997; Tothill & Mott, 1985; Young & Solbrig, 1993). They are host to approximately one-fifth of the world's population (Young & Solbrig, 1993), a fact that signifies an increasing effect of human impact and extraction practices (e.g. agriculture) on savanna systems. The main economic enterprise in savannas is pastoralism, and rangelands cover significant areas of savannas are for agricultural crops (with attendant human settlements) and for wildlife/wilderness reserves (often with significant tourism enterprises) (Werner, 1990). Despite this, the cerrado (Brazilian savanna) and tropical savannas in general have received very little interest from scientists in comparison to the tropical forests (e.g. Amazonian forests, Furley, 1999). The stability of the savanna ecosystem is maintained by the fact that they use different sources of water in the soil (Walter, 1971). Grasses are more efficient than trees in extracting water from the upper layers of the soil whereas trees make use of deeper water levels. The herbaceous layer occurs partially outside the influence of the rooting zone of the woody component, and partially in direct interaction with the lateral roots of the woody plants. Thus competition for water between these two components is an essential element of many savanna models (Walter, 1971; Walker *et al.*, 1981; Walker & Noy-Meir 1982; Walker, 1987). However, Weltzin & Coughenour (1990) stated that by emphasizing competition in these models, one has not considered that trees may facilitate understorey herbaceous growth (Radwanski & Wickens, 1967; Kellmann, 1984), and in fact influence the overall species composition. Savanna trees and shrubs may reduce the sub-canopy solar radiation by 45% to 60% (Tiedemann & Klemmedson, 1977; Belsky *et al.*, 1989; Georgiadis, 1989). This may lower the soil temperature and evapo- transpiration, which may subsequently increase the soil moisture content. Reduced sub-canopy soil temperature has been shown in a desert area (Shreve, 1931), in arid grassland (Tiedemann & Klemmedson, 1977), and in semi-arid savanna (Belsky *et al.*, 1989; Georgiadis, 1989). Facilitation from nurse plants (e.g. the thorny shrub *Rosa rubiginosa* L.) is an important process for natural tree establishment in wood-pastures as tree saplings frequently die due to cattle activity (Smit *et al.*, 2006), particularly when grazing intensity is high (Vandenberghe *et al.*, 2007). The probability of a sapling being browsed and killed as a result depends on grazing intensity (Hester *et al.*, 1996) and browsing resistance of the species (Hester *et al.*, 2006). Resistance includes appearance (e.g. size or structure), mechanical or chemical defences (e.g. stiff needles, secondary compounds) and specific intrinsic abilities (i.e. tolerance) to survive and re-grow after biomass loss under different environmental conditions (Boege & Marquis, 2005; Rosenthal & Kotanen, 1994). Factors that reduce soil water content are likely to increase competition intensity in these environments, while factors that increase soil water content will favour seedling success through decreased competition for water with herbaceous vegetation (Davis *et al.*, 1998). The theory that the majority of savannas are simply a

transient landscape, continuously moving towards either forest or pure grassland, is easily dispelled with fossil evidence indicating that the present global savanna distribution has shown marked persistence in the historical record, at least since the mid-Pliocene (van der Hammen, 1983; Cole, 1986). Since savannas support a large proportion of world's human population and a majority of its rangeland and livestock (Scholes & Archer, 1997), understanding the role of herbivores in vegetation patterning in these ecosystems is urgently required (Sankaran *et al.*, 2005), moreover because savannas are among the ecosystems that are most sensitive to future changes in land use and climate (Sala *et al.*, 2000; Bond *et al.*, 2003; House *et al.*, 2003).

The Indian savannas are majorly a product of degradation of forest lands and formation of farmlands (Misra, 1983). These are maintained by shifting cultivation, grazing, burning and deforestation. If these biotic influences are effectively withdrawn, the savanna will pass on to the forest in the process of secondary succession. Since the climatic climax of India is forest (Champion & Seth, 1968) the tropical savannas are recognised as stages of forest degradation or dis-climax in terms of succession theory (Misra, 1946), which remain stabilised through grazing and periodic burning (Misra, 1987). In India, the savanna vegetation is largely distributed in the semi-arid tracts of western, central and southern peninsula. Sariska Tiger Reserve, Rajasthan (western) India, is one of the few protected areas (PAs) where natural savannas can be seen which also support a considerable biomass of native herbivores. These grasslands are also important as cover for carnivores in the Tiger Reserve. For the scientific management of natural savanna ecosystem within such PAs, it would be important to establish the ecological status of savanna vegetation and ascertain community structure and composition.

Table 1.1 A typology of commonly used savanna related terminology (Foxcroft *et al.* 2010)

Term	Geographical distribution	Meaning
Cerrado	Brazil	The Brazilian cerrados comprise a gradient from the grassland form (named 'campo limpo') to a sclerophyllous woodland form (named 'cerradão'), where the herbaceous layer gives place to arboreal elements, and the most apparent variation is in tree density and height. The intermediate ecotonal scrub forms are: 'campo sujo', 'campo cerrado' and 'cerrado sensu stricto', in an increasing density of trees. In cerradão, the canopy cover is *30–60%; in cerrado sensu stricto *30–40%; in campo cerrado, *10%; in campo sujo, up to 1%, and there is no tree cover in campo limpo.
Caatinga	Brazil	Caatinga is found in northeastern Brazil and has a characteristic semiarid climate with average precipitation of 800 mm/annum. The vegetation is

		largely xerophytic, spiny and caducifoliate. The term Caatinga is means “white forest”, and is often referred to as dry or scrub forest.
Llanos	Colombia and Venezuela	Los Llanos (meaning the flat plains) is a vast tropical grassland plain situated at the east of the Andes in north-western South America. Because of infertile sandy soils and regular flooding, this area represents anomalously low plant species richness in the tropics.
Pastizal	Mexico	In the most commonly used classification of Mexican vegetation, all grassland types, both natural and induced, from both tropical and temperate regions, were clumped together into a single category-pastizal-meaning grassland.
Pine savanna	USA	Characterized by an open canopy of pines (<i>Pinus palustris</i> P. Mill. and/or <i>P. elliottii</i> Engelm.) and a diverse understorey of grasses and forbs maintained by frequent fires. Further characteristics include wet soils of low pH and relatively low nutrients.
(Blue) Oak savanna	Coastal ranges and foothills of the Sierra Nevada in California	An oak savanna is a plant community with scattered “open-grown” oaks. Other terms for these savannas are “oak openings” and “oak barrens”. The savanna canopy ranges from about 10 to 50%. In such a habitat, the ground layer receives dappled sun and shade, which permits growth of a wide diversity of grasses and flowering plants. This is one of the Californian communities that is most invaded by alien plant species.
Mesic savanna	Southern Africa	Moist savanna systems, generally between 600 and 1500 mm rainfall per annum, found largely in the eastern parts of southern Africa; similar to fine leaved savanna.
Arid savanna	Southern Africa	Relatively arid regions with generally between 400 and 800 mm rainfall per annum, found largely in the western parts of southern Africa; similar to broad leaved savanna Fine leaved (nanophyllous) Southern Africa Nutrient rich, arid regions give rise to the fine leaved (nanophyllous) savanna Broad leaved (mesophyllous) Southern Africa Nutrient poor, moister regions give rise to the broadleaved (mesophyllous) savannas.
Grass and shrub savanna	North and eastern Africa	Savanna type stretching across northern Africa, from northern Senegal and Mauritania to Sudan. The northern border (the Sahel) is dominated by <i>Acacia</i> . It continues into the <i>Acacia-Commiphora</i> savanna of the horn of Africa, eastern Ethiopia, and east Africa as the Somali-Masai dry savanna.
Tree and shrub savanna	Central Africa	Two separated blocks of vegetation, lying north and south of the rainforest and miombo woodland savannas of central Africa. The northern area is dominated by <i>Terminalia</i> and <i>Combretum</i> trees and shrub and <i>Pennisetum purpureum</i> grass. The southern section is dominated by <i>Colophospermum mopane</i> tree and shrubs.
Woodland savanna	Central/South Africa	Two distinct blocks of savanna, namely, Miombo (central/south Africa), which is dominated by <i>Brachystegia boehmii</i> , and doka (in the north),

		which is dominated by <i>Isobertinia doka</i> .
Forest-savanna mosaic	Africa	Encircles the tropical rainforest of the Congo basin, forming the edge of the 'true' savanna. Highly dynamic vegetation, interlacing forest, savanna and grassland.
Tropical savanna	Australia	The Australian tropical savannas are landscapes of dense grass and scattered trees that stretch across northern Australia from Broome to Townsville. They cover a huge area—around 1.9 million square kilometres—or around a quarter of mainland Australia's land area.

1.2 Literature Review:

Whilst many aspects of savanna functioning remain poorly understood (Jeltsch *et al.*, 2000), most authors agree that a subset of four interacting factors determine the balance of trees and grasses. These factors were plant available moisture (PAM), plant available nutrients (PAN), fire and herbivory (Frost & Robertson, 1987; Medina, 1987; Walker, 1987; Scholes & Archer, 1997). Belsky *et al.*, (1989) and Georgiadis (1989) remarked that interactions between the trees and the field layer were little discussed in savanna literature.

According to Scholes & Archer (1997) and Breshears (2006), savanna trees were important for structuring understory plant communities through their modification of understory microclimate especially understory light and soil moisture, soil nutrients, and species composition. Through direct influences on microclimate and indirect effects on competing understory plants, savanna trees also affected tree regeneration. However, impacts varied according to water availability and savanna trees may have facilitated seedling survival below canopies in more xeric savannas (Borchert *et al.*, 1989; Hoffmann, 1996; Weltzin & McPherson, 1999) or limited recruitment to inter-canopy gaps by out-competing seedlings, as was often true in more mesic savannas (Borchert *et al.*, 1989; Rebertus & Burns, 1997; Holmgren *et al.*, 2000). Several studies suggested that below rather than aboveground competition had the greatest influence on woody plant seedling establishment in grass-dominated patches (Adams *et al.*, 1992; McPherson, 1993; Wilson, 1993a, b, 1998). A review and comparison of savannas and determinants of their physiognomic structures on a broader scale by Belsky (1992) suggested that woody plant to grass ratio changed across gradients of precipitation and/or nutrients. Shade might have been an important factor here in determining the occurrence of herbs under bushes. In a shade experiment performed at Tanzania, it was shown that herbs were more tolerant to shade than open grassland grasses. When *Acacia tortilis* trees started to grow, the first major environmental change for under storey herbaceous species was shade and this light reduction probably caused the open grassland species to disappear which were then replaced by herbs (Ludwig, 2001).

Scholes & Archer (1997) did a detailed work on the effects of trees on herbaceous species composition, phenology, production and biomass allocation. They reported a positive interaction between the two in terms of amelioration of harsh environmental conditions and increased resource availability for herbaceous layer. A five year study by Belsky (1992) revealed that the vegetatively reproducing species benefited more than sexually reproducing species from protection from grazing. Grime (1979, 1985 & 1988) gave a C-S-R model stating that the intensity of competition (C) increased as disturbance (R) and stress (S) declined. Hibbard *et al.*, (2003) suggested that in many of the world's semi arid regions human-induced alteration of grazing and fire regimes over the past century had promoted the replacement of grasses by woody vegetation. Clements (1928), well known for his classification of innumerable vegetation communities, indicated in his book "Plant Succession and Indicators" that the transition from savanna to woodland was gradual, and it was impossible to draw a sharp line between the two.

Though very little ecological studies have been done on Indian savanna, a few authors have opined that savannas of north eastern India have been derived following the destruction of the forests through shifting cultivation, burning and grazing practices (Yadava, 1990). It is apparent from a review of Indian literature on savannas that much more work is needed to understand their structural and dynamic relationships under the abiotic and biotic stresses in relation to the total resilience of the system

1.3 Conservation issues and information gaps

With the establishment of Sariska Tiger Reserve (STR), the tourism industry has increased manifold. The local people continue to live within the core areas of the reserve violating regulatory laws. They being completely dependent on the forest for their daily needs have serious issues with the management for relocating to non-forested areas and turning to alternate income sources. A lack of regeneration in major community species, invasion of exotic species resulting in replacement of native vegetation and loss of biodiversity is an inevitable result of these changes. A substantial amount of studies have been conducted at the site but are more focussed on the faunal diversity of the area rather than floral diversity hence leading to existence of major research gaps in the STR pertaining to studies of vegetation dynamics particularly in the savanna type of vegetation in the valley area.

The lack of regeneration and its causes led us to the research on tree seedling growth in savannas which would eventually help to resolve whether the recruitment bottleneck was mediated by disturbance and resource availability alone, or whether competition with the grass layer further limited the recruitment. Comparative studies of the seedling growth of multiple species abundant at different positions along environmental gradients would tell us whether and how species have adapted to local resource conditions and whether these adaptations have affected their ability to grow in competition with grasses. Unfortunately, worldwide research on tree seedling growth of savanna species is largely descriptive

(Tomlinson *et al.* in lit.), focusing on spatio-temporal patterns of seedling recruitment in response to disturbance events such as fire and herbivory (e.g. Hoffmann, 1996; Bond *et al.*, 2001; Li *et al.*, 2003), or on the consequences of seed characteristics for seedling demography and growth such as dispersal mechanisms (e.g. Barot *et al.*, 1999; Goheen *et al.*, 2004) and seed size (Khurana & Singh, 2000). Less research has involved formal experiments designed to elucidate the relative importance of different resources to seedling growth, or the relative importance of competitive inhibition versus resource limitation for growth of seedlings (Davis *et al.*, 1998; Brown & Archer, 1999; Gordon & Rice, 2000; Kanegae *et al.*, 2000; Kraaij & Ward, 2006; Dickie *et al.*, 2007). Differences in these strategies would have important consequences for the manner of tree-grass interactions in local savanna assemblages, and for the generality or specificity of management applied to direct the development of those savannas. If differences in ability to compete with grass species are associated with continents (presumably as a consequence of biogeography) this would have consequences for the invasibility of continental savannas by foreign species. In spite of the apparent environmental and potential continental differences, there do not appear to have been any comparative studies of savanna seedling growth across species occupying different positions along gradients of soil fertility and water availability within continents, and consequently little is known about how growth strategy at this stage may advantage tree seedlings across these gradients, or how these growth strategies are modified by local biotic influences (Tomlinson *et al.*, in prep.). There also do not appear to have been any comparisons of tree seedling growth between continental savannas designed to investigate whether species on different continents show consistent growth responses associated with their environment of abundance, or whether there are consistent differences, either due to phylogeny, competition with local grass species, or differences in defoliation pressure. Given the diversity of selection pressures faced by savanna tree seedlings both within and across continents, Wageningen University formulated to conduct a worldwide project to disseminate the relative importance of different resources - water, nutrients, light to the growth of tree seedlings, how their growth is affected by competition from local grasses, and whether their growth has been modified in response to defoliation pressures. This project was known as Global Experiments on Savanna Tree Seedlings (GEST) and Sariska TR was chosen to be the dry savanna site for the Asian continent. This experiment forms part of this thesis.

This study is aimed to document the role of various abiotic and biotic factors playing a vital role in the co-existence of trees and grasses. Attempts have been made to bridge the research gaps related to the structure and composition of forest vegetation, phenology diversity and regeneration patterns along the landscape. Hence, present study was initiated with a view to collect baseline data that would be helpful in monitoring the forest changes in future.

1.4 Study Objectives

- To study the structure, composition and factors affecting the savanna vegetation in Sariska Tiger Reserve
- To study the phenology of savanna species
- To study the aut-ecology of dominant savanna grasses and tree species of Sariska with reference to biotic and abiotic factors
- To study the impact of invasive species and management implications: case study of *Adhatoda vasica*

1.5 Study period

The field work for this study was conducted from April 2009 to June 2011 at Sariska Tiger Reserve, Rajasthan.

1.6 Organization of thesis

This thesis consists of 7 chapters; the first chapter Introduction, which provides information about the savanna vegetation and the dynamics and the objectives of the study. Chapter 2 gives an insight about the study area, physical features and its natural floral and faunal composition. Chapter 3 deals with the vegetation composition, species diversity, richness and other phyto- sociological parameters. Chapter 4 provides the findings about phenological studies on the major tree, shrub and grass species of the study area. Savanna experiment and its methods and results are enlisted in chapter 5. Chapter 6 is dedicated to the invasion of *Adhatoda vasica* and the implications of management practices over two productive years and further recommendations. References are listed in Chapter 7.

Along with the above mentioned chapters, the thesis also includes the results of ANOVA, a list of plants recorded from the study area during the study period, colour plates, maps, design of the experiment and figures.

Chapter 2

STUDY AREA

2.1 Introduction

The study was conducted at Sariska Tiger Reserve (STR), western India. The area was a hunting reserve of the erstwhile princely state of Alwar before being declared as a Sanctuary in 1958. It was included in the list of Tiger Reserves by Government of India in 1978 as the 11th Tiger Reserve. In 1982, an area of 274 km² was declared as Sariska National Park vide Preliminary Notification No. F.11 (22) Raj-8/78 JPR dated 27 August 1982 under Wild Life Protection Act 1972 (Central Act No. 53) section 35 (1). It is the third largest protected area among the 93 protected areas in India's semi arid bio-geographic region (Rodgers & Panwar, 1988). It is about 110 km from Jaipur on Jaipur-Alwar State Highway (Plate 2.1). Tourism in Sariska is of miscellaneous nature based on religious, cultural, scholastic, scientific, casual and specialized (Sharma, 1983). The 9th and 10th century ruins of the Siva temple of Garh Rajor, the medieval fort of Kankwari, the temple of Mahavira at Neelkanth, ruins of ancient structures at Ajabgarh and Bhangarh (Plate 2.2, 2.3) and the temple of Pandupole believed to be from the Mahabharata era are evidence of a rare amalgamation of natural history and archaeology (Parmar, 1985). The name Sariska, has been derived from Siris tree (*Albizzia lebbek*) that was once abundant in the area.

2.2 Topography

The topography of undulating plateau- lands and wide valleys otherwise unknown in the Aravalli system constitute the major part of the reserve of Sariska. Still the hills maintain the Aravalli character of sharp hogback ridges (Sharma, 1983). It is situated between Longitude 79°17'N to 76°34' N and Latitude 27° 5' E to 27° 33' E covering an area of 881 km², with 274 km² as a notified National Park (Figure 2.1). The major part of the area is occupied by rocks of the pre-Cambrian era comprised of Banded Gneissic Complex, Delhi system and Aravalli system of quartzites, conglomerates, grits, limestone, phyllite, granites and schists (Pascoe, 1950; Sankar, 1994). STR is characterized by rugged terrain, valleys and plateaus with the altitudinal variation from 540 m to 777 m. The hills are homogeneous, regular in height, level summits and uniform in appearance stretching out from north-east to south-west in more or less parallel lines. The two main plateaus are *Kankawari* and *Kiraska* which holds the Sariska valley and the characteristic savanna vegetation within. The study area is bisected by Alwar Thanaghazi- Jaipur state highway (SH-13) and Sariska-Kalighati-Tehla-Dausa state highway (SH-29A) (Sankar, 1994). The depth of the soil layer is more than 1 m in valleys, whereas it is only a few centimetres deep on the hill slopes. The soil is sandy loam and alkaline with pH varying from 7.25 to 8 (Yadav & Gupta, 2006).

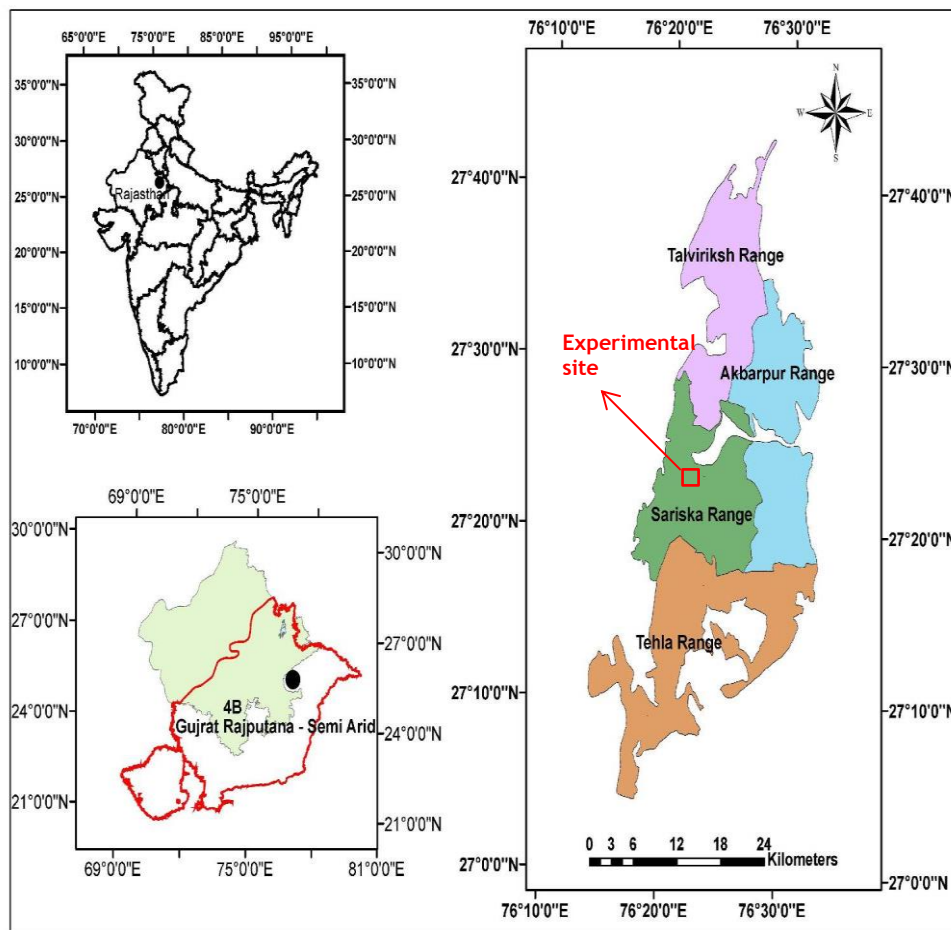


Figure 2.1 Study Area: Sariska Tiger Reserve (STR) and location of Global Experiments on Savanna Tree Seedlings (GEST) site

2.3 Climate

Although, latitudinally the study area falls under sub-tropical zone, climatically it reflects tropical characteristics. It has a distinct winter from December to February, summer is dry and extends from mid-March to June accompanied by hot westerly winds known as *loo*, monsoon commences from July until mid-September and post-monsoon from mid-September to October. The study area also receives occasional winter and summer rains. Presence of fog during winters has also been observed.

2.3.1 Temperature

Temperature is an important factor deterministic in the vegetation composition. The temperature for the study area was recorded daily during July 2009 to April 2011. The temperature varied from 52 oC to 1 oC during the study period (Figure 2.2). Frosts are common especially in depressions and valleys all over the area during December and January affecting vegetation including old trees.

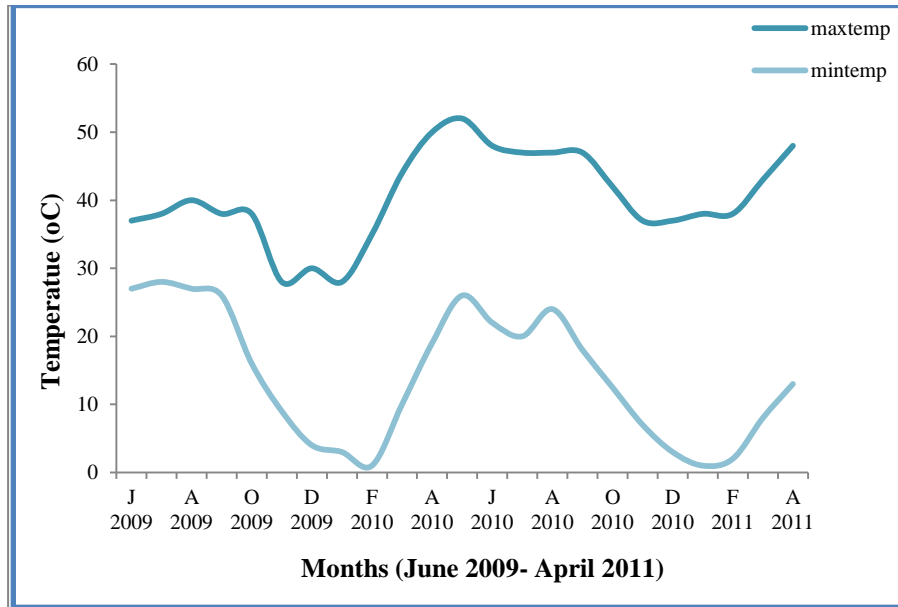


Figure 2.2 Mean Minimum & Maximum Temperatures recorded in Sariska Tiger Reserve (2009-2011)

2.3.2 Rainfall and Humidity

The rainfall pattern in study area is monsoon dependent. The south-west monsoon commences towards the end of June and it rains until mid-September. August is the wettest month in the region. North-East monsoon causes occasional winter showers during December to February. Rainfall is accompanied by hailstorms at times (observed during study period) destroying the agricultural crop. The relative humidity is high during monsoon and ranged from 52% to 2% (Figure 2.3). The annual rainfall recorded for the study period (June 2009-July 2010) was 735.1 mm. Precipitation in the form of dew occasionally occurs during winter favoring plant life.

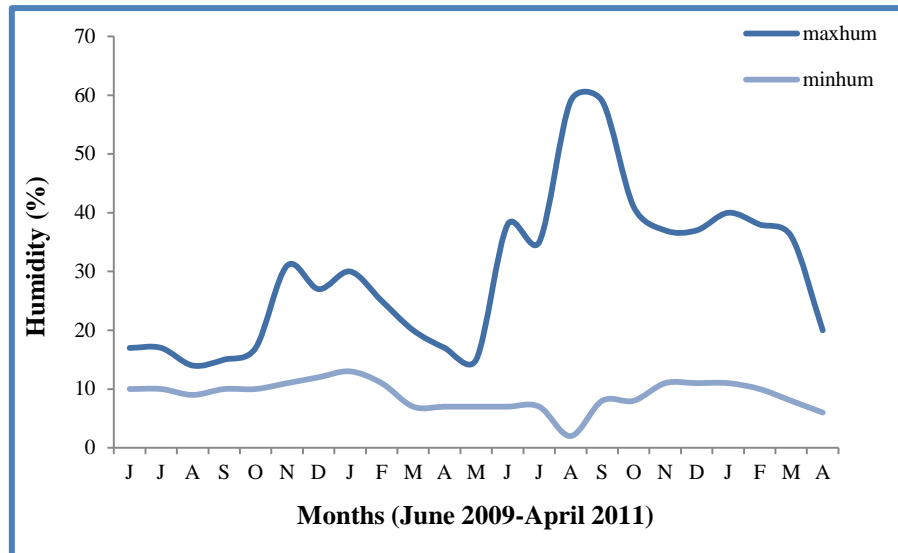


Figure 2.3 Mean Minimum & Maximum Humidity recorded in Sariska Tiger Reserve (2009-2011)

2.4 Ecological attributes

2.4.1 Flora

The vegetation of Sariska corresponds to Northern tropical dry deciduous forests (TDD) (subgroups 5B; 5/E1 and 5/E2) and Northern Tropical Thorn forest (TTF) (subgroup 6B) as per the classification by Champion & Seth (1968) (Figure 2.4). The forests being scattered over a large area and occurring on various geological and soil formations vary greatly in composition and quality. Approximately 35% of the forest area is either occupied by bare rocks or covered sparsely with degraded and poor type of scrub growth (Mathur & Saxena, 1968) (Plate 2.4). *Anogeissus pendula* is the dominant tree species covering over 40 per cent area of the forest. *Boswellia serrata* and *Lannea coromandelica* grow on rocky patches. *Acacia catechu* is common tree in the valleys along with *Butea monosperma* and *Zizyphus mauritiana*. There are a few patches of bamboo (*Dendrocalamus strictus*) along well drained, moist and cooler parts of the valleys. *Albizia lebbek*, *Diospyros melanoxylon*, *Mallotus philippensis*, *Holoptelea integrifolia* and *Ficus* spp. are found in moist localities (Sankar, 1994).

The valley portion of the STR gives an appearance of savanna with scattered trees on a continuous herbaceous ground layer. The typical tree species in the savanna type of vegetation are *Zizyphus mauritiana*, *Acacia leucophloea*, *Butea monosperma*, *Balanites aegyptiaca* and *Acacia catechu*. Areas close to human habitation, heavily grazed by domestic livestock represent thorn scrub or scrub savanna dominated by thorny species such as *Capparis sepiaria*, *C. decidua*, *Zizyphus nummularia* and a native unpalatable and invasive shrub *Adhatoda vasica*. Grasses such as *Chloris dolichostachya*, *Heteropogon*

contortus, *Cenchrus ciliaris* and *Dicanthium annulatum* occur in varying proportions both in tree and scrub savanna (Shahabuddin *et al.*, 2006).

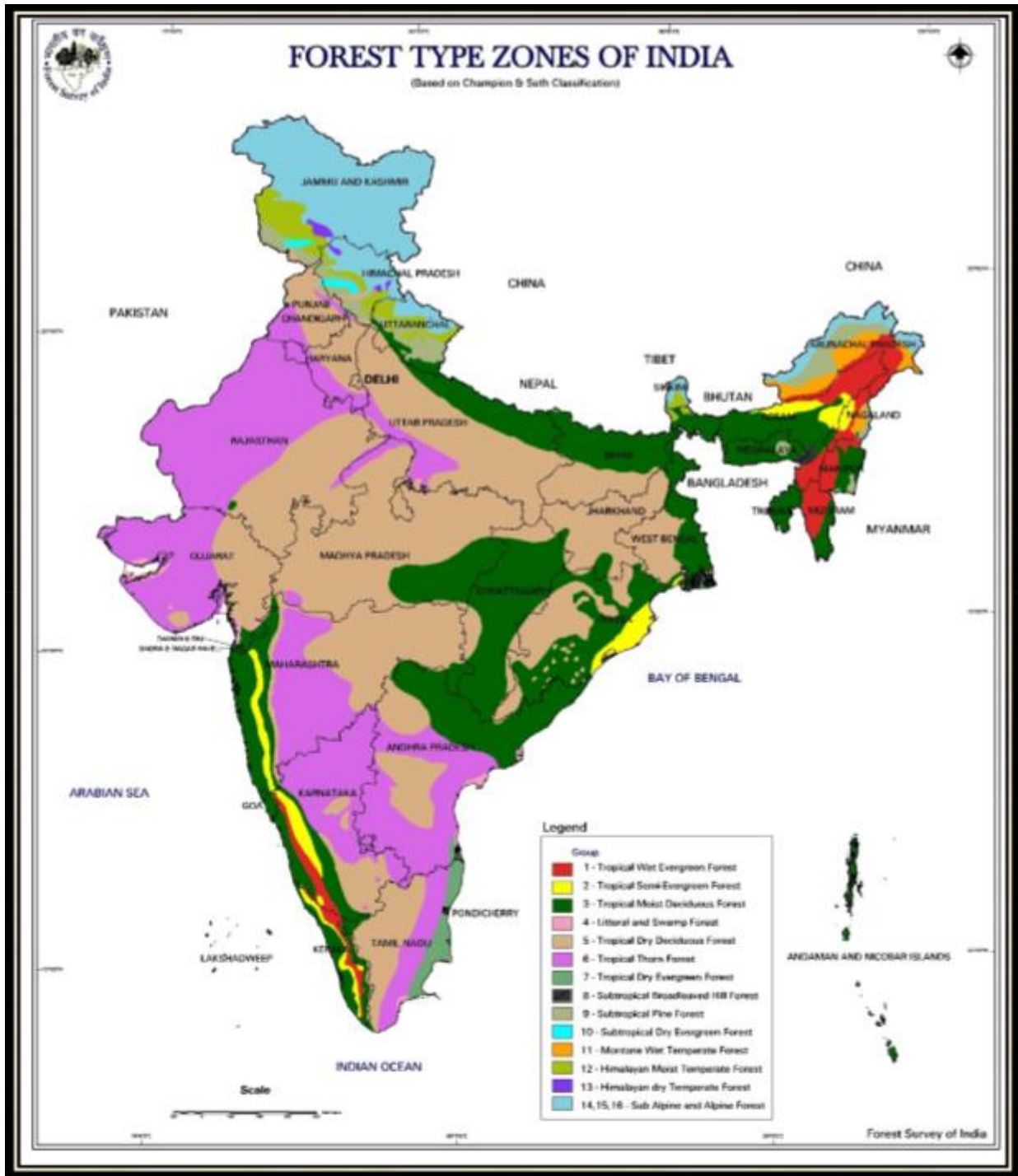


Figure 2.4 Forest types of India as per Champion and Seth (1968) classification

Parmar (1985) classified vegetation of Sariska as follows:

1. *Anogeissus pendula* forest
2. *Boswellia serrata* forest
3. *Acacia catechu* forest and
4. Miscellaneous forest, which can be further sub-divided into three categories viz.
 - a) *Butea monosperma* forest
 - b) Riverine forest
 - c) Thorn Scrub

2.4.2 Fauna

Wild herbivores found in STR are chital (*Axis axis*), sambar (*Rusa unicolor*) and nilgai (*Boselaphus tragocamelus*). Omnivores found are wild pig (*Sus scrofa*) and golden jackal (*Canis aureus*). The park supports carnivore species such as reintroduced tigers (*Panthera tigris*), leopard (*Panthera pardus*) and striped hyena (*Hyaena hyaena*). Small carnivores found are jungle cat (*Felis chaus*), common mongoose (*Herpestes edwardsii*), small Indian mongoose (*H. auro punctatus*), ruddy mongoose (*H. smithi*), palm civet (*Paradoxurus hermaphroditus*), small Indian civet (*Viverricula indica*) and ratel (*Mellivora capensis*). In 2009, desert cat (*Felis selvestris*) was reported from STR (Gupta *et al.*, 2009). Wild dog or dhole (*Cuon alpinus*) was reported in STR (Sankar, 1994) but they have not been sighted in recent past. Rhesus macaque (*Macaca mulatta*) and common langur (*Semnopithecus entellus*) are the two primates found here. Porcupine (*Hystrix indica*), rufous tailed hare (*Lepus nigricollis ruficaudatus*) and eleven species of rodents are also found in STR. Sankar *et al.*, (1993) listed a checklist of 211 bird species belonging to 52 families in STR. These include 73 migratory and 120 resident species and a number of aquatic birds also visit the park during winter.

2.5 Human Habitation

There are 32 villages within the Tiger Reserve boundary and out of them ten are situated in the notified National Park. The people residing within the reserve belong to *gurjar* and *meena* communities. These local residents are mainly occupied in agriculture and animal husbandry. Their only source of income is the production of milk and milk-based products. Apart from grazing, local people commonly collect grasses and lop forest vegetation for their livestock (Kumar & Shahabuddin, 2005). *Anogeissus pendula* was found to be the most preferred tree species, collected for fuelwood by all the villagers inside and outside the Tiger

Reserve. Among the grass species, *Apluda mutica* and *Heteropogon contortus* were largely collected by the villagers for stall feeding to buffaloes. Incidentally these grass species grow only on hill slopes and for collecting the same people have to travel long distances from their respective villages. *Anogeissus pendula*, *Zizyphus mauritiana*, *Phoenix sylvestris* and *Butea monosperma* are heavily lopped for stall feeding to their livestock i.e. the buffaloes, cows and goats, etc. in and around all the villages. As a result, *Zizyphus mauritiana* known to be an important fodder plant for wild ungulates is not allowed to flower and fruit near *Kiraska* and *Kankwari* (Sankar, 1994).

Due to presence of villages inside and on the periphery of STR a large number of livestock such as buffalo, cattle, goat along with feral cattle are found in the study area which increases the grazing pressure on the limited grazing source and also putting these resources on the verge of depletion. A number of fruits, leaves and other plant parts are used for food and medicine. The Tiger Reserve faces a serious threat from livestock grazing and degradation of wildlife habitat due to human dependence from villages located inside the notified National Park zone which results in selective removal of palatable forage, invasion by opportunistic species such as *Adhatoda vasica*, *Prosopis juliflora*, *Cassia tora* and *Pupalia lappacea* and lack of regeneration in *Zizyphus mauritiana*.

There are twelve villages due for relocation since 1984 in the notified National Park. Of these, village *Bhagani* had been relocated during November 2007, *Umri* was relocated during March 2012 and other villages are under process. The relocation of *Bhagani* has led to a gradual restoration of the place within a span of just 4 years.



Plate 2.1 Entrance to the Sariska Tiger Reserve, Rajasthan



Plate 2.2 Archeological ruins at Bhangarh



Plate 2.3 Ancient temple at Neelkanth



Plate 2.4 Savanna landscape with scattered trees and shrubs and continuous grass layer

VEGETATION STRUCTURE AND COMPOSITION

3.1 Introduction

Structure and composition of the vegetation reflect the ecosystem properties and ecological conditions in an area that form the basis for further scientific studies and management (Lindenmayer & Franklin, 1997). The most important constituents of vegetation are plant species and their assemblages, which are strongly influenced by various factors such as climate, geology and soil, topography, herbivory and anthropogenic activities. Most eco-regions of the world are characterized by their distinct plant communities (Kent & Coker, 1992). Many plant species serve as indicators of ecological conditions and have been used for site evaluation (Rowe, 1956, Barnes *et al.*, 1997). Information on these parameters at spatio-temporal scale also helps in conservation planning and restoration of degraded ecosystems. Even Frederick Clements (1928), well known for his classification of innumerable vegetation communities, indicated in his book “Plant Succession and Indicators” that the transition from savanna to woodland is gradual, and it is impossible to draw a sharp line between the two. An important concept in our understanding of how vegetation is distributed on the landscape is that each species of plant has a unique distribution across environmental gradients. Species tend to form groupings that we can recognize as vegetation communities because they have similar, but not identical, environmental requirements. Consequently, across a gradient such as woodland-savanna-prairie, a gradual change in species composition is expected, with each species having its own area of optimal success. This concept was first defined on a theoretical basis by Henry Gleason (1926) and has been documented by vegetation scientists during the past 35-40 years. Thus the implication that savannas were composed of species that were unique to this vegetation seems unsupported. Open spaces between trees in savannas were dominated by prairie grasses and forbs, whose abundances declined as the density of trees in the savanna increased. It is likely that some species reached their highest abundances in savannas. But these species may have gradually decreased in abundance across the gradients from savanna toward prairie and toward closed forest, making the distinct separation of savanna from forest and prairie on the basis of floristic composition impossible (Anderson, 1991). Anthropogenic activities such as commercial harvesting of various products, over exploitation of forests for fodder, fuel and uncontrolled livestock grazing are the major reasons for forest degradation. Most of the tropical forests have been greatly modified due to over exploitation (Paliwal, 1984). The sustainability of watersheds, livelihood of the local communities and the status of native flora and fauna depends on the structure, composition and productivity of these forests.

History tells a lot about our future and hence when we look at the past observations we come to understand that the historical evidences indicated that with the beginning of Pliocene period, the deciduous trees replaced the evergreen vegetation over much of the country, while parts of Thar Desert came to be covered by desert scrub (Gadgil & Meher-Homji, 1985). Even during this dry epoch, however there was hardly any natural grassland, with only a few species of grasses at the border or in dry open forest (Whyte, 1980). Furthermore, studies of floral pollen suggested no major change in the vegetation pattern over the last 6000 years where human interference would have been negligible (Vasanthy *et al.*, 1980). When the hunter-gatherers first colonized India about 50000 years ago, they must have encountered a land with an almost unbroken forest cover. The fire brought in by these human bands must have played its part in modifying this forest cover, but the changes so brought about were likely to have been negligible till the introduction of agriculture and animal husbandry beginning some 5000 years ago (Kosambi, 1965). Traditionally woodlots were maintained as *orans* or sacred groves where the use of iron implements was prohibited. These also used to be protected grazing reserves. However, in spite of such traditions, it is likely that the original vegetation cover of the rather extensively uncultivated tracts of the arid lands was gradually degraded and converted into very open savanna. This picture of the land was at the time of British conquest in late 18th century (Gadgil & Meher-Homji, 1985).

Nestled in the world's oldest hill ranges, i.e. Aravallis, Sariska Tiger Reserve, with its repository of serene forests, wide valleys and sprawling plateaus, has unfortunately attracted the world's attention for the loss of its flagship species i.e. Tiger. However, this part of the country believes in giving trees their due as most of the landmarks are named after indicator tree species such as *Amla Paaj*, *Dhoki road*, *Katthala*, *gular ghoom*, *jalebi chowk*, *talvriksh*, *beherawala* and *sariska*. Despite everything, Sariska is still a natural grandeur for biodiversity. The region is of global significance and is the richest in species diversity in western Indian landscape. The forest being scattered over a large area and occurring on various geological and soil formations vary greatly in composition and quality (Mathur & Saxena, 1968). There is a heavy demand of grass for thatching and for fodder during scarcity period i.e. summer. *Prosopis juliflora* was one of the species to be planted at the worse types of soil such as eroded isolated tops and area with extremely loose soil with stones as per the early forest management plans (1968) but the extremely unpalatable species has invaded the otherwise fertile areas and removed native vegetation and grasslands.

According to Champion and Seth (1968), the forest of Sariska falls within Northern Tropical Dry deciduous (TDD) (Group V) and Northern Tropical Thorn Forests (TTF) (Group VI). Tropical dry deciduous forest constitutes about 38% of the total forest area in India (Dixit, 1997). The sub categories of forest types met within Sariska can be grouped into following types.

- (a) *Acacia catechu* (*Khair*) forest
- (b) *Butea monosperma* (*Dhak/Cheela*) forest
- (c) *Zizyphus mauritiana* mixed forest (*Ber*) forest
- (d) Thorn-scrub
- (e) *Boswellia serrata* (*Salar*) forest
- (f) *Anogeissus pendula* forest, locally known as "*Dhok* forest"
- (g) *Dendrocalamus strictus* (Bamboo) forest
- (h) Riverine forest

Based on remote sensing data, Sankar *et al.* (2008) reported nine different vegetation and land cover categories within STR which are as follows:

Table 3.1 Forest types and cover in Sariska Tiger Reserve

Vegetation/Landcover type	Area (sq. km.)	Percentage
<i>Anogeissus</i> dominated forest	283.25	35.43
Scrubland	152.46	19.07
<i>Boswellia</i> dominated forest	123.54	15.45
Agriculture/Habitation	74.68	9.34
<i>Butea</i> dominated forest	63.56	7.95
<i>Zizyphus</i> mixed forest	47.511	5.943
<i>Acacia</i> mixed forest	32.19	4.03
Barren land	20.63	2.58
Water body	1.62	0.20
Total	799.43	100

Source: Ecological Studies (Sankar *et al.* 2008)

Acacia mixed forest: The *Acacia* mixed forest occupied 4% of the total vegetation cover in STR. The *Acacia leucophloea* is one of the dominant species in this type of forests. Other associated species include *Prosopis juliflora* and *Acacia senegal* (Plate 3.1). The understorey is formed by *Capparis sepiaria*, *Dichrostachys cinerea* and *Maytenus emarginatus*. Grasses found are *Apluda mutica*, *Cynodon dactylon* and *Desmostachya bipinnata*.

Butea dominated forest: *Butea* dominated forest occupies ca 8% of the Tiger Reserve. This species is found in association with *Zizyphus mauritiana*, *Cordia myxa*, *Phoenix sylvestris* (along the streams), *Holoptelea integrifolia* and *Cassia fistula*. *Capparis sepiaria*, *Grewia flavescens* and *Rhus mysorenses* are the common under storey. Common grasses forming ground layer are *Heteropogon contortus* and *Chloris dolichostachya*.

Zizyphus mixed forest: This vegetation community that occupies 5.9% of the total vegetation cover in STR is dominated by *Zizyphus mauritiana* in combination with *Acacia catechu*, *A. leucophloea* and *B. monosperma* (Plate 3.2). The understorey is formed by *Adhatoda vasica*, *Cassia tora*, *Capparis sepiaria* and *Zizyphus nummularia*. *Cynadon* spp., *Eragrostis* spp., and *Chloris* spp. are typical grasses found along with this type of vegetation.

Thorn Scrub: This vegetation type occupies ca 19% of the geographical area in STR. Characteristic species include *Prosopis juliflora*, *Acacia leucophloea*, *Acacia nilotica*, *Acacia senegal*, *Maytenus emarginatus* and *Balanites aegyptiaca*. Associate shrubs include *Capparis decidua*, *C. sepiaria*, *Rhus mysorenses*, *Grewia flavescens*, *G. tenax*, *Zizyphus nummularia*, *Adhatoda vasica* and *Dichrostachys cinerea* (Plate 3.3). Grass cover is sparse and is mainly formed by *Cynodon dactylon*, *Chloris dolichostachya*, *Sporobolus coromandalianus* and *Cenchrus setigerus*.

Boswellia forest: *Boswellia serrata* occupies nearly 15% of the overall vegetation cover in STR and is found largely on steep slopes and plateaus (Plate 3.7). This species is found in association with *Anogeissus pendula*, *Diospyros melanoxylon*, *Acacia catechu*, *Wrightia tinctoria*, *Bauhinia racemosa* and *Ehretia laevis*. The under storey comprises of *Eurphobia nerifolia*, *Grewia flavescens*, *G. tenax* and *Capparis sepiaria*. Grass cover is sparse and is formed by *Apluda mutica* and *Chloris dolichostachya*.

Anogeissus dominated forest: The *Anogeissus pendula* forest occupies about 35% of the vegetation cover in STR (Plate 3.6). This species is found in association with *Acacia catechu* and *Lannea coromandelica*. The under storey is formed by *Adhatoda vasica*, *Grewia flavescens* and *Capparis sepiaria*. Ground cover mainly comprises of *Aristida adscensionis*, *Setaria intermedia* and *Chloris dolichostachya*. The trees are generally slow growing and attain poor height however in moist localities may grow upto 12 m.

Only a few attempts have been made to evaluate the structure of plant community of these forests (Singh & Misra, 1978; Khan, 1996; Pauline *et al.*, 1996; Dixit, 1997; Parthasarthy & Sethi, 1997). Although Vyas in 1967 had documented some flora of Sariska as a part of floral study of North-East Rajasthan including Sariska, Parmar (1985) was the first to study the flora of Sariska TR exclusively. Rodgers (1985) also classified the vegetation types of Sariska TR and enlisted 155 species belonging to 45 families and 118 genera. In 1990, Rodgers (1990a) studied the importance of *Capparis sepiaria*, one of the most important fodder plants in Sariska. He also estimated its browse volume and biomass in different vegetation types (Rodgers, 1990b). In the same year, Rodgers (1990c) studied the stream side vegetation to understand the

ecological importance of Algal spring, which is a perennial and an important water sources for wild animals in Sariska. In 2008, Sankar *et al.* studied vegetation composition and structure and mapped vegetation types of the entire Sariska TR. The Sariska valley, which appears as savanna is mostly dominated by *Acacia* dominated forest, *Butea monosperma* forest, *Zizyphus mauritiana* forest and thorn scrub and this study focused on investigating the structure and composition of savannas in Sariska.

Such studies, particularly in and around PAs, can serve as baseline information and would be useful in predicting the future course of succession and habitat conditions in the region. The information on the community composition, species diversity and impact of anthropogenic activities on these parameters would be useful in predicting the future changes in the ecological conditions. Therefore, present study was initiated with a view to collect baseline data that would be helpful in monitoring the forest changes in future.



Plate 3.1 *Acacia* woodland



Plate 3.2 *Zizyphus mauritiana* woodland



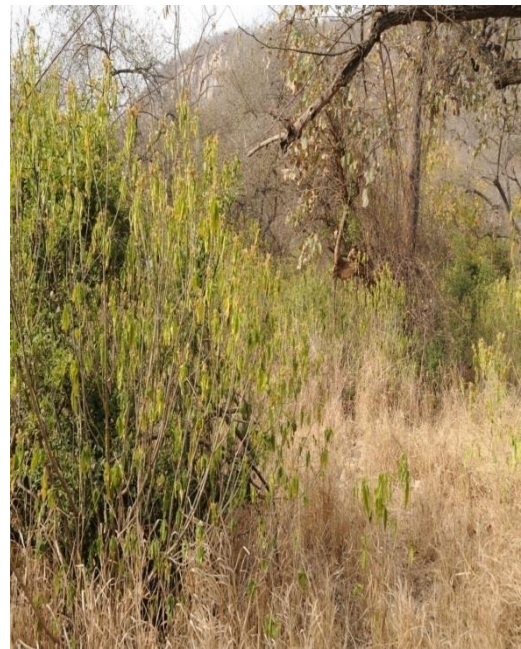
Plate 3.3 Scrubland vegetation



Plate 3.4 Riverine forest (*Phoenix* forest)



(a)



(b)

Plate 3.5 (a,b) *Adhatoda* infestation across the landscape



Plate 3.6 *Anogeissus pendula* forest in a deciduous state

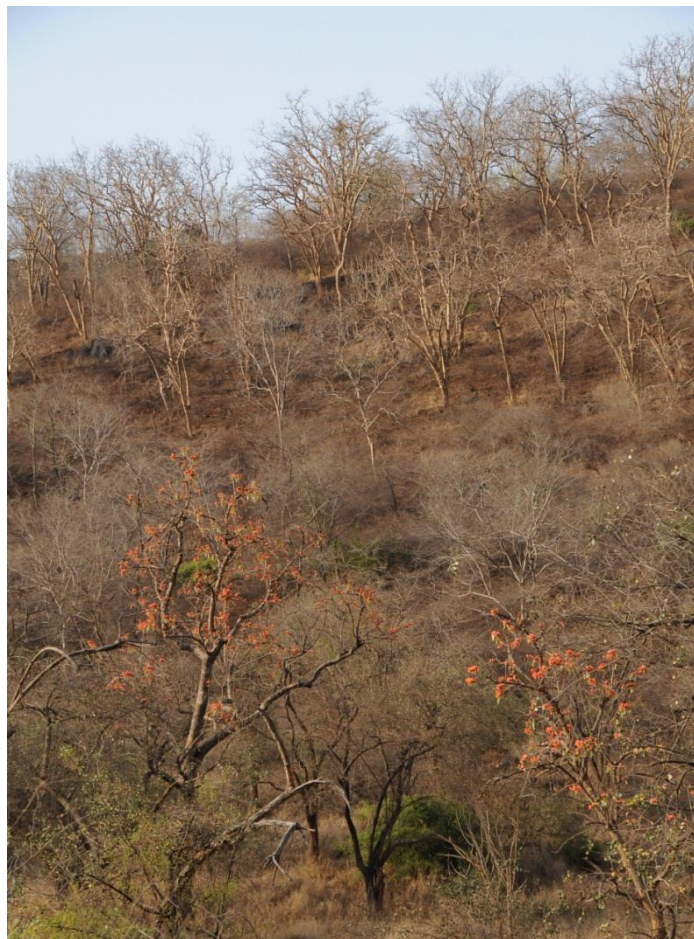


Plate 3.7 Gradient along the slope (*Acacia* woodland, *Butea monosperma*, *Anogeissus pendula* and *Boswellia serrata* in an order from bottom to top)

3.2 Methodology:

The intensive study was conducted within the valley portion of the Tiger Reserve where savanna vegetation predominates. This area lies on either side of the state highway and stretches for about 10 kms. It is widest at the entrance of the Reserve and tapers towards Kalighati. The study area is approximately 20 km². Five transects of 1.5 km were randomly laid in the intensive study area. Vegetation plots were laid at every 50 m on either side of a transect alternately (Figure 3.1, 3.2). Vegetation data from 149 plots in 5 transects in the Sariska valley was collected for winter, pre-monsoon and post monsoon period. At each sampling site 10 m radius plot was laid for tree layer, followed by 5 m radius concentric plot for shrub layer and 6 random quadrats of 1 m² for the ground layer for herbaceous and grass cover. Following vegetation parameters were collected from each sampling plot:

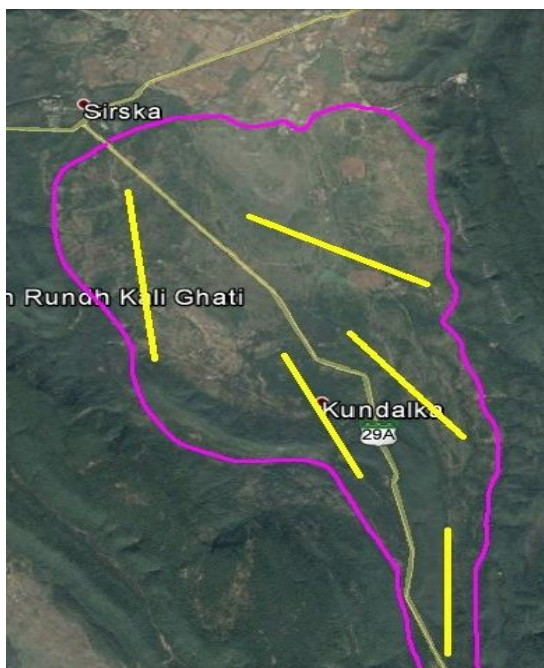


Figure 3.1 Location of the study area showing line transects

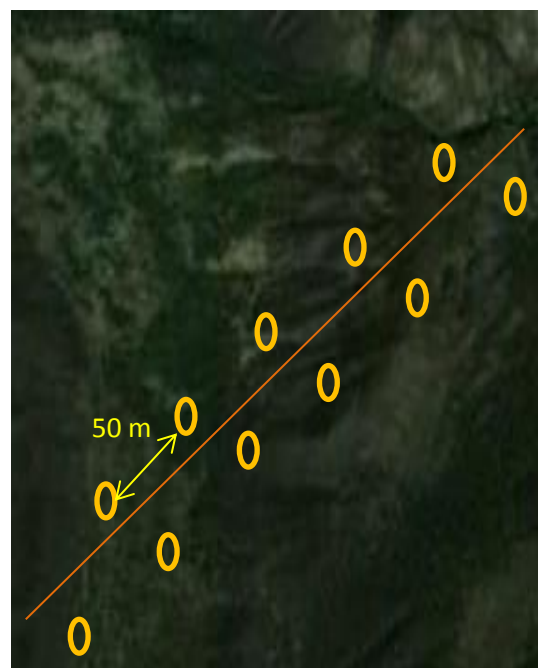


Figure 3.2 Vegetation quantification plots along the line transect

Tree species: Name of the species, number, circumference at breast height (GBH, at 1.37 m from the ground), height and canopy cover were measured. Plants with > 30 cm gbh and > 3 m straight bole were considered as trees following Muller-Dombois & Ellenberg (1974). Pole size (20-30 cm), saplings (< 20 cm gbh) and seedling (one or two leaf stage to 10 cm gbh) of tree species were recorded to see the regeneration pattern (Singh & Singh, 1992).

Shrub species: The woody species which had gbh < 20 cm, height < 3 m and those have branching from base of the stem were considered as shrubs (Muller-Dombois & Ellenberg, 1974). Shrub species and woody climber with their number were recorded within 5 m radius plots concentric to 10 m plots.

Herb species: Overall ground cover of herbaceous vegetation (%) was recorded by ocular estimation. Within each sample plot, number of individuals of each species and proportion of grasses were recorded within six 1m × 1m quadrats. At each sample plot various site factors such as canopy cover of trees and grass cover were recorded using standard techniques and equipment. The vegetation data was analysed for various parameters such as density, abundance, IVI, diversity and richness for three seasons, winter (Dec to Jan), pre-monsoon (June) and post monsoon (October).

Field Identification of plant species was made with the help of local flora (Sharma & Tiagi, 1979, Maheshwari, 1963) and field guides and unidentified specimens were preserved following Jain & Rao (1977) and brought to the Wildlife Institute of India, Dehradun for further examination and identification from standard herbarium.

3.3 Analysis

3.3.1 Sampling effort

Adequate sampling effort is a characteristic of an improvised data collection method in which general presumption is that presence can be detected with some reliability given minimal effort is put to use. Time and energy devoted to getting an accurate count in a single area is subsequently unavailable to repeat counts and reduce the variance of an estimate and increase its precision. Species richness is used as a variable for calculating sampling adequacy and is expressed as the number of species present in a given habitat or season (McIntosh, 1967). However, since it is not often possible to enumerate all species in a community, other methods may be used. One of these methods is the Rarefaction method that standardizes samples to a common size so that they can be compared between communities or within the same community over time. Adequacy of sampling effort was analysed using EstimateS ver. 8.2.0. (Colwell *et al.*, 2012).

3.3.2 Cluster Analysis

The community based vegetation analysis was done using 'PC - ORD' (McCune & Mefford, 1999) software ver. 4.34 and TWINSpan (Hill, 1979; Gauch & Whittaker, 1981) was used to determine different plant communities by using similarities within vegetation plots. This analysis is based on hierarchical divisive clustering technique and was used to prepare the dendrogram for the community. A plant community can be defined as a collection of plant species growing together in a particular location that

show a definite association or affinity with each other (Mueller-Dombois & Ellenberg, 1974). The species in a community grow together in a particular environment because they have similar requirements for existence in terms of environmental factors such as light, temperature, water drainage and soil nutrients (Billings, 1973; Muller-Dombois & Ellenberg, 1974; Ter Braak, 1987). The communities are segregated and named after dominant species, which are evident in most of the clusters. Companion species are mentioned with those species, which had near weightage to the dominant species. The species having higher weightage than other available companion species were ranked second in the community. The plots were divided into *Adhatoda* present and absent and the communities were formed. This segregation was done to understand the possible changes in the forest structure that could have possibly occurred due to invasion of *Adhatoda*.

Several standard measures of absolute and relative abundance are used to assess the contribution of each species to a community (Barbour *et al.* 1999). These measures include: density, the number of individuals within a chosen area (e.g., m², hectare); relative density, the density of one species as a percentage of total density; frequency, the percentage of total quadrats or points that contains at least one individual of a given species; relative frequency, the frequency of one species as a percentage of total frequency; dominance, the total basal area of a given species per unit area within the community; relative dominance, the dominance of one species as a percentage of total dominance; and importance, expressed as the relative contribution of a species to the entire community expressed as a combination of relative density, relative frequency, and relative dominance. Each of these measures offers a different insight into the abundance of the species composing a community. Saplings, for example, typically have a much higher density but much lower dominance than mature trees. Density tells us the number of individuals per unit area but density is not necessarily proportional to dominance because dominance for a given species expresses the area occupied by the species per unit area (e.g., per m²). A species composed of primarily large individuals can have high dominance but it will likely have low density, and unless regularly distributed, it will also have low frequency. Frequency, which is often independent of density, expresses one measure of the distribution of individuals within the community. A clumped species can have high density but also low frequency because it occurs in a limited portion of the community. In contrast, a species that is individually and regularly distributed over the landscape will have a high frequency but can have low density. Relative importance, as a combination of relative values for density, frequency, and dominance, is used as a summary of the influence that an individual species may have within the community. Recognize that two species with the same relative importance can have markedly different values for relative density, frequency, or dominance as any differences can be overshadowed by the addition process (Barbour *et al.* 1999).

Individuals of a species can be randomly distributed across a community i.e., the location of one individual of a given species has no relationship with the location of other individuals of that species. Individuals of

other species might be singly and regularly distributed throughout the community (an extreme example is the uniform spacing of orchard trees), while the individuals of still other species could be clumped i.e., the presence of one individual of a given species increases the probability of finding another individual of that species nearby. Thus, ecologists recognize three primary patterns of distribution: random, regular(uniform) or hyperdispersed and clumped (aggregated) or underdispersed (Barbour *et al.* 1999).

There are a number of reasons why plants show clumped distributions. Many plants are highly clonal (i.e., they can propagate by vegetative means as do goldenrods and aspens) so once a seedling establishes at a given site, the plant spreads to produce numerous, spatially separated (but genetically identical), aboveground stems. In addition, environmental gradients are common in nature so that a site that is good for one individual of a given species is likely to be good for other individuals of that species. Yet there are forces in nature that counteract clumping. Competition among individuals for water in deserts or light in forests can favor regular spacing. Similarly plants that are clumped are more likely to be found by their herbivores or pathogens (Barbour *et al.* 1999).

The structure and composition of the vegetation was evaluated using various parameters such as species richness, diversity, evenness and Importance Value Index (IVI) of tree species (Cottam & Curtis, 1956). The structural aspect of vegetation such as density, frequency, abundance and dominance of constituent species were determined following Misra (1968). The Importance Value Index (IVI) was computed for all the tree species by adding the relative values of frequency, density and dominance (basal area) following Curtis & McIntosh (1951), Brown & Curtis (1952). The A/F ratio indicates regular distribution if the value is <0.025, random distribution between 0.025 to 0.050 and contiguous distribution if >0.050 (Curtis and Cotton, 1956). The following formulae were used for evaluating vegetation parameters.

$$\text{Density} = \frac{\text{Total number of individuals of a species in all the circular plots}}{\text{Total circular plots laid}}$$

$$\text{Frequency} = \frac{\text{Total number of circular plots in which the species occur}}{\text{Total circular plots laid}} \times 100$$

$$\text{Abundance} = \frac{\text{Total number of individuals in all circular plots}}{\text{Number of circular plots in which species occur}}$$

$$\text{Mean Basal Area (MBA)} = (\text{Circumference})^2 / 4\pi$$

$$\text{Total Basal Area (TBA)} = \text{MBA} \times \text{Density}$$

$$\text{Relative density} = \frac{\text{Density of a species}}{\text{Total density of all species}} \times 100$$

$$\text{Relative Dominance} = \frac{\text{Total basal area of a species}}{\text{Total Basal Area of all species}} \times 100$$

$$\text{Relative Frequency} = \frac{\text{Frequency of a species}}{\text{Total frequency of all species}} \times 100$$

Importance Value Index = sum of Relative density, frequency and dominance

The diversity index makes the assumption that individuals are randomly sampled from an infinitely large population and also assumes that all the species from the community are included in the sample. Species diversity was computed using Shannon-Wiener Index (Shannon and Wiener, 1949).

$$H' = \sum (ni/N) \times \ln (ni/N)$$

Where, H' = Shannon's information index of species diversity

ni = Total number of individuals of one species

N = Total number of individuals of all the species in one stand

Richness was calculated by counting total number of species observed in each habitat.

Evenness (Equability) was calculated using the Pielou's (1966) equation

$$\text{Evenness (E)} = H' / H' \text{ max.} = H' \log S \text{ or } H' / \ln S$$

Where, S = Number of species

H' = Diversity

Evenness ranges between 0 and 1. If the evenness value is higher, the variation in communities between the species would be less.

3.4 Result

3.4.1 Sampling effort adequacy

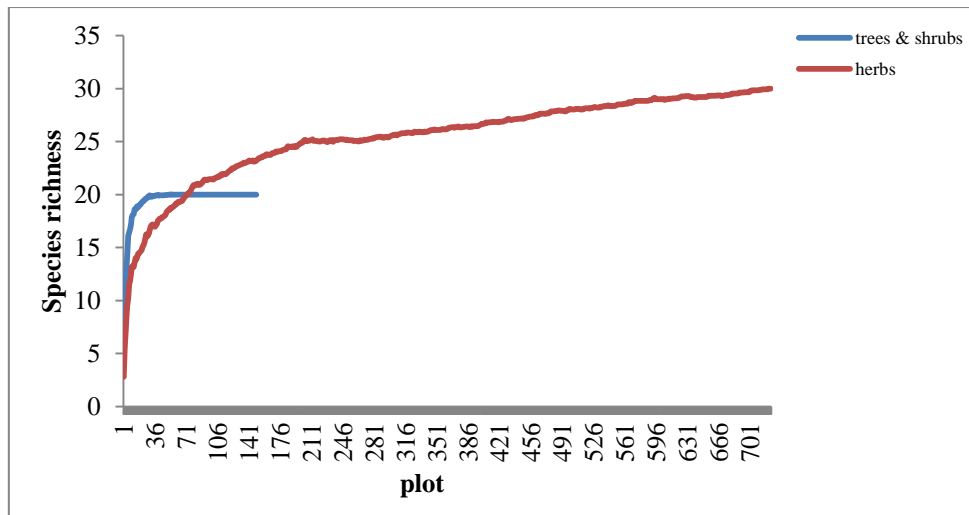


Figure 3.3 Species richness curve (Chao1 mean)

The sampling adequacy curve (Figure 3.3) implies that the tree and shrub species richness got stabilised at 55 plots and species richness for herbs was reaching a stable point at 722 plots and thereafter any new species was not found. Hence, it could be concluded that my sampling efforts were adequate.

3.4.2 Cluster Analysis of Vegetation

In total, 149 plots were segregated on the basis of *Adhatoda vasica* presence or absence, as an earlier attempt at clustered analysis in which all the plots were taken together, did not reveal substantial results as *Adhatoda vasica* was featured as the dominant component and top community component for all communities thus hindering results and creating confusion. The segregation resulted in the formation of following two groups (Table 3.2) and these groups remained the basis of all the further analysis.

Table 3.2 Vegetation categories and corresponding communities and plots

S.no	Vegetation type	No. of communities	No. of plots
1	<i>Adhatoda</i> present	5	73
2	<i>Adhatoda</i> absent	6	76

3.4.2.1 Communities with *Adhatoda* presence

A total of 73 plots were analysed within this category and 5 communities were identified with the help of PC-ORD ver. 4.34 (Table 3.3) and the dendrogram for the same is shown as Figure 3.4.

Table 3.3 Communities and corresponding dominant, constant and constituent species

S.no	Community	Dominant species(IVI)	Constituent species	Constant species (Frequency >50%)
1	<i>Adhatoda-Balanites aegyptiaca</i>	<i>Adhatoda vasica, Balanites aegyptiaca</i>	<i>Grewia flavescens</i> <i>Zizyphus nummularia, Lantana camara, Dichrostachys cinerea</i>	<i>Grewia flavescens</i> <i>Zizyphus nummlaria</i> <i>Dichrostachys cinerea</i>
2	<i>Adhatoda- Acacia leucophloea</i>	<i>Adhatoda vasica, Acacia leucophloea</i>	<i>Grewia flavescens, Zizhyphus nummularia</i>	<i>Grewia flavescens</i> <i>Zizyphus nummlaria</i> <i>Capparis sepiaria</i>
3	<i>Adhatoda-Acacia leucophloea-Butea monosperma</i>	<i>Adhatoda vasica</i> <i>Acacia leucophloea</i>	<i>Capparis sepiaria</i> <i>Grewia flavescens</i> <i>Prosopis juliflora</i>	<i>Grewia flavescens</i> <i>Capparis sepiaria</i>
4	<i>Adhatoda-Acacia catechu- Zizyphus mauritiana</i>	<i>Adhatoda vasica</i> <i>Acacia catechu</i>	<i>Grewia flavescens</i>	<i>Grewia flavescens</i>
5	<i>Adhatoda-Prosopis juliflora</i>	<i>Adhatoda vasica</i> <i>Acacia senegal</i>	<i>Prosopis juliflora, Capparis decidua</i>	<i>Capparis decidua</i> <i>Prosopis juliflora</i>

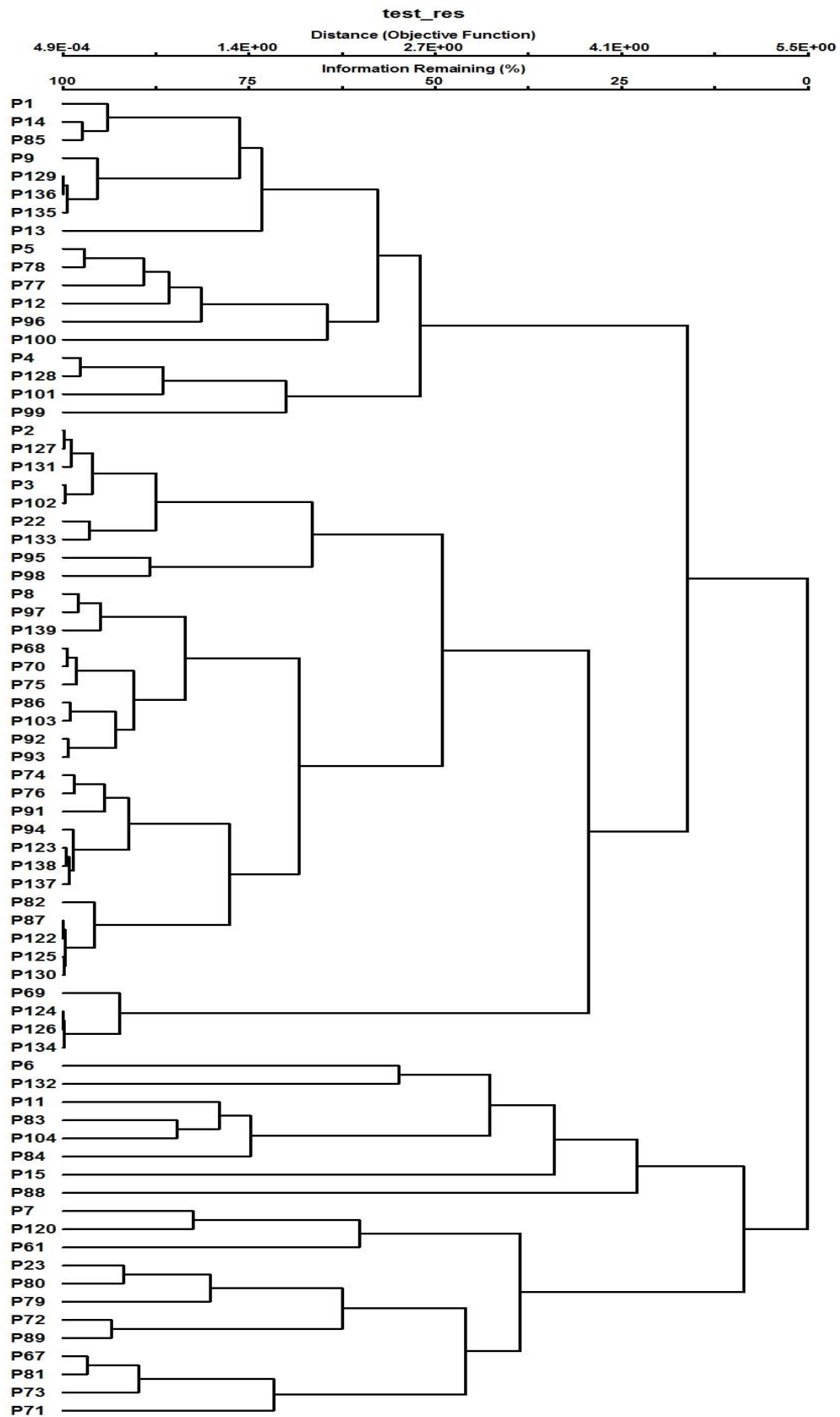


Figure 3.4 Dendrogram showing tree communities in *Adhatoda* infested area

1. *Adhatoda vasica*-*Balanites aegyptiaca* community (11 plots)

This community was dominated by *Balanites aegyptiaca* with an IVI of 300 and A/F ratio of 0.0253 indicating a regular distribution across the community (Table 3.4). Among shrubs, *Grewia flavescens*, *Zizyphus nummularia*, *Lantana camara* and *Dichrostachys cinerea* formed an important constituent of the community.

Table 3.4 Density, Freq (frequency), TBA (total basal area), IVI, A/F ratio of different species in community 1

Species	Density/ha	Freq (%)	TBA(m ² /ha)	IVI	A/F ratio
<i>Balanites aegyptiaca</i>	66.589	90.91	1.127	300	.025
<i>Adhatoda vasica</i>	2748.6	100			
<i>Grewia flavescens</i>	556.1	81.81			
<i>Zizyphus nummlaria</i>	652.4	63.63			
<i>Lantana camara</i>	245.98	36.36			
<i>Dichrostachys cinerea</i>	459.89	81.81			

Understorey vegetation: Among herbs, *Cassia tora*, *Sida acuta*, *Pupalia lappacea* and *Dicliptera verticillata* were the most abundant in their order of occurrence. *Cynodon dactylon* and *Dichanthium annulatum* were the most abundant grass species. The shrub, herb and grass richness in the community was 12 and 17 and 11 respectively (Table 3.5). Abundance for herbs and density for grasses were considered as the comparison factor for all the following communities.

Table 3.5 Diversity, Richness, Evenness of shrubs and herbs in community 1

	Shrub species	Herb species
Diversity	1.58	2.04
Richness	12	17
Evenness	0.63	0.72

2. *Adhatoda vasica*-*Acacia leucophloea* community (18 plots)

Acacia leucophloea was the dominant species followed by *Balanites aegyptiaca* and *Zizyphus mauritiana* with IVI values of 162.63, 69.64 and 38.14 respectively (Table 3.6). *Acacia leucophloea* was found to be randomly distributed while *Balanites aegyptiaca*, *Zizyphus mauritiana*, *Prosopis juliflora* and *A. senegal*

followed contiguous distribution. Among shrubs, *Zizyphus nummularia* and *Grewia flavescens* were highly abundant. Density for *Adhatoda vasica* was found to be 2431 ind/ha.

Table 3.6 Density, Freq (frequency), TBA (total basal area), IVI, A/F ratio of different species in community 2

Species	Density/ha	Freq (%)	TBA(m ² /ha)	IVI	A/F ratio
<i>Acacia leucophloea</i>	23.001	44.44	.822	162.63	.0365
<i>Balanites aegyptiaca</i>	12.38	22.22	.238	69.641	.078
<i>Zizyphus mauritiana</i>	7.07	11.11	.138	38.146	.18
<i>Prosopis juliflora</i>	3.53	5.55	.046	17.282	.36
<i>Acacia senegal</i>	1.76	5.55	.029	12.292	.18
<i>Adhatoda vasica</i>	2431.3	100			
<i>Grewia flavescens</i>	366.01	55.55			
<i>Zizyphus nummlaria</i>	1111.1	94.44			
<i>Capparis sepiaria</i>	183.0	66.66			
<i>Dichrostachys cinerea</i>	104.5	27.77			

Understorey vegetation: *Cassia tora*, *Achyranthus aspera*, *Indigofera linnaei*, *Dicliptera verticilliata* and *Elytraria acaulis* were abundant species among herbs. *Cynodon dactylon*, *Dichanthium annulatum* and *Heteropogon contortus* were abundant in grass species. Species richness in this community for shrub, herb and grass is 13, 16 and 13 respectively (Table 3.7).

Table 3.7 Diversity, Richness, Evenness of shrubs and herbs in community 2

	Shrub species	Herb species
Diversity	1.32	1.72
Richness	13	16
Evenness	0.51	0.62

3. *Adhatoda vasica*-*Acacia leucophloea*-*Butea monosperma* community (23 plots)

Acacia leucophloea and *Butea monosperma* were observed to be the dominant species in this community with little difference in IVI among the two, the former having IVI as 95.234 whereas the latter with IVI value of 92.177 (Table 3.8). *Acacia leucophloea* and *Zizyphus mauritiana* followed random distribution while *Butea monosperma*, *Balanites aegyptiaca*, *Acacia catechu* and *Prosopis juliflora* followed contiguous distribution. In shrubs, the highest numbers of individuals were observed for *Capparis sepiaria*,

Grewia flavescens and *Prosopis juliflora*. *Adhatoda vasica* was observed with a density of 6030 ind/ha and 100% frequency.

Table 3.8 Density, Freq (frequency), TBA (total basal area), IVI, A/F ratio of different species in community 3

Species	Density/ha	Freq (%)	TBA(m ² /ha)	IVI	A/F ratio
<i>Acacia leucophloea</i>	19.38	34.78	1.193	95.234	.050
<i>Butea monosperma</i>	12.46	26.08	1.884	92.177	.057
<i>Balanites aegyptiaca</i>	5.53	13.04	.175	26.635	.102
<i>Zizyphus mauritiana</i>	8.3	26.08	.313	45.046	.038
<i>Acacia catechu</i>	2.76	8.69	.057	12.406	.115
<i>Prosopis juliflora</i>	4.15	13.04	.378	28.067	.076
<i>Adhatoda vasica</i>	6030.6	100			
<i>Grewia flavescens</i>	286.4	69.56			
<i>Capparis sepiaria</i>	393.8	100			

Understorey vegetation: *Achyranthus aspera* was the most abundant herbaceous species followed by *Cassia tora*, *Indigofera cordifolia* and *Borreria stricta*. Among grasses, *Cynodon dactylon* was the most abundant followed by *Digitaria ciliaris*, *Heteropogon contortus* and *Chloris dolichostachya*. Species richness for shrubs, herbs and grasses for this community is 10, 20 and 12 respectively (Table 3.9).

Table 3.9 Diversity, Richness, Evenness of shrubs and herbs in community 3

	Shrub species	Herb species
Diversity	0.68	2.22
Richness	10	20
Evenness	0.29	0.74

4. *Adhatoda vasica*-*Acacia catechu*-*Zizyphus mauritiana* community (17 plots)

Acacia catechu was most abundant species in the community with an IVI value of 153.66 followed by *Zizyphus mauritiana* (55.13) and *Butea monosperma* (30.50). *Acacia catechu* follows random distribution and *Acacia leucophloea*, *Butea monosperma*, *Zizyphus mauritiana*, *Acacia senegal* and *Anogeissus pendula* follow contiguous distribution (Table 3.10). Among shrubs, *Grewia flavescens* and *Capparis sepiaria* were found to be most abundant. *Adhatoda vasica* undoubtedly had the maximum density with 5259.5 ind/ha and 100% frequency.

Table 3.10 Density, Freq (frequency), TBA (total basal area), IVI, A/F ratio of different species in community 4

Species	Density/ha	Freq (%)	TBA(m ² /ha)	IVI	A/F ratio
<i>Acacia leucophloea</i>	1.87	5.88	.137	10.326	.17
<i>Butea monosperma</i>	5.62	11.76	.512	30.508	.127
<i>Zizyphus mauritiana</i>	14.98	29.41	.594	55.138	.054
<i>Acacia catechu</i>	48.71	76.47	1.51	153.665	.026
<i>Acacia senegal</i>	7.49	17.64	.100	23.052	.075
<i>Anogeissus pendula</i>	7.49	17.64	.231	27.308	.075
<i>Adhatoda vasica</i>	5259.5	100			
<i>Grewia flavescens</i>	532.8	88.23			
<i>Capparis sepiaria</i>	131.4	41.17			
<i>Lantana camara</i>	62.2	23.52			

Understorey vegetation: *Achyranthus aspera* had the highest abundance, followed by *Indigofera linnaei*, *Cassia tora* and *Dicliptera verticillata*. Among grasses, *Cynodon dactylon* and *Digitaria ciliaris* were found to be the most abundant. Species richness for shrub, herb and grass species was found to be 9, 18 and 13 respectively (Table 3.11).

Table 3.11 Diversity, Richness, Evenness of shrubs and herbs in community 4

	Shrub species	Herb species
Diversity	0.59	1.98
Richness	9	18
Evenness	0.26	0.68

5. *Adhatoda vasica- Prosopis juliflora* community (4 plots)

This community showed the 100 % presence of *Prosopis juliflora* as shrub species hence, despite having a lower IVI value (97.1) than *Acacia senegal* (202.88), *Prosopis juliflora* has been expressed as a major constituent in the community (Table 3.12). *Prosopis juliflora* followed random distribution while *Acacia senegal* followed contiguous distribution. Among shrubs, *Capparis decidua* (117.6 ind/ha) and *Securinega*

leucopyrus (117.6 ind/ha) had the highest densities. The density of *Adhatoda vasica* was found to be highest among all at 1382.3 ind/ha.

Table 3.12 Density, Freq (frequency), TBA (total basal area), IVI, A/F ratio of different species in community 5

Species	Density/ha	Freq (%)	TBA(m ² /ha)	IVI	A/F ratio
<i>Prosopis juliflora</i>	7.96	25	.096	202.88	.04
<i>Acacia senegal</i>	15.92	25	.603	97.1	.08
<i>Adhatoda vasica</i>	1382.3	100			
<i>Securinega leucopyrus</i>	117.6	75			
<i>Capparis decidua</i>	117.6	25			

Understorey vegetation: The understorey comprises of *Achyranthus aspera* and *Cassia tora* as the most abundant species with densities 35833.3 ind/ha and 31250 ind/ha. Among grasses, *Cynodon dactylon* was highly abundant (30.42 %). The species richness for shrubs, herbs and grass for this community are 8, 12 and 7 respectively (Table 3.13).

Table 3.13 Diversity, Richness, Evenness of shrubs and herbs in community 5

	Shrub species	Herb species
Diversity	1.16	1.77
Richness	8	12
Evenness	0.56	0.71

3.4.2.2 Communities without *Adhatoda* presence

A total of 76 plots were analysed in this category and 6 communities (Table 3.14) were identified with the help of PC-ORD software (Figure 3.5)

Table 3.14 Communities and corresponding dominant, constant and constituent species

S.no	Community	Dominant species(IVI)	Constituent species	Constant species (Frequency >50%)
1	<i>Zizyphus mauritiana</i> - <i>Butea monosperma</i>	<i>Zizyphus mauritiana</i> , <i>Acacia catechu</i>	<i>Grewia flavescens</i> <i>Capparis sepiaria</i>	<i>Capparis sepiaria</i>
2	<i>Acacia catechu</i> - <i>Zizyphus mauritiana</i>	<i>Acacia catechu</i> , <i>Zizyphus mauritiana</i>	<i>Grewia flavescens</i> , <i>Capparis sepiaria</i>	<i>Capparis sepiaria</i> <i>Grewia flavescens</i>
3	<i>Prosopis juliflora</i> - <i>Lantana camara</i> scrubland	<i>Prosopis juliflora</i> , <i>Lantana camara</i>	<i>Capparis sepiaria</i> <i>Grewia flavescens</i> <i>Prosopis juliflora</i>	<i>Lantana camara</i> <i>Grewia flavescens</i>
4	<i>Acacia-Grewia</i> <i>flavescens</i>	<i>Acacia catechu</i> <i>Acacia senegal</i>	<i>Grewia flavescens</i>	<i>Grewia flavescens</i> <i>Zizyphus nummularia</i>
5	<i>Acacia leucophloea</i> - <i>Zizyphus nummularia</i> - <i>Prosopis juliflora</i>	<i>Grewia flavescens</i>	<i>Prosopis juliflora</i> , <i>Capparis decidua</i>	<i>Zizyphus nummularia</i> <i>Prosopis juliflora</i>
6	<i>Prosopis juliflora</i>	<i>Prosopis juliflora</i> <i>Zizyphus nummularia</i>		<i>Prosopis juliflora</i>

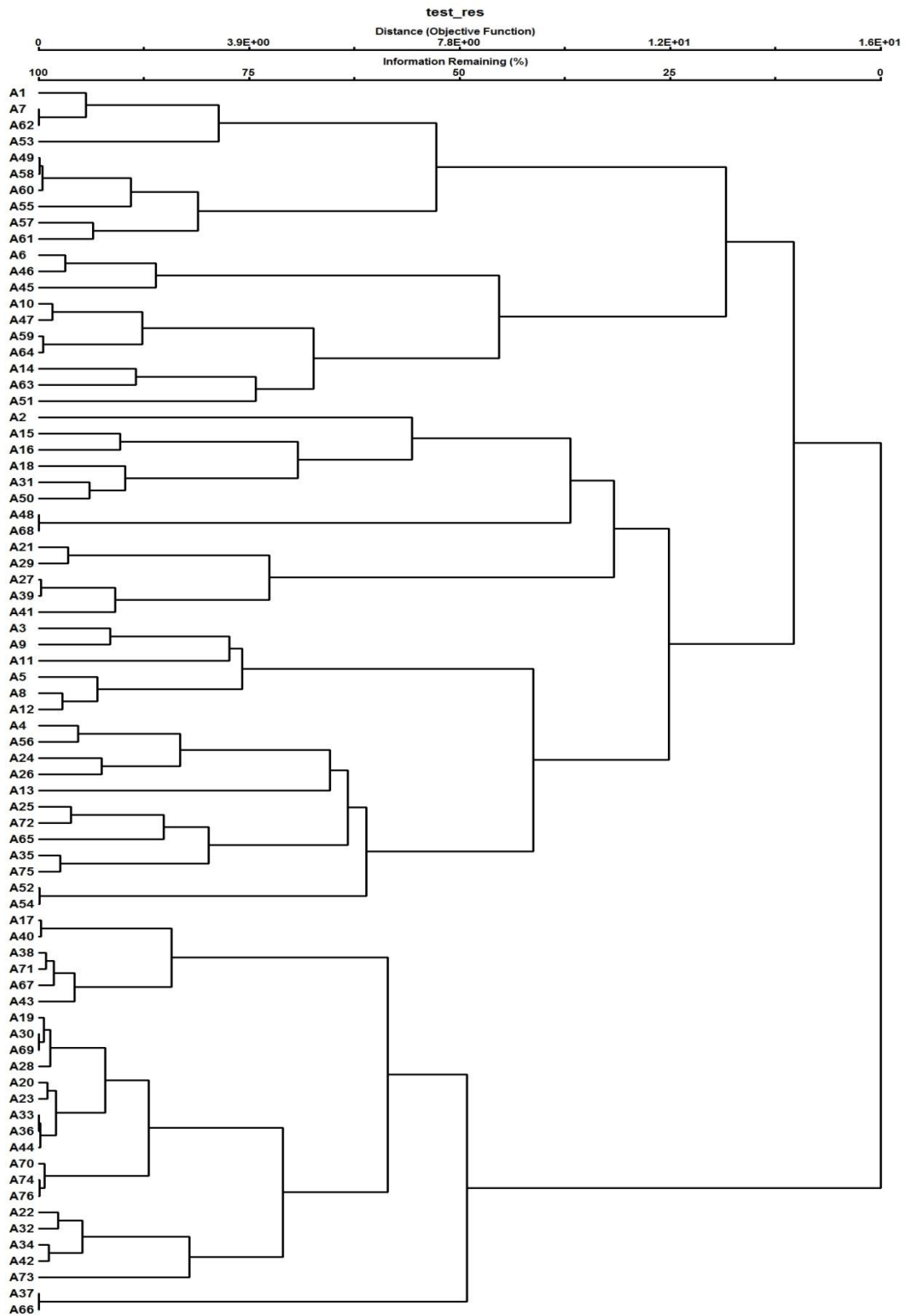


Figure 3.5 Dendrogram showing tree communities in *Adhatoda* absent area

1. *Zizyphus mauritiana*-*Butea monosperma* community (25 plots)

Zizyphus mauritiana was identified as the most important species of the community with the highest IVI value of 201.794 (Table 3.15). This species also showed a regular distribution with A/F ratio of .022. *Acacia catechu*, *Butea monosperma* and *Balanites aegyptiaca* followed contiguous distribution pattern. Among shrubs, *Capparis sepiaria* (2.62) was the most abundant of all species followed by *Dichrostachys cineria* (1.83) and *Grewia flavescens* (1.12).

Table 3.15 Density, Freq (frequency), TBA (total basal area), IVI, A/F ratio of different species in community 1

Species	Density/ha	Freq (%)	TBA(m ² /ha)	IVI	A/F ratio
<i>Zizyphus mauritiana</i>	49.1	83.33	1.82	201.79	.022
<i>Acacia catechu</i>	7.96	20.83	.200	35.46	.057
<i>Butea monosperma</i>	5.31	12.5	1.00	50.98	.106
<i>Balanites aegyptiaca</i>	2.65	8.33	.030	11.74	.12
<i>Capparis sepiaria</i>	258.8	84			
<i>Dichrostachys cineria</i>	103.5	48			
<i>Grewia flavescens</i>	42.3	32			

Understorey vegetation: The understorey vegetation was found to be dominated by *Cassia tora* (39333.3 ind/ha), followed by *Achyranthus aspera* (15400 ind/ha) and *Sida acuta* (6333.3 ind/ha). *Chloris dolichostachya* and *Heteropogon contortus* were the most abundant within the grass species. Species richness for shrub, herb and grass for this community was 5, 18 and 11 respectively (Table 3.16).

Table 3.16 Diversity, Richness, Evenness of shrubs and herbs in community 1

	Shrub species	Herb species
Diversity	0.97	1.63
Richness	5	18
Evenness	0.60	0.56

2. *Acacia catechu*-*Zizyphus mauritiana*- scrubland community (20 plots)

In this community, *Acacia catechu* is the dominant species with IVI value of 184.23 and *Zizyphus mauritiana* is the sub-ordinate species with IVI value of 84.56. *Acacia catechu* and *Zizyphus mauritiana* followed a regular distribution with an A/F ratio of 0.018 and 0.024 respectively while *Anogeissus pendula* and *Acacia leucophloea* followed contiguous distribution (Table 3.17). Among shrub species, *Capparis sepiaria* and *Grewia flavescens* dominated the landscape.

Table 3.17 Density, Freq (frequency), TBA (total basal area), IVI, A/F ratio of different species in community 2

Species	Density/ha	Freq (%)	TBA(m ² /ha)	IVI	A/F ratio
<i>Acacia catechu</i>	38.2	80	1.363	184.23	.018
<i>Zizyphus mauritiana</i>	19.1	50	.390	84.569	.024
<i>Anogeissus pendula</i>	3.18	10	.126	18.266	.1
<i>Acacia leucophloea</i>	1.59	5	.139	12.934	.2
<i>Capparis sepiaria</i>	229.4	75			
<i>Grewia flavescens</i>	347.0	75			

Understorey vegetation: Among herbs, *Cassia tora* was found to be highly abundant (3.754) followed by *Achyranthus aspera* (2.312), *Dicliptera verticillata* (1.379) and *Sida acuta* (1.245). *Chloris dolichostachya* (27.29 %) was the most abundant among grasses followed by *Heteropogon contortus* (24 %). The species richness of shrub, herb and grass for this community was found to be 7, 14 and 13 respectively (Table 3.18).

Table 3.18 Diversity, Richness, Evenness of shrubs and herbs in community 2.

	Shrub species	Herb species
Diversity	1.29	1.71
Richness	7	14
Evenness	0.66	0.65

3. *Prosopis juliflora*-*Lantana camara* scrubland (8 plots)

Prosopis juliflora had the highest IVI value in the community followed by *Acacia senegal* and *Balanites aegyptiaca* (Table 3.19). *Prosopis juliflora* and *Acacia senegal* were randomly distributed and *Balanites*

aegyptiaca followed contiguous distribution in the community. Among shrubs, *Lantana camara* and *Grewia flavescens* were the most abundant species.

Table 3.19 Density, Freq (frequency), TBA (total basal area), IVI, A/F ratio of different species in community 3

Species	Density/ha	Freq (%)	TBA(m ² /ha)	IVI	A/F ratio
<i>Prosopis juliflora</i>	75.64	75	4.731	193.29	.042
<i>Acacia senegal</i>	15.92	37.5	.441	44.48	.035
<i>Balanites aegyptiaca</i>	15.92	25	.290	34.18	.08
<i>Lantana camara</i>	397.06	62.5			
<i>Grewia flavescens</i>	397.06	100			

Understorey vegetation: Among herbs, *Achyranthus aspera*, *Ocimum canum*, *Peristrophe bicalyculata* and *Sida acuta* were dominant species. Among grasses, *Digitaria ciliaris* and *Cynodon dactylon* were the most abundant species. Species richness of shrub, herb and grass for this community was 8, 11 and 7 respectively (Table 3.20).

Table 3.20 Diversity, Richness, Evenness of shrubs and herbs in community 3

	Shrub species	Herb species
Diversity	1.49	0.83
Richness	8	11
Evenness	0.72	0.34

4. *Acacia-Grewia flavescens* scrubland (8 plots)

Acacia leucophloea and *Acacia Senegal* were the important constituent species of this community with IVI values 141.44 and 90.24 respectively. *Acacia leucophloea* showed a regular distribution (Table 3.21) with an A/F ratio of 0.019, whereas *Acacia senegal*, *Acacia catechu* and *Anogeissus pendula* showed a contiguous distribution with A/F ratio of 0.12, 0.08 and 0.16 respectively. Among shrubs, *Grewia flavescens* had the highest density with 514.7 ind/ha, followed by *Securinega leucopyrus* (191.18 ind/ha) and *Zizyphus nummularia* (161.76 ind/ha).

Table 3.21 Density, Freq (frequency), TBA (total basal area), IVI, A/F ratio of different species in community 4

Species	Density/ha	Freq (%)	TBA(m ² /ha)	IVI	A/F ratio
<i>Acacia leucophloea</i>	23.89	62.5	.825	141.44	.019
<i>Acacia senegal</i>	23.89	25	.504	90.24	.12
<i>Acacia catechu</i>	3.98	12.5	.298	34.34	.08
<i>Anogeissus pendula</i>	7.96	12.5	.171	33.96	.16
<i>Grewia flavescens</i>	514.71	100			
<i>Securinega leucopyrus</i>	191.18	37.5			
<i>Zizyphus nummularia</i>	161.176	62.5			

Understorey vegetation: For herbs, *Indigofera linnaeii*, *Cassia tora*, *Dicliptera verticillata*, *Indigofera cordifolia* were the dominant species with densities as 15625 ind/ha, 11875 ind/ha, 8958.3 ind/ha and 8333.3 ind/ha respectively. Among grass species, *Cynodon dactylon*, *Digitaria ciliaris* and *Tragus roxburghii* were abundant than other species. Species richness for shrubs, herbs and grasses for this community was found to be 12, 17 and 8 respectively (Table 3.22).

Table 3.22 Diversity, Richness, Evenness of shrubs and herbs in community 4.

	Shrub species	Herb species
Diversity	1.94	2.43
Richness	12	17
Evenness	0.78	0.85

5. *Acacia leucophloea*-*Zizyphus nummularia*-*Prosopis juliflora* scrub (9 plots)

Acacia leucophloea had the highest IVI value among trees (Table 3.23) followed by *Zizyphus mauritiana*. *Acacia leucophloea*, *Zizyphus mauritiana*, *Prosopis juliflora* and *Balanites aegyptiaca* showed a contiguous distribution (A/F ratio= 0.27, 0.18, 0.09, 0.09 respectively). Among shrubs, *Zizyphus nummularia* (2013.07 ind/ha) was the most abundant species.

Table 3.23 Density, Freq (frequency), TBA (total basal area), IVI, A/F ratio of different species in community 5

Species	Density/ha	Freq (%)	TBA(m ² /ha)	IVI	A/F ratio
<i>Acacia leucophloea</i>	10.62	11.11	.501	121.77	.27
<i>Zizyphus mauritiana</i>	7.08	11.11	.260	81.60	.18
<i>Prosopis juliflora</i>	3.54	11.11	.101	50.19	.09
<i>Balanites aegyptiaca</i>	3.54	11.11	.066	46.41	.09
<i>Zizyphus nummularia</i>	2013.07	100			

Understorey vegetation: Among herbs, *Achyranthus aspera*, *Sida acuta* and *Cassia tora* were the most abundant species with densities as 17592.5 ind/ha, 13703.7 ind/ha and 11111.1 ind/ha respectively. *Cynodon dactylon* and *Digitaria ciliaris* were the most abundant among grass in this community. Species richness in this community for shrubs, herbs and grasses was found to be 8, 16 and 9 respectively (Table 3.24).

Table 3.24 Diversity, Richness, Evenness of shrubs and herbs in community 5.

	Shrub species	Herb species
Diversity	0.58	2.21
Richness	8	16
Evenness	0.28	0.79

6. *Prosopis juliflora* community (6 plots)

Prosopis juliflora was the major species in the community with an IVI value of 261.19 (Table 3.25). However, the distribution for *Prosopis juliflora* and *Acacia senegal* was found random (A/F ratio=0.03) and contiguous (A/F ratio= 0.06) respectively. Among shrubs, *Capparis decidua* was found to be the most abundant species among all species.

Table 3.25 Density, Freq (frequency), TBA (total basal area), IVI, A/F ratio of different species in community 6

Species	Density/ha	Freq (%)	TBA(m ² /ha)	IVI	A/F ratio
<i>Prosopis juliflora</i>	42.46	66.66	2.34	261.19	.03
<i>Acacia senegal</i>	5.31	16.66	.195	38.80	.06
<i>Capparis decidua</i>	39.2	33.33			
<i>Dichrostachys cineria</i>	19.6	16.66			

Understorey vegetation: Among herbs, *Achyranthus aspera* (24722.2 ind/ha) had the highest density followed by *Cassia tora* (8055.5 ind/ha). Among grasses, *Cynodon dactylon* and *Digitaria ciliaris* were the most abundant species with percentage cover of 25.13 % and 12.63 %. The species richness for shrubs, herbs and grass for this community was found to be 3, 8 and 7 respectively (Table 3.26).

Table 3.26 Diversity, Richness, Evenness of shrubs and herbs in community 6

	Shrub species	Herb species
Diversity	0.75	0.92
Richness	3	8
Evenness	0.69	0.44

3.4.3 Population structure and Regeneration

There are several methods to study the regeneration status of forest communities such as dominance-diversity curve (Whittaker, 1972), density-diameter curve (Spurr, 1952; Rollet, 1974; Saxena & Singh, 1984) and population structure (Singh & Singh, 1987). The most appropriate methods seem to be population structure, which is a very useful in predicting the future composition of the forest by highlighting the regeneration behavior and reproductive strategy of different species (Saxena *et al.*, 1979). Population structure of five dominant tree species from each community was evaluated separately dividing them into seedlings, saplings and different girth classes *viz.*, 30-61.4 cm, 61.5-91.4 cm, 91.5- 121.4 cm, 121.5-151.4 cm, 151.5-191.4 and above 191.5 cm.

3.4.3.1 Communities with *Adhatoda* presence

Community 1. *Adhatoda vasica*-*Balanites aegyptiaca*

The community had an overall seedlings and saplings density of 256.85 ind/ha and 469.01 ind/ha respectively. *B. aegyptiaca* had the maximum seedlings (219.33 ind/ha) and saplings (402.43 ind/ha) (Figure 3.11). Higher girth class individuals (GBH > 30 cm) were not observed for other species in the community (Figure 3.6).

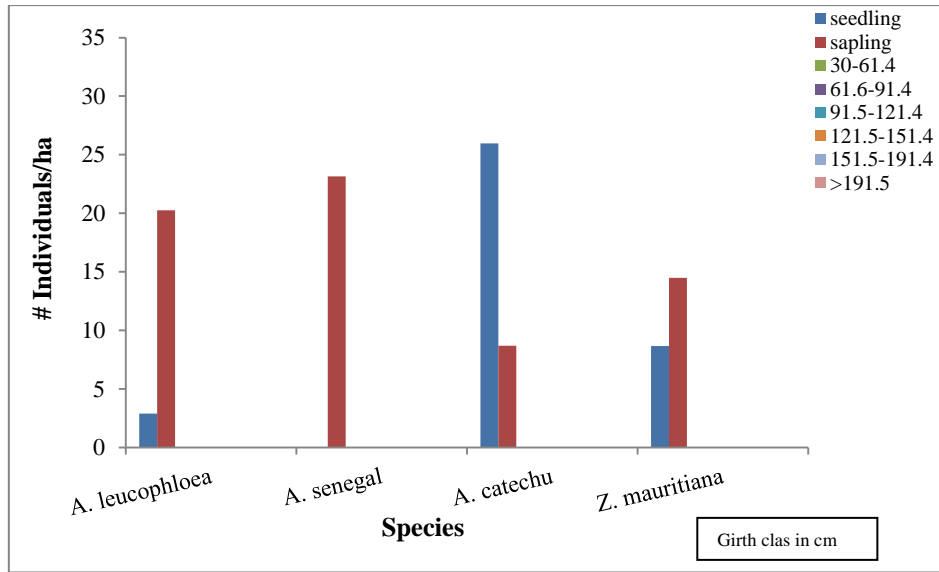


Figure 3.6 Population structure of tree species in *Adhatoda vasica*-*Balanites aegyptiaca* community

Community 2. *Adhatoda vasica*-*Acacia leucophloea*

The community had an overall seedlings and saplings density of 164.47 ind/ha and 495.24 ind/ha respectively. *B. aegyptiaca* had the maximum number of seedlings (139.7 ind/ha) and saplings (495.2 ind/ha) (Figure 3.11). In this community, *Z. mauritiana* showed a better regeneration (reverse J curve) than other species (Figure 3.7) that means individuals were present in all the girth classes and there were highest number of seedlings. While *A. leucophloea* had all categorised girth classes, *A. catechu* had only higher girth class members (GBH > 150 cm) and *A. pendula* showed presence of seedling and sapling only.

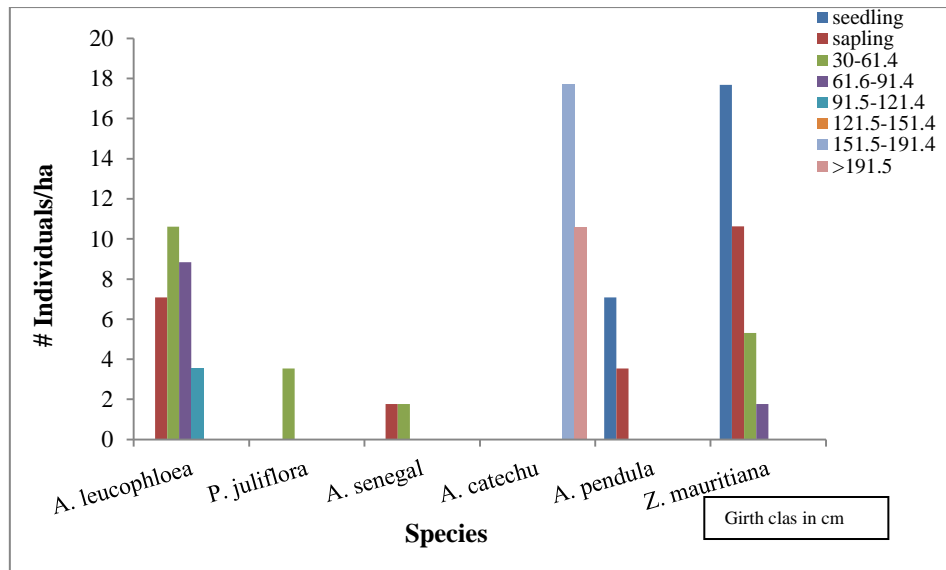


Figure 3.7 Population structure of tree species in *Adhatoda vasica*-*Acacia leucophloea* community

Community 3. *Adhatoda vasica*-*Acacia leucophloea*-*Butea monosperma*

The community had an overall seedlings and saplings density of 323.99 ind/ha and 272.77 ind/ha respectively. *B. aegyptiaca* had the maximum seedlings (304.6 ind/ha) and saplings (254.7 ind/ha) (Figure 3.11). *Z. mauritiana* showed an ideal regeneration pattern (reverse J). *A. leucophloea* showed individuals of all girth classes whereas *B. monosperma* had maximum individuals in higher girth classes (GBH > 91 cm) (Figure 3.8).

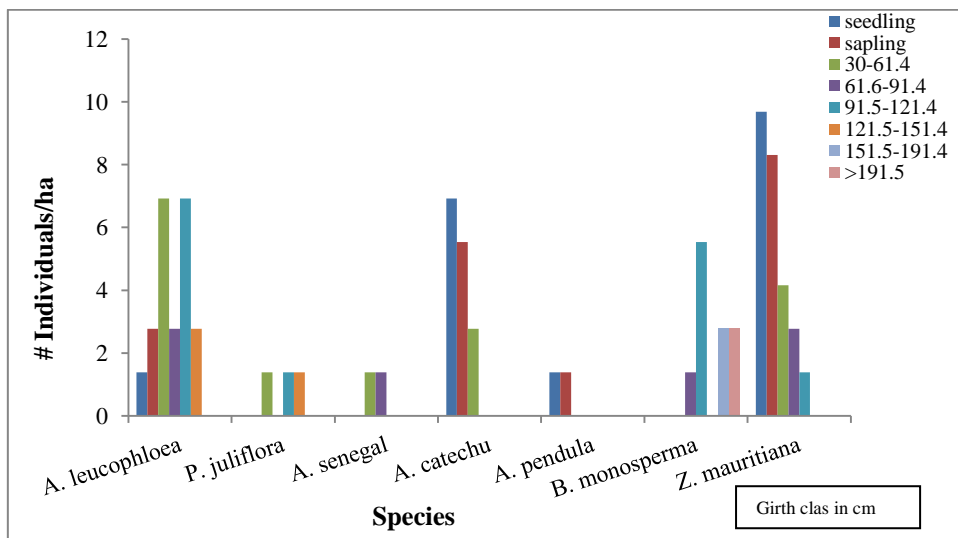


Figure 3.8 Population structure of tree species in *Adhatoda vasica*-*Acacia leucophloea*-*Butea monosperma* community

Community 4. *Adhatoda vasica*-*Acacia catechu*-*Zizyphus mauritiana*

The community had an overall seedlings and saplings density of 262.26 ind/ha and 43.09 ind/ha respectively. *A. pendula* had the maximum seedlings (226.6 ind/ha) while *B. aegyptiaca* had maximum sapling (26.2 ind/ha). *B. monosperma*, *A. catechu*, *A. leucophloea* and *Z. mauritiana* showed presence of older trees in the community but lesser girth trees were not reported in *B. monosperma* and *A. leucophloea* indicating considerable issues of regeneration (Figure 3.9).

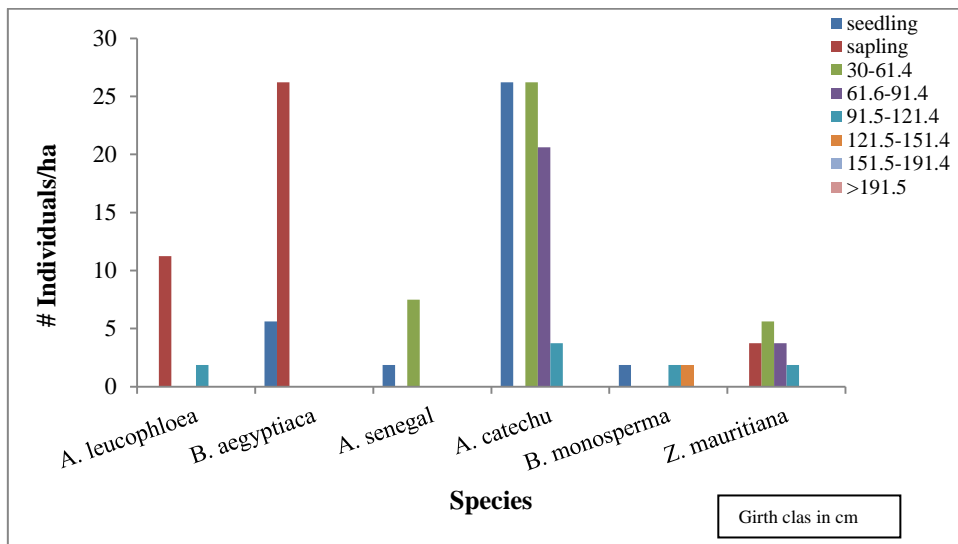


Figure 3.9 Population structure of tree species in *Adhatoda vasica*-*Acacia catechu*-*Zizyphus mauritiana* community

Community 5. *Adhatoda vasica*- *Prosopis juliflora*

The community had an overall seedlings and saplings density of 684.71 ind/ha and 652.86 ind/ha respectively. *B. aegyptiaca* had the maximum seedlings (676.75 ind/ha) and sapling (557.32 ind/ha) but no higher girth class densities were observed (Figure 3.11). In this community, sporadic presence of individuals in various girth classes was seen (Figure 3.10).

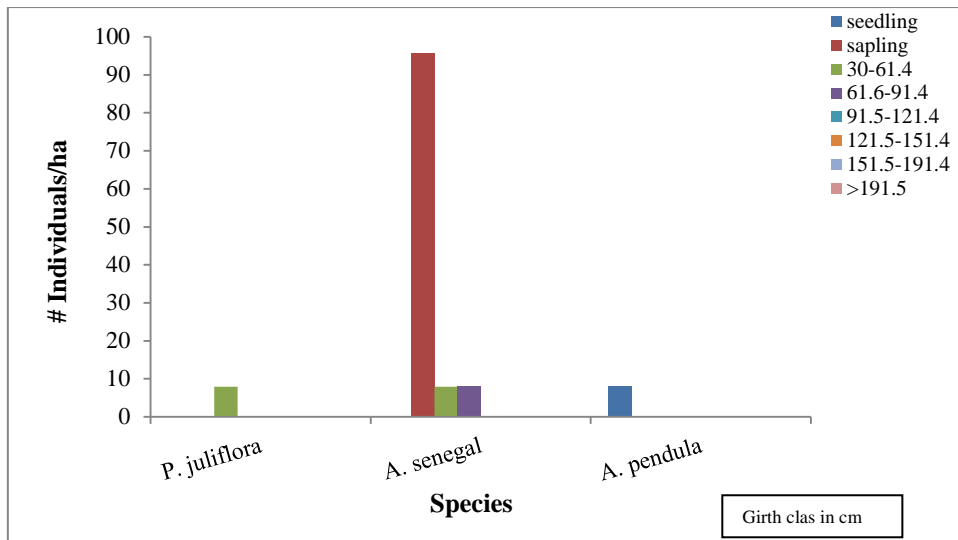


Figure 3.10 Population structure of tree species in *Adhatoda vasica- Prosopis juliflora* community

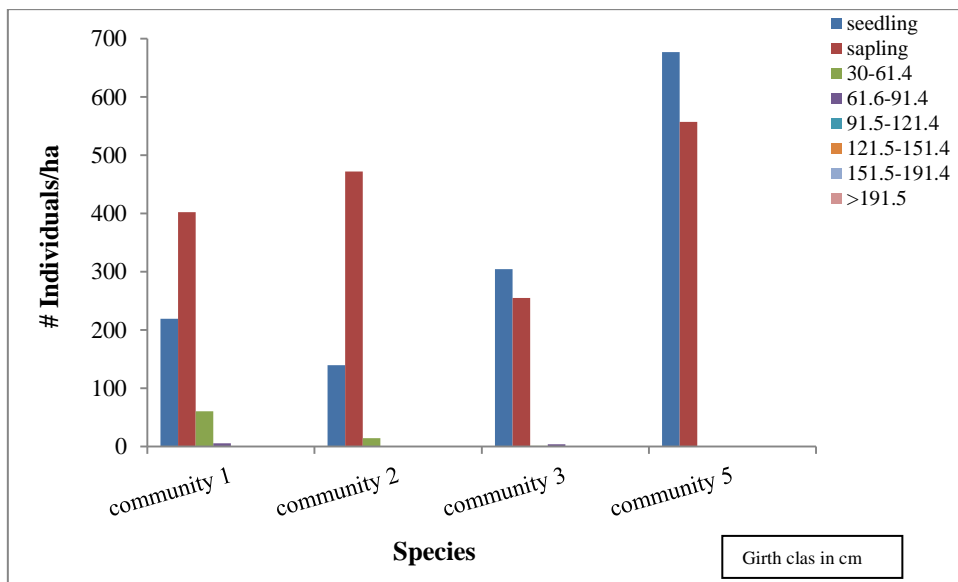


Figure 3.11 Population structure of *Balanites aegyptiaca* in different communities

3.4.3.2 Communities without *Adhatoda* presence

Community 1. *Zizyphus mauritiana-Butea monosperma*

The community had an overall seedlings and saplings density of 84.07 ind/ha and 113.37 ind/ha respectively. *A. catechu* had the maximum seedlings (40.76 ind/ha) while *B. aegyptiaca* had maximum saplings (78.98 ind/ha) (Figure 3.18). In this community, *Z. mauritiana* showed a “reverse J” curve whereas *B. monosperma* had a constant girth class distribution (Figure 3.12).

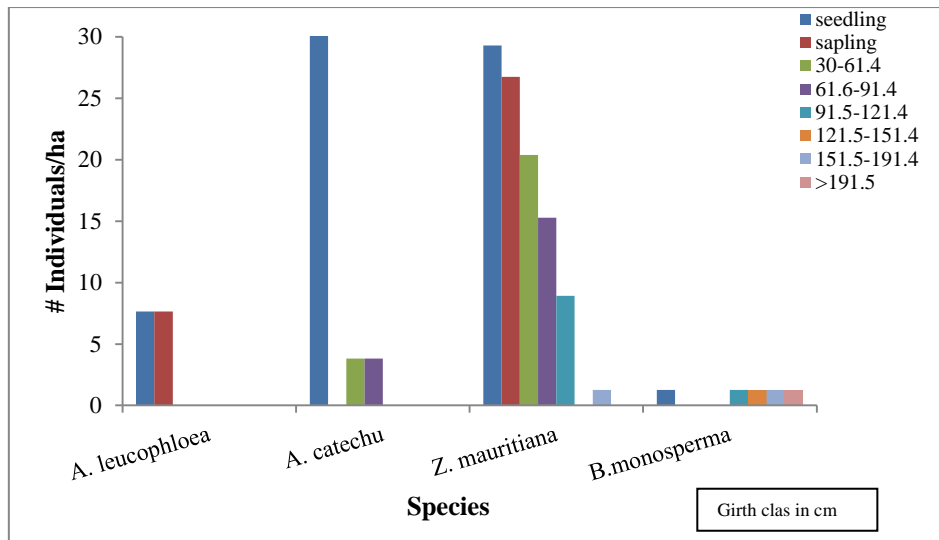


Figure 3.12 Population structure of tree species in *Zizyphus mauritiana*-*Butea monosperma* community

Community 2. *Acacia catechu*-*Zizyphus mauritiana*

The community had an overall seedlings and saplings density of 401.27 ind/ha and 278.66 ind/ha respectively. *Z. mauritiana* had the maximum seedlings (254.7 ind/ha), while *B. aegyptiaca* had maximum sapling density (175.1 ind/ha) (Figure 3.18). *Z. mauritiana* and *A. catechu* showed an ideal regeneration pattern (reverse J). *A. pendula* had higher seedling establishment but poor conversion of seedling into higher girth class individuals (Figure 3.13).

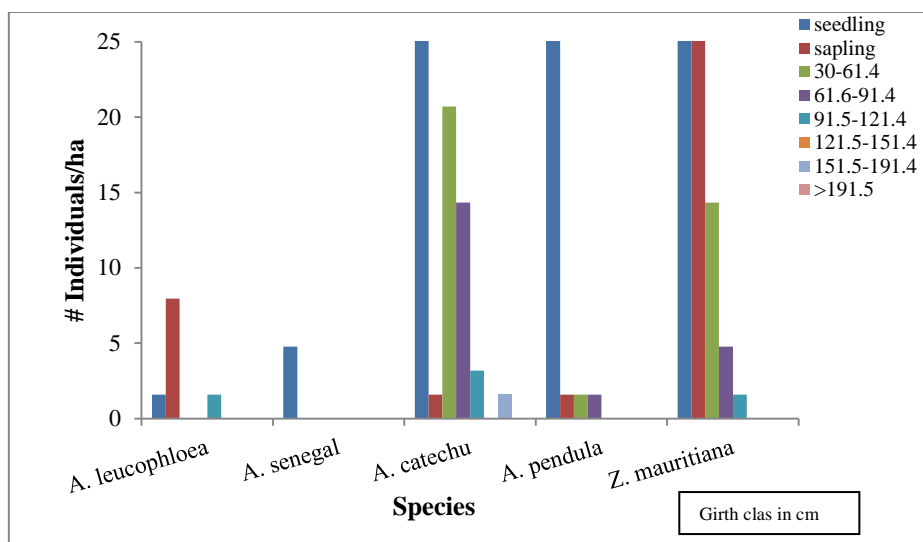


Figure 3.13 Population structure of tree species in *Acacia catechu*-*Zizyphus mauritiana* community

Community 3. *Prosopis juliflora*-*Lantana camara* scrubland

The community had an overall seedlings and saplings density of 298.56 ind/ha and 955.41 ind/ha respectively. *B.aegyptiaca* had the maximum seedlings (298.5 ind/ha), saplings (955.4 ind/ha) and also had good number of higher girth class distribution (Figure 3.18). In this community, *Prosopis juliflora* showed presence of higher girth class individuals (GBH > 30 cm) but no seedlings and saplings were found (Figure 3.14).

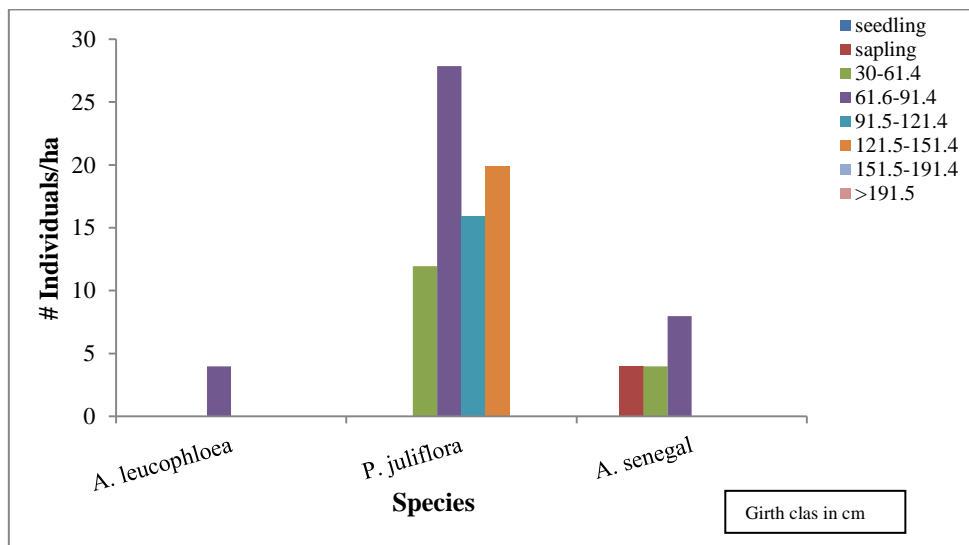


Figure 3.14 Population structure of tree species in *Prosopis juliflora-Lantana camara* scrubland community

Community 4. *Acacia-Grewia flavescens*

The community had an overall seedlings and saplings density of 346.33 ind/ha and 441.87 ind/ha respectively. *B. aegyptiaca* had the maximum seedlings (342.3 ind/ha) and saplings (382.1 ind/ha) but had poor conversion into higher girth class (Figure 3.18). *A. catechu* also showed poor conversion as medium and lower girth classes (30 cm < GBH < 90 cm) were not observed despite seedlings being present (Figure 3.15).

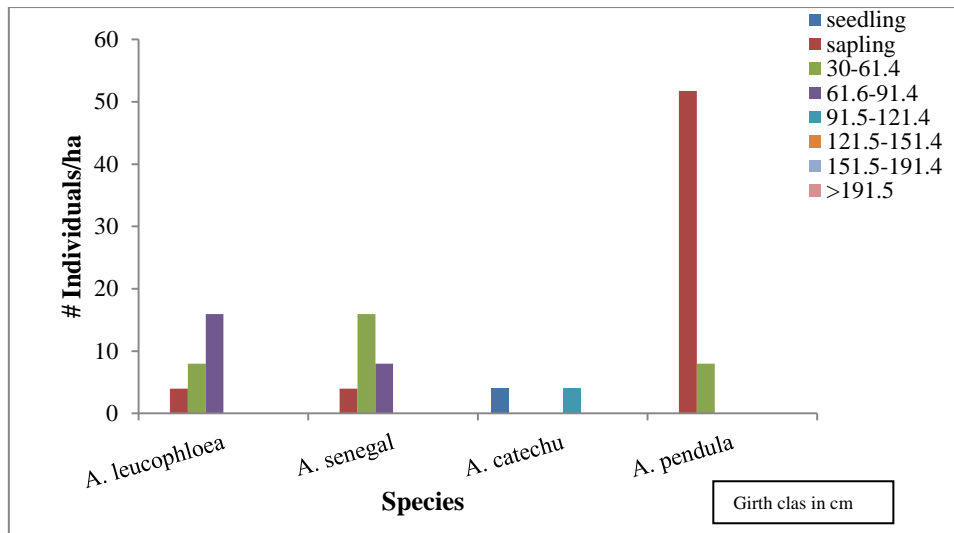


Figure 3.15 Population structure of tree species in *Acacia-Grewia flavescens* community

Community 5. *Acacia leucophloea-Zizyphus nummularia-Prosopis juliflora* scrubland

The community had an overall seedlings and saplings density of 60.15 ind/ha and 127.38 ind/ha respectively. *B. aegyptiaca* had the maximum seedlings (56.6 ind/ha) and sapling (109.7 ind/ha) but had poor representation in higher girth class densities (GBH > 30 cm) (Figure 3.18). In this community, *A. leucophloea* showed a bell shaped curve and *Z. mauritiana* had presence of saplings but no greater girth classes (GBH > 30 cm) except one in particular inferring to a stagnant growth for this species (Figure 3.16).

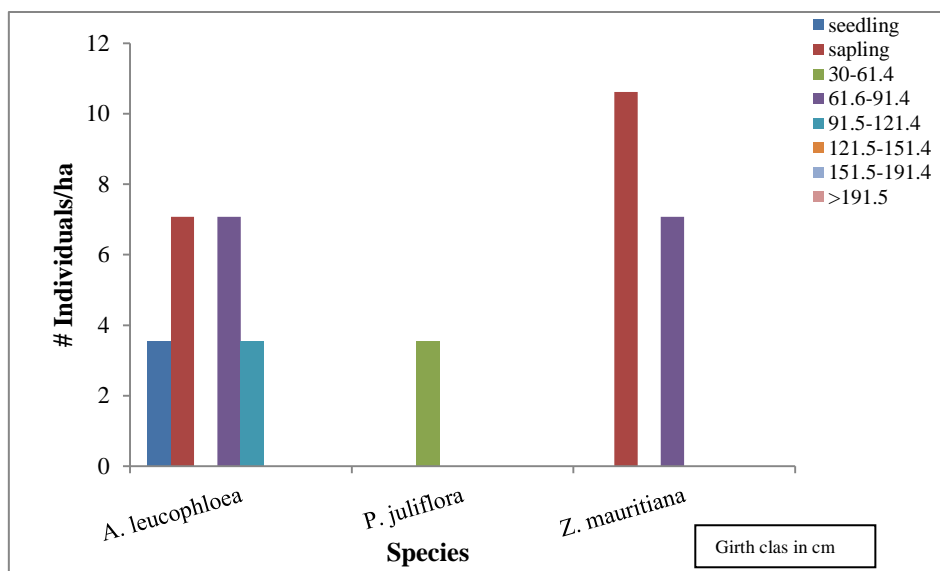


Figure 3.16 Population structure of tree species in *Acacia leucophloea-Zizyphus nummularia-Prosopis juliflora* scrubland community

Community 6. *Prosopis juliflora*

The community had an overall seedlings and saplings density of 5.31 ind/ha and 5.31 ind/ha respectively represented by *B. aegyptiaca* solely. *P. juliflora* showed presence in middle girth and higher girth classes (GBH > 30 cm) but no seedlings and saplings were recorded (Figure 3.17).

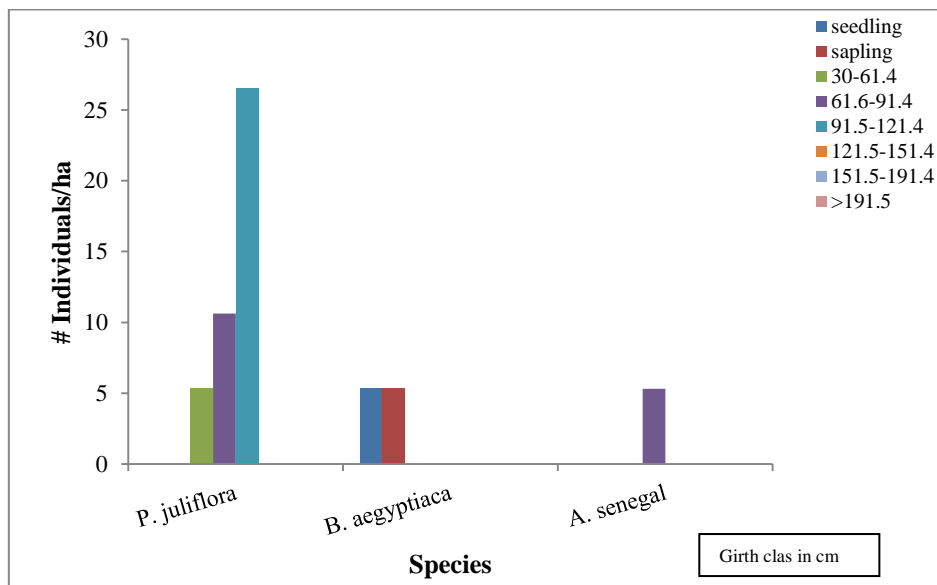


Figure 3.17 Population structure of tree species in *Prosopis juliflora* community

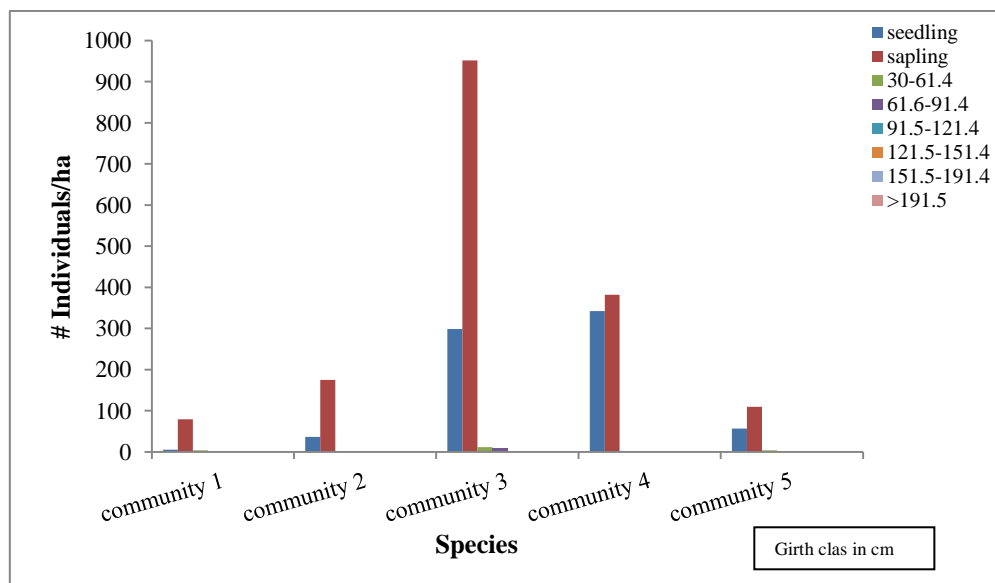


Figure 3.18 Population structure of *Balanites aegyptiaca* in different communities

3.5 Discussion

3.5.1 Vegetation classification and composition

Vegetation analysis of the savanna of STR provided a valuable insight into the distribution of tree species across the landscape. The plant communities are considered sub-divisions of a vegetation type and wherever the vegetation shows obvious spatial changes, one may distinguish a different community (Shimwell, 1971; Muller-Dombois & Ellenberg, 1974; Gauch, 1982). The ultimate aim of classifying the vegetation data is to find the 'natural' or near natural groupings to make ecological sense (Rawat, 2007). This study was performed for identifying and describing the major woody plants communities and their structure along the landscape.

The study area was divided into *Adhatoda vasica* present and absent areas and in total, 11 communities were identified with TWINSpan with the help of PC-ORD software. Out of these 11 communities, 5 were identified for *Adhatoda* present area and 6 from *Adhatoda* absent area. *Balanites aegyptiaca* figures out as one of the highly distributed species in the scrub savanna landscape.

***Adhatoda* present:** Five communities were found where, *A. leucophloea* was found to be the dominant species in two communities and *A. catechu* and *A. senegal* in one community each. The shrub layer was dominated by *G. flavescens* and *C. sepiaria*. *Adhatoda vasica* was dominant in all the communities with a 100% occurrence. The highest density of *Adhatoda vasica* was found to be in *Adhatoda-Acacia leucophloea-Butea monosperma* community (6030 ind/ha). The highest tree density was found in *Adhatoda-Acacia catechu-Zizyphus* community (86.16 ind/ha) and highest basal area was found in *Adhatoda-Acacia leucophloea-Butea monosperma* community (4 m²/ha). Herb density was found to be highest in *Adhatoda vasica- Balanites aegyptiaca* community (10.05 ind/m²) and lowest in *Adhatoda vasica-Acacia leucophloea-Butea monosperma* community (5.77 ind/m²). In case of shrubs, *Adhatoda vasica- Acacia leucophloea-Butea monosperma* community (7110 ind/ha) had highest density and *Adhatoda vasica-Prosopis juliflora* community had the lowest density (2088.2 ind/ha). The tree diversity ranged from 0 - 1.59 with the highest tree diversity being observed in *Adhatoda- Acacia leucophloea-Butea monosperma* community (1.59) and lowest in *Adhatoda vasica- Balanites aegyptiaca* community (0). The highest shrub diversity was observed in *Adhatoda vasica-Balanites aegyptiaca* (1.58) community and lowest in *Adhatoda vasica-Acacia catechu- Zizyphus mauritiana* community (0.59). The highest herb diversity was observed in *Adhatoda vasica-Acacia leucophloea-Butea monosperma* community (2.22). The herb diversity ranged from 1.77- 2.22. The highest species richness for trees was found in *Adhatoda vasica-Acacia leucophloea-Butea monosperma* community (6) and *Adhatoda vasica-Acacia catechu-Zizyphus mauritiana* community (6), for shrubs in *Adhatoda vasica-Acacia leucophloea* community (13), for herbs in *Adhatoda vasica-Acacia leucophloea-Butea monosperma* community (20).

Adhatoda absent: Six communities were found in this category and *Z. mauritiana* and *A. leucophloea* were the dominant constituents in these communities. Understorey was dominated by *G. flavescens* and *C. sepiaria*. The highest tree density of 107.48 ind/ha and highest basal area of 5.462 m²/ha was observed for *Prosopis juliflora-Lantana camara* scrubland community. *Acacia leucophloea-Zizyphus nummularia-Prosopis juliflora* scrubland community had the highest tree diversity (1.27) whereas *Prosopis juliflora* community had the lowest tree diversity. *Acacia leucophloea-Zizyphus nummularia-Prosopis juliflora* community (2300.6 ind/ha) and lowest shrub density was observed in *Prosopis juliflora* community (215.7 ind/ha). For herbs, *Prosopis juliflora- Lantana camara* community showed maximum density (9.41 ind/m²) and *Prosopis juliflora* community showed minimum density (3.55 ind/m²). The highest species richness for trees was found in *Prosopis juliflora-Lantana camara* scrubland community (5), for shrubs in *Acacia-Grewia flavescens* scrubland community (12), for herbs in *Zizyphus mauritiana-Butea monosperma* community (18).

When we compare both scenarios we can conclude that the species richness was found to be higher for *Adhatoda* infested communities which can be attributed to the fact that since *Adhatoda* prefers moist localities and hence more species were found here. Tree density was better in the absence of *Adhatoda*. It is clearly understood that the presence of *Prosopis juliflora* which is also an invasive species has an antagonistic effect on the native vegetation. The forest structure was highly modified by monsoonal activity as there is a two fold increase in the number of species of herbaceous layer (Figure 3.19) and activity limited to a water limited growth period also indicating resource niche separation between tree and herb layer.

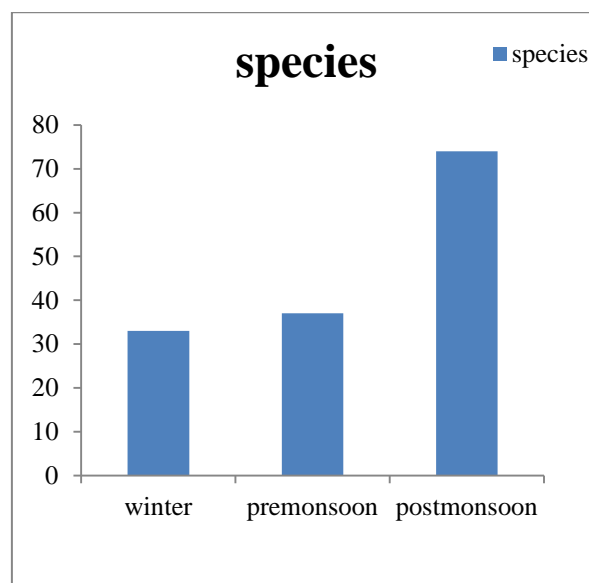


Figure 3.19 Species richness in herbs during different seasons

3.5.2 Population structure and Regeneration pattern

Based on population structure four categories of regeneration can be visualized: 1) expanding or stable type with many seedlings and smaller number of tree size classes, 2) declining type with nodal values in small classes and individuals of many size classes, 3) interrupted indicating gap phase of regeneration and 4) youthful with seedling and sapling only (Singh & Singh, 1992).

Dominant tree species were observed for each community and it was observed that in *Adhatoda vasica* present area, *Z. mauritiana* showed a stable population growth, *A. leucophloea* and *A. catechu* showed interrupted regeneration. However, *A. pendula* had higher number of seedlings but they were unable to survive due to high anthropogenic pressures. Hence, a few trees of lower girth classes were represented in *A. pendula* forests. *B. monosperma* trees showed presence of higher girth class individuals and no sapling and lower girth class individuals. In *Balanites aegyptiaca*, seedlings were represented by nearly half of the communities which is higher than saplings.

In *Adhatoda* absent communities, *Z. mauritiana* and *A. catechu* showed a stable population growth. *A. leucophloea* showed a youthful population structure. *B. monosperma* showed a declining type of structure. *A. pendula* showed extremely high number of seedling and sapling but due to grazing pressures, very few could successfully survive to the next girth class. For *Balanites aegyptiaca*, seedlings were found to be lesser than saplings in all the communities.

I also compared the differences in sapling and seedling densities, diversity indices for effect of *Adhatoda* infestation in similar communities and four communities could be marked for the evaluation as these were found to have similar species composition. In *Acacia –Zizyphus* woodland and *Balanites aegyptiaca* scrubland, seedling and sapling density was found to be greater in *Adhatoda* absent area. In *Prosopis juliflora* scrubland, *Adhatoda* infestation facilitates the sapling and seedling establishment and no seedling and sapling occurrence was observed in non-infested area (Figure 3.20). In *Acacia-Grewia* scrubland, seedlings were reported to be more in non-infested area while saplings were more in *Adhatoda* infested area. Species count for shrubs was found to be higher in *Adhatoda* absent areas for all the communities however (Figure 3.21) Evenness was found to be higher in *Adhatoda* present areas. Diversity was lower in *Adhatoda* present areas for *Prosopis juliflora* scrubland and *Balanites aegyptiaca* scrubland but higher in *Acacia- Zizyphus* woodland and *Acacia- Grewia* scrubland. Species count (Figure 3.22) for herbs also showed a similar trend as shrubs. Evenness and Diversity in herbs was lower in *Adhatoda* present areas for three out of four communities. Thus, I could conclude that presence of *Adhatoda* limited the sapling and seedling density in most communities and also it increased the species richness and diversity for shrubs and herbs and Evenness in herbs. In case of scrubland, *Adhatoda* infestation did not seem to have a significant

effect on grass cover (Figure 3.23), however, grass cover for *Acacia-Zizyphus* woodland was significantly decreased by the infestation of *Adhatoda*.

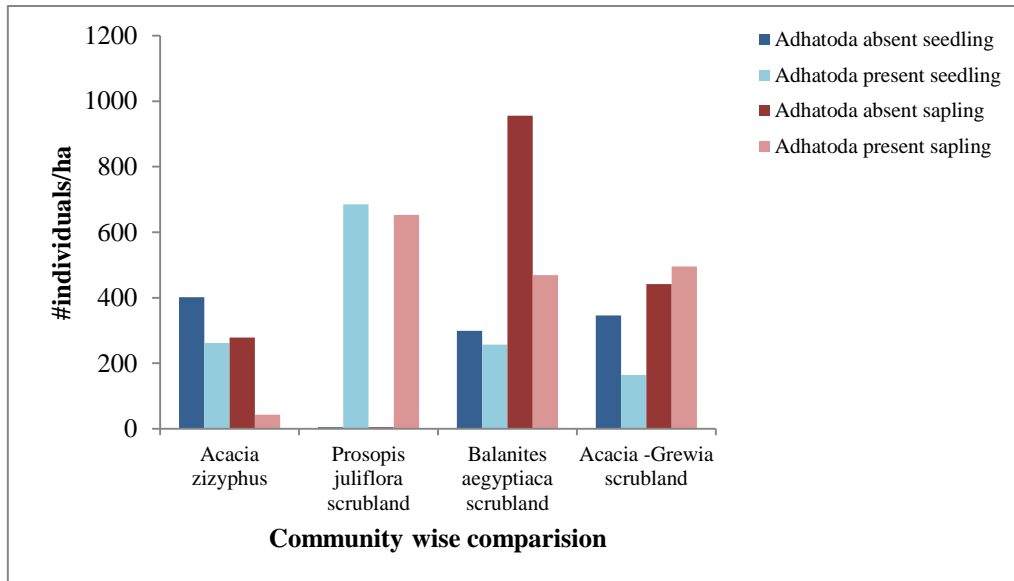


Figure 3.20 Seedling and sapling population for various communities under presence and absence of *Adhatoda*

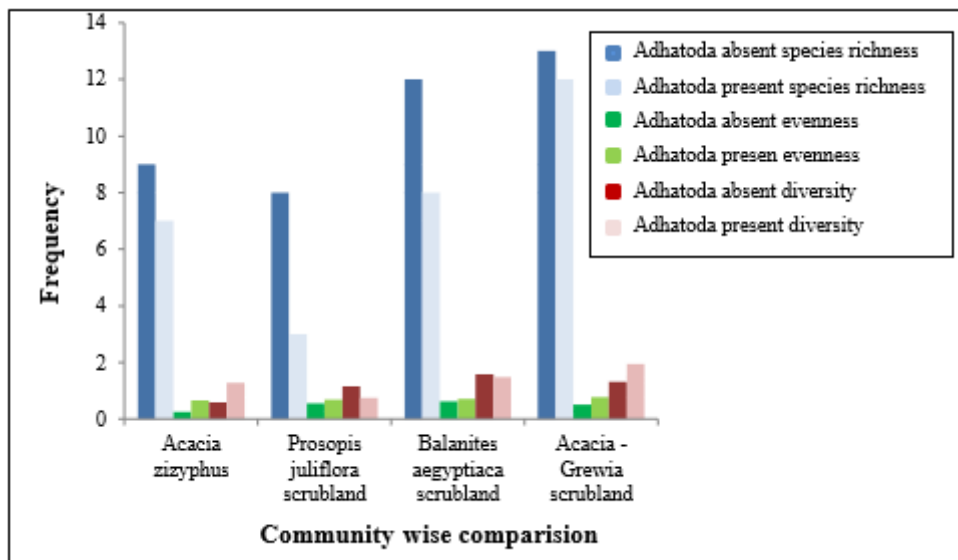


Figure 3.21 Variation in Richness, Evenness and Diversity indices for shrubs in different plant communities

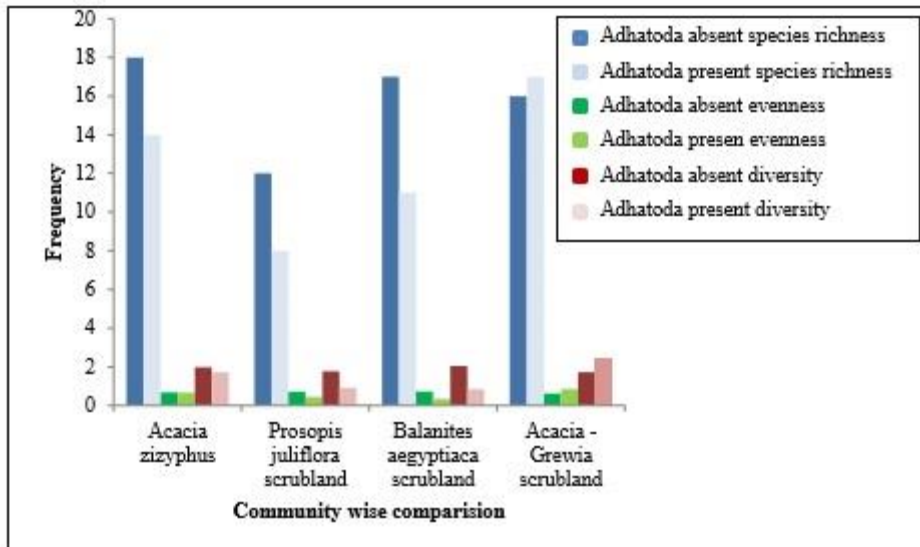


Figure 3.22 Variation in Richness, Evenness and Diversity indices for herbs in different plant communities

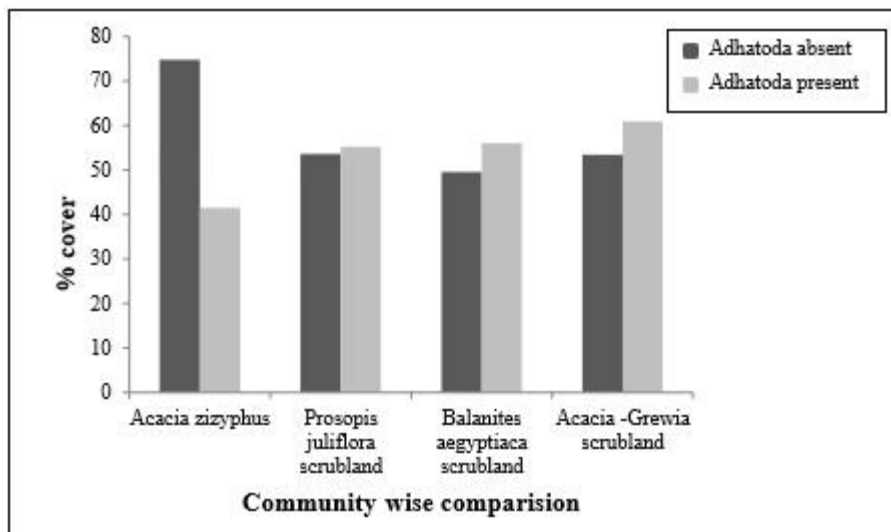


Figure 3.13 Grass cover in various communities in *Adhatoda* infested and non-infested area

The study reveals that two categories of savanna vegetation are predominant in STR: (a) Tree savanna, and (b) Scrub savanna.

Tree savanna: It was commonly observed to consist of a canopy dominated by species viz. *Acacia leucophloea*, *Butea monosperma*, *Acacia catechu* and *Zizyphus mauritiana* occurring solely or two species

interspersed throughout the landscape. The common grasses were *Chloris dolichostachya*, *Heteropogon contortus*, *Desmostachya bipinnata* etc. which were approx. 1-1.5 m high and acted as an excellent cover for small carnivores. These grasses also caused mortality in young seedlings due to lack of sunlight reaching the ground but protected them from frost bite and grazing by herbivores such as spotted deer. *Grewia flavescens* and *Capparis sepiaria* were major shrubs found here. The grazing potential of the landscape was represented distinctly by grasses, however, grazers such as spotted deer turned to *Capparis decidua* bushes during the lean season.

Scrub savanna: The landscape was found to be dominated by *Balanites aegyptiaca* and *Zizyphus nummularia* along with dominant grass species with features such as short height as in *Cynodon dactylon*, *Tragus roxburghii* and *Sporobolus coromandalianus*. The grass layer was low enough to allow penetration of sunlight for seedlings but provided no protection to seedlings during frost bite. Thickets of *Grewia flavescens*, *Capparis sepiaria*, *C. decidua*, *G. tenax*, *Ehretia laevis*, *Lantana camara*, *Adhatoda vasica*, *Prosopis juliflora* and *Dichrostachys cinerea* formed the savanna mosaic and provided major cover for small and large carnivores. Fodder for wild ungulates was majorly provided by shrubs such as *Grewia flavescens* and *Capparis sepiaria* and *Acacia* spp. among trees. *Capparis sepiaria* fulfilled fodder requirements during dry season when all other species had lost their green matter (Rodgers, 1990a).

Available soil moisture is used by the roots of annual plants and perennial shrubs and trees from the end of rainy season (September) until this water is depleted by the beginning of winter (November), when most of the annual plants disappear and the perennial plants begin to show certain adaptive changes. During remainder of the rainless earlier cold and later hot season, a partial or absolute status quo is maintained in the soil moisture mainly in the open. Transpiration is eliminated by shedding of leaves especially when temperature reaches peak values even in perennial plants. Leaflessness is a characteristic physiognomic feature of the Indian arid zone vegetation (Sen, 1973). There was a distinct seasonal behaviour pattern among the ungulates and carnivore species in the landscape. During monsoon when water and food was abundant everywhere, the ungulates were observed at all places as opposed to winter and dry season when they formed aggregates and flocked near artificial and supplemented water resources. Grazers turn browsers during the dry season. Similarly with carnivores, un-skewed water and prey availability restricted their migration in monsoons till the dry season forced them to take long journeys for food and water (pers. obs.). Hence we can conclude by saying that savanna landscape in Sariska is defined by abiotic factors such as moisture availability, soil nutrients and biotic factors viz. grazing by wild ungulates, domestic and feral cattle, human disturbance and invasive species.

Chapter 4

PHENOLOGY OF SAVANNA SPECIES

4.1 Introduction:

Phenology is derived from a Greek word *phaino* meaning to show or to appear and deals with the study of periodic biological events in the animal and plant world as influenced by the environment, especially temperature changes driven by weather and climate. Sprouting and flowering of plants in the spring, colour changes of leaves in the fall, bird migration and nesting, insect hatches and animal hibernation are all examples of phenological events (Dubé *et al.*, 1984). It is the art of observing life cycle phase of plants and animals in their temporal occurrence throughout the year (Lieth, 1970). Thus, phenology is the calendar of events in the life history of plants (Abu-Asab *et al.*, 2001). Phenological behaviour determines competition or associations amongst various populations. Competition is avoided and association is favoured by the occurrence of vegetative growth, flowering, fruiting *etc.* at different times of the season (van Schaik *et al.*, 1993).

Human knowledge and activities connected to what is now called phenology are probably as old as civilization itself. Phenological calendar also form the basis of farm work and act as biological indicators to detect seasonality. It has been applied to agriculture to determine timing of planting and harvesting in order to achieve the maximum crop yield (Sakamoto *et al.*, 2005), and also used to decide the timings of applying pesticide and herbicide (Moola & Mallik, 1998). In forest management, tree phenology has been used to estimate forest productivity (Goetz & Prince, 1996), variation of biochemical mass in leaves

(Kause *et al.*, 1999) and to improve seed zoon selections (Hamann & Wang, 2006). In addition, plant phenology is considered the key element that affects the carbon balance of terrestrial ecosystems (Gill *et al.*, 1998) and characterizes plant competition capabilities (Rathcke & Lacey, 1985). These calendars can be of use to understand the past climatic events and prepare models for future. Climate change studies may increase the need to have long term phenological research. The importance of recognizing and accounting for phenological development in plants in relation to ecological studies has been emphasized by Lieth (1970). The seasonal timing of flowering and fruiting, i.e. the reproductive phenology of plants, is directly associated with resource availability to animals and consequently has effects on herbivory, pollination and seed dispersal (Mduma *et al.*, 2007; Stevenson *et al.*, 2009; van Schaik *et al.*, 1993). Phenological studies are also being formed as the basis of climate change studies (Abu-Asab *et al.*, 2001; Moza & Bhatnagar, 2005). The local characteristics of trees (size, foliage, phenology and their spatial arrangement in forests) also have a large influence on the performance of the parasitic generation and the size of succeeding generations. Phenology (the timing of critical stages in their life cycle) is affected by the seasonal development of environmental conditions such as ambient temperature and moisture availability. The spatial distribution is also affected by the geographical range of suitable conditions. The morphology and physiology are responsive to temperature, moisture, and the availability of nutrients (including CO₂), while their risk of extinction is a result of both average and extreme event conditions in climate (e.g., frost or drought). Plants are fine tuned to the seasonality of their environment and shifts in the timing of plant activity provide some of the most compelling evidence that species and ecosystems are being influenced by global environmental change (Cleland *et al.* 2007). In Japan and China the time of blossoming of cherry and peach trees is associated with ancient festivals and some of these dates can be traced back to the eighth century. India also celebrates harvest season which earmarks the onset of spring season.

The savanna habitat is characterized by a period of (severe) drought, the occurrence of fire and herbivory; where the major environmental restriction is the seasonality in rainfall. The savanna species present periodic variations in flower and fruit production that may represent adaptations to biotic and abiotic factors (van Schaik *et al.*, 1993). The general characteristics of vegetation are that rapid growth is observed in the first rains for savanna grasses as the nutrients become available through decomposition of litter (Bourliere & Hadley, 1983). Contrary to herbs, woody trees and shrubs produce new leaves before the first rain possibly triggered by photoperiodicity, temperature and moisture (de Bie *et al.*, 1998). The species constituting the savanna vegetation exhibit population fluxes due to succession, but are usually stabilised by continuing external forces of grazing, trampling, burning, lopping, shifting cultivation and timber removal. The time and intensity of biotic and human pressure arrest the savanna succession at various seral stages particularly in regard to tree/shrub/grass-forb biomass ratios (Misra, 1987). The phenological developments in the study area have been described in the working plan of forest department by Sharma (1983) as the “change in the landscape colour from luscious green in the rains to copper brown to grey in winter, finally to drab grey in the summer and the monotony of the grey being broken by the splash of red

by the “Flame of the forest” in March-April”. (Plate 4.1- 4.7). Hence the main objectives of the study were to document the seasonal patterns of flowering and fruiting in relation to leafing events in common tree species, shrubs and herbs in a tropical dry deciduous forest, to evaluate the relationship between flowering and monsoonal activity and to determine the peak period for leaf fall, fruiting, flowering and leaf formation.

The study was carried out in the savanna woodland of STR in an approximate area of 20 km². The data was collected from June 2009 to May 2010. The study area falls under the semi-arid region. There is a marked seasonality comprising of clear dry (November to May) and wet (June to October) with occasional winter rains. A reconnaissance survey was carried out in the study area and major savanna tree species viz. *Acacia leucophloea*, *A. catechu*, *A. senegal*, *Anogeissus pendula*, *Butea monosperma*, *Balanites aegyptiaca*, *Zizyphus mauritiana*; shrubs viz. *Grewia flavescens*, *Capparis sepiaria*, *C. decidua* and *Z. nummularia* and grasses viz. *Chloris dolichostachya* and *Heteropogon contortus* were identified on the basis of occurrence and availability (Sankar *et al.*, 2008). The bark of *A. senegal* was white in colour and hence was easily identified among other Acacias. *B. aegyptiaca* is known as the date of the desert. It is a slow growing small tree about 20 ft. high with bifoliate ashy green leaves. The species, which occurs in arid zones, grows very slowly and has a slow fruit development. *Z. nummularia* is a small, evergreen much branched tree or a large shrub. Fruit is a drupe, 12 - 15 mm in diameter, globose, fleshy-smooth, yellow or orange when ripe (Rathore, 2009). This species formed a large part of the diet of herbivores and omnivores like Jackal (28.6%) (Gupta, 2011). The species was under a high grazing pressure and poor regeneration. *G. flavescens* is known to provide the best hideout for predators like tiger and leopard, as it turned yellow-brown during dry season thus camouflaging the coat pattern. *C. sepiaria* was a widespread and evergreen shrub which provided palatable forage throughout the year. It was a typical component of *Acacia-Anogeissus pendula* forest (Rodgers, 1990a). *C. decidua* remains leafless throughout its lifecycle with extensive shoots and spines, it has a shrub like growth in the early phase of life and later produces a tree like trunk. Locally known as *kair*, it formed an important ingredient in a rajasthani relish called *kair sangri*. *Z. mauritiana* was a most commonly occurring much branched thorny shrub species in the Indian desert with a height of 1-2 m and light coloured bark. The fruits were mostly round berries with black skinned fruits in early stage which later turned pale and finally dark brown (CAZRI, 1981). This species provided an alternative fruit source to *Z. mauritiana* and was both consumed by animals and human beings. They were collected by local villagers and sold in the local markets (pers. obs.).

4.2 Methodology:

The method used for different layers was as follows:

4.2.1 Trees:

Ten individuals for each of the species selected were marked for observations. Markings were made by roughly slicing a portion of the trunk big enough so that the individual could be marked with permanent paint. The Field tour and Technique Guide for Sariska TR by Wildlife Institute of India (WII), Dehradun was referred for data collection pattern and the datasheet given in the manual was used for this study. The plant phenophases viz. young leaf (YL), mature leaf (ML), flower (FL), young fruit (YF), mature fruit (MF) and no leaf (NL) were recorded on fortnightly basis for one year. Flowering was recorded as percentage of flower visible on the canopy, while foliation meant the flower formation, where 100 % foliage meant all the leaves on the tree are young. Fruiting was recorded in terms of percentage of fruit formation. Data was recorded for all individuals for each species, it was based on approximate ocular estimation. Every 15 days the marked trees were visited and data was recorded for fruiting, flower and foliage. The individuals were chosen away from the roads and villages so that these are less prone to lopping or felling. An average for the ten individuals was taken for analysis. If a change in the phenology was observed in even one individual, the phenophase was assumed to be initiated. Flowering, foliation and fruiting for each species were correlated with rainfall, temperature and humidity. Here fruiting and foliation meant fruit formation and leaf formation respectively. Phenograms were made and phenological patterns were analysed on a temporal scale.

4.2.2 Shrubs:

Ten individuals for the four species were marked by painting the shoots with a permanent paint and tagged by putting plastic ribbon with a number on it. Data for shrubs was collected for 1 year starting from July 2009 to June 2010 and method followed was the same as done for trees. Data for the marked individuals was recorded every fortnight. An ocular estimation was done for any phenophase and data was recorded as a percentage of the respective phase. As an example to be followed, if data on flower was to be recorded for a shrub, then the canopy was divided into four quarters and choosing a random quarter, depending on if the quarter is fully covered with flowers or half covered, was recorded as 100% flower or 50% flower respectively.

4.2.3 Grass:

For grasses, instead of individual grass swards, 5 plots of 1m x 1m for each species were marked by pegs and rope and data on this plot was recorded. The data for each phenophase was expressed as a percent of how much of it is observed approximately in that plot. Data on grasses was recorded every 15 days. The plots were laid at least grazed areas and far from the roads and pathways.

4.3 Results:

The detailed results for leaf flushing, flowering, fruiting, leaf fall and leaf less durations are depicted in the table (Figure 4.1).

4.3.1 Phenological behaviour of tree species:

a) *Acacia catechu*:

A. catechu started flowering in May, peak flowering was observed in June and ceased by August. Flowering lasted from June to August and foliation from mid-May to September. Fruit formation started in June and maximum fruits were available in September and then it subsided by November after which maturation of leaf took place.

b) *A. leucophloea*:

Foliation started in April, reached a peak value in May and discontinued after June. Flowering was initiated in late July with maximum flower formation in September. An overlap was observed between flowering and fruiting as the latter started in September and lasted up to December. Fruits reached maturation by April and dehiscence occurred. Leaf fall was observed during January-March.

c) *A. senegal*:

Flowering, foliation and fruiting for *A. senegal* was initiated in May, April and August respectively and showed a peak for the same in June, July and October respectively. Leaf fall was observed during December-February and trees were bare till April.

d) *Anogeissus pendula*:

Foliation started in late May and continued until October, flowering started in mid- July until mid-August and the fruiting period extended from August to November. It remained leafless from March to May.

e) *Butea monosperma*:

Flowering started in early April after the trees were devoid of all leaves, increased to a maximum flower formation by May and decreased rapidly. Fruiting was also initiated after 15 days of flower burst, fruits started to mature in May and disperse, leaf formation began after fruits had fallen off the branches and by August the canopy was 100 percent green. The leaf formation decreased by now and new leaves ceased to grow after October.

f) *Balanites aegyptiaca*:

Flowering and foliation in *B. aegyptiaca* was initiated in April and continued up to August and October respectively. After foliation, fruiting was observed from June to October and leaf fall from February to April. There were some individuals which did not produce flowers and fruits in the year 2009-2010.

g) *Zizyphus mauritiana*:

Z. mauritiana did not start foliating until June followed by flower formation initiated in July and fruiting by August. It was observed that foliation and flowering periods overlapped each other and fruiting overlapped partially with both of them. The maximum leaf and flower formation happened during August and maximum fruiting occurred in September.

4.3.2 Phenological behaviour of shrub species:

a) *Grewia flavescens*:

Leaf formation started at the beginning of the monsoon during late June and attained full canopy cover by August. Flowering initiated in July and continued till October. Simultaneously fruiting started in September, increased until November, decreased by December and fruits ripened in March

b) *Capparis sepiaria*:

In *Capparis sepiaria*, observations revealed that leaf flushing was triggered in April, new leaves replaced the matured leaves simultaneously and the maximum leaf formation took place during June and reduced thereafter. The flowering period overlapped with the foliation period, reached a highest point in May and continued until July. Fruiting started once flowers matured and fruits continued to be formed till August.

c) *C. decidua*:

Flowers were produced in gregarious numbers during March followed by fruiting during April to June with highest production of fruits in May, which was also of a commercial value (Singh & Singh, 2011) and was being extensively used in pickles and cooking apart from providing food for frugivorous birds and mammals. The leaf formation took place during monsoon and was short lived thus giving a leafless appearance throughout the year and hence the name decidua was used. *C. decidua* and *C. sepiaria* were found to be two sympatric species found in the open *Zizyphus*- *Acacia* habitat of STR. (Rodgers, 1990a).

d) *Z. nummularia*:

The foliation was set in by early June and increased till August and no further new leaf formation took place after September. The flowering was initiated in July, maximum

flowers being formed in September. Fruiting also began simultaneously by September and maturation of fruits was observed in December.

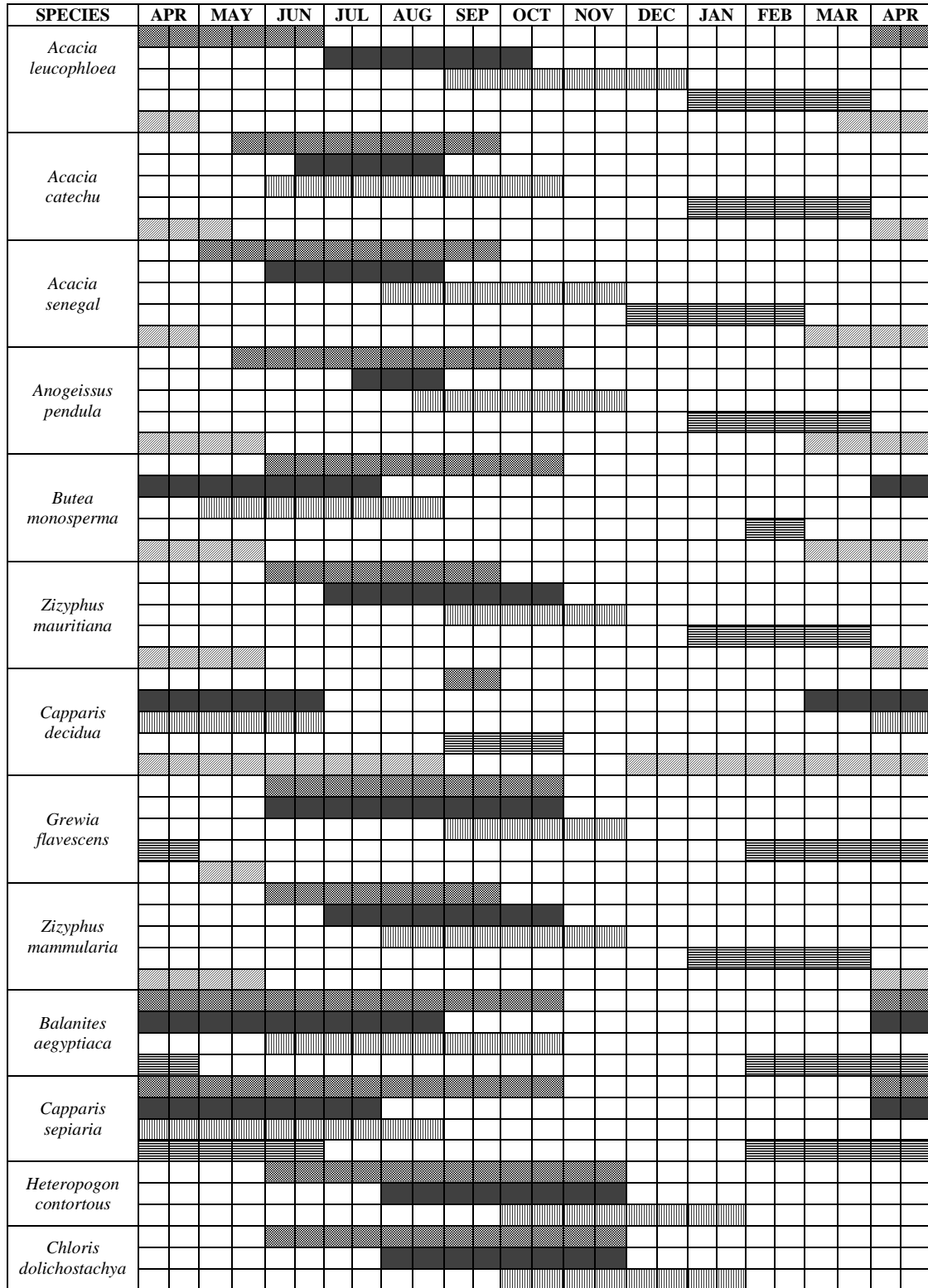
4.3.3 Phenological behaviour of grass species:






The two grass species displayed similar features as their foliation also started at the same time i.e. after the onset of rains. Flowering commenced in early August and continued up to November. The fruit formation began in October and continued till January, and then the seeds started maturing and ripened seeds were dispersed by anemochory, anthrochory and epizoochory. The seeds remained dormant until the next monsoon began. However, grazing posed a threat at flowering stage and hence seed formation.

4.3.4 Phenological dependence on environmental factors:

The mean minimum and maximum temperatures for the study area were recorded during July 2009 to April 2011. The temperature varied from 52 °C to 1°C during the study period. The relative humidity was high during monsoon and ranged from 52% to 2%. The annual rainfall recorded for the study period (June 2009-July 2010) was 735.1 mm. August was the wettest month in the region. Pearson's correlation analysis of the effects of climatic parameters such as rainfall, temperature and humidity on fruiting and flowering for trees revealed a significantly positive correlation. The linear regression procedure used in the analysis by SPSS 16.0 software detected that rainfall and humidity were highly correlated and hence one of them was dropped from the analysis to minimize the effects of collinearity. Flowering in species showed significant positive correlation to rainfall and temperature (Figure 4.2) ($p_{\text{rainfall}} = 0.015$, $p_{\text{temp}} = 0.003$; $r_{\text{rainfall}} = 0.451$, $r_{\text{temp}} = 0.059$; $R^2_{\text{adj}} = 0.612$). Fruiting was also significantly correlated to rainfall ($p_{\text{rainfall}} = 0.008$, $p_{\text{temp}} = 0.325$; $r_{\text{rainfall}} = 0.776$, $r_{\text{temp}} = (2.815E-4)$; $R^2_{\text{adj}} = 0.409$). However, its correlation with temperature was positive but not significant ($p > 0.05$).

Figure 4.1 Comparative Annual Phenological chart of the study species in 2009-2010 cycle



 Foliation
  Flowering
  Fruiting
  Leaf fall
  Leaf less

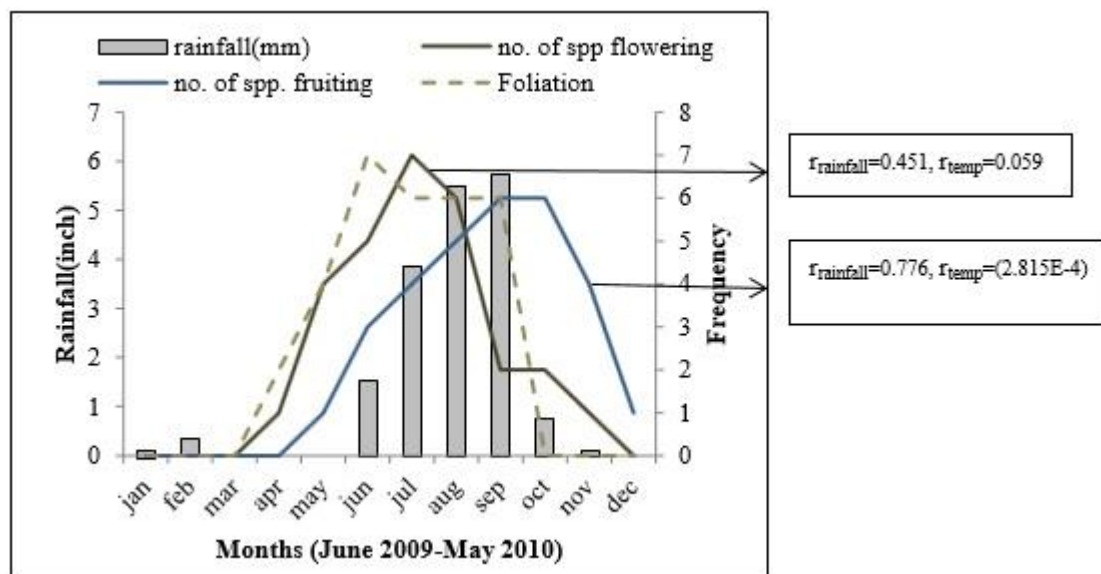


Figure 4.2 Species in reproductive phase in correlation to rainfall

4.4 Discussion:

It was observed that there was a distinct phenological pattern for the study species. It was evident that the foliage in all the woody species began before the rains set in and most of them were in their flowering phase during the month of June. Leaf flushing before the onset of monsoon resonated with temperature and humidity fluctuations (Rutherford & Panagos, 1982; Monasterio & Sarmiento, 1976; Rutherford, 1984; Milton, 1987; Chidumayo, 1993). The phenomenon of pre-monsoon leaf flushing is not, however, universal in the savannas and forests of seasonal tropics. Flushing may commence at the beginning of the wet season (Opler *et al.*, 1980; Prasad & Hegde, 1986; Boinski & Fowler, 1989; Bullock & Solis-Magalanes, 1990; Borchert, 1994a) or in the mid-wet season (Lieberman, 1982; Lieberman & Lieberman, 1984). The data of Frankie *et al.*, (1974); Reich & Borchert (1984) and Borchert (1994a) indicate that both pre-rain and post-rain flushing may occur in seasonally dry forests of Costa Rica, even in the same species. In contrast to co-occurring herbaceous species, the woody species studied generally showed leafing over most of the year, which demonstrated their higher degree of independence from rain water resource and suggested a superior exploitation of soil water resources during the year (Crawley, 1986). Additionally their vaster and deeper root systems allowed them to reach water reserves out of reach of the herbaceous stratum, *i.e.* below 20 cm (Seghieri, 1990). Since the herbaceous layer is supposed to have a shallow root system, the access to moisture becomes a limiting factor at all stages. These species gradually developed their shoots and reproductive structures (Sarmiento & Monasterio, 1983) when water reserves had been amply recharged (Seghieri *et al.*, 1995). In such a deciduous landscape when palatable resource depleted, herbivores like spotted deer turned to the evergreen *Capparis sepiaria* bushes during lean season, hence

making up for the browsing potential of the ecosystem (Rodgers, 1990a). Plantation of such palatable keystone species could be undertaken to reduce forage demands.

Proenca & Gibbs (1994) found that the flowering concentrated in the transition between dry and wet season. Flowering closely followed, or just preceded, the appearance of leaves. Atmospheric relative humidity improved rapidly in this period, a change which might be the environmental signal triggering flowering in these species. Such pattern was also observed in STR. *B. aegyptiaca* was observed to be producing flowers before leaf formation similar to results of a study conducted at the Sylvo-pastoral reserve of Sogobe Ferio, north Senegal (Akpo, 1997). Strategic patterns of producing flowers before leaf formation was also shown by *B. monosperma*, where the flowering occurred during peak summer and signifies an adaptation to drought like conditions, floral display to attract pollinators and anemophily (Singh & Singh, 1992). There were some individuals which did not produce flowers and fruits in the year 2009-2010 (pers. obs.). Such traits could be attributed to water stress previously described by Poupon (1979). Rainfall was observed to be the highest in the month of August-September, during this period fruiting was achieved by maximum species and thus displayed their maximum reproductive potential and competition for resources. Two fruiting strategies were observed in the study area. Once during May-June by *A. catechu*, *B. Monosperma*, *B. aegyptiaca*, *C. sepiaria* and *C. decidua*, which was of shorter duration, where the ripe fruits were released before the monsoons and another longer cycle during July- August by *A. pendula*, *A. leucophloea*, *Z. mauritiana*, *A. senegal*, *G. flavescens*, *Z. nummularia*, *C. dolichostachya* and *H. contortus*, which had an extended fruiting period and fruit maturation got extended until the following rainy season. Rainfall played an important role in fruiting as maximum fruiting was observed in October, this was found to be similar to Gir in Gujarat (Khan, 1999) and dissimilar to the sub tropical forests of north east India (Shukla & Ramakrishnan, 1982) and Bandipur in south (Prasad & Hegde, 1986). The species under observation can be classified as deciduous in nature, which begin flowering soon after, or occasionally just before, the first rains. Generally, there were no or very few trees with emergent leaves from December through to April and stood bare for almost 2-3 months in a year. At the beginning of the dry season their leaves start to dry out and are shed, an important strategy of plants to avoid water losses. In a few species the leaves, once dried out, remain on the branches until the end of the dry season. Shutting down their growth system in the cold and dry season helped plants to reduce their nutrient and energy requirements and invest this energy into producing leaves before monsoon and ensure that maximum resource was utilized (Singh & Singh, 1992). This temporal separation in the shoot mainly during the growing periods suggests that factors that trigger phenological events in the tree and grass components may be different and this feature of savannas is considered to contribute to the coexistence of trees and grasses (Walker & Noy-Meir, 1982). In general, we may consider phenological patterns of plant species to be evolutionary adaptations to their environment. It has been argued that the timing of leaf fall is related to reduction in soil moisture indicating the onset of dry season (Rutherford & Panagos, 1982; van Rooyen *et al.*, 1986b), and that this may vary from year to year (Murphy & Lugo, 1986). In this way a species is able

to survive under specific biotic and abiotic events of its ecosystem. It has also been demonstrated in savannas and deciduous dry forests in the seasonal tropics elsewhere in the world by: Frankie *et al.*, (1974) in Costa Rica; Menaut & Cesar (1979) in West Africa; Chidumayo (1990) in Zambia; Monasterio & Sarmiento (1976) in Venezuela; Shukla & Ramakrishnan (1982) in India; and Rundel & Becker (1987) in Central America. Wilson *et al.* (1996), Bowman *et al.*, (1991) and Williams *et al.*, (1997) showed a similar observation in north Australian tropical savanna vegetation. In an environment where the limiting factor is water, competition is inevitable among plants occupying the same above-ground stratum and the same soil horizons. This forces each species to optimize its use of water in both time and space (Granier & Cabanis, 1975). Moreover, co-occurring species that show similar phenological rhythms in the vegetative phase often differ in the timing of their reproductive phase (Monasterio & Sarmiento, 1976). As we have seen, environmental degradation leads to a considerable reduction of the period during which soil water is available to plants, and thereby limits reproduction in many species and life forms. Finally, the wide variety of phenological rhythms encountered among the species occurring in savanna landscape of STR indicates the great number of solutions available to tropical plants, at the present time, in the pursuit of survival and reproduction (Seghieri *et al.*, 1995). Climatic factors seem to be more important than phylogenetic history in determining the reproductive period of plants in savannas (Silva *et al.*, 2011). Semi-arid landscapes will be the worst hit by climate changes with the equilibrium between grasslands and forest getting disturbed leading to increasing aridity and ir-reversible desertification of such areas (IPCC, 1995) thus affecting the ecosystem and its various services. Climate change impact models predicted an increase of 10-40 % in “threatened” mammal species between 2050 and 2080 (Thuiller *et al.*, 2006a), leading to economic losses through direct (tourism revenue) and indirect (medicinal plants, fodder, food and other NTFP’s) ways (IPCC, 2007). Hence, long term phenology studies should be the mandate of the hour.



Plate 4.1 Sariska landscape in summer (3rd April 2010)



Plate 4.2 Sariska landscape in summer (17th April 2010)



Plate 4.3 Sariska landscape during monsoon (20th July 2010)



Plate 4.4 Sariska landscape during monsoon (28th August 2009)



Plate 4.5 Vegetation during peak summer (8th April 2009), wherein *C. sepiaria* manages to remain foliated



Plate 4.6 (a) Gregarious flowering in *C. decidua* (29th March 2010), (b) Flowering subsided with time (23th May 2010)



Plate 4.7 Difference within the woody and herbaceous layer with regard to the biomass and leaf matter (October 30th 2010)

GLOBAL EXPERIMENTS ON SAVANNA TREE SEEDLINGS (GEST)

5.1 Introduction

The savanna ecosystem occurs, where trees and grasses interact positively (facilitation) or negatively (competition) to create a biome that is neither purely forest nor grassland (Scholes & Archer, 1997). The relative abundance of these two components is regulated by external determinants such as climate, soil, fire and herbivory (Walker, 1987). The essential description of a savanna ecosystem is the relative amount and spacing of woody plants to herbaceous cover, often referred to as the tree/grass ratio (Plate 5.1). Environmental factors that are usually identified as deterministic in savannas are water (resource), nutrients (resource), fire (disturbance) and herbivory (disturbance) (Walter, 1971; Scholes & Archer, 1997; Illius & O'Connor, 1999; Higgins *et al.*, 2000; Jeltsch *et al.*, 2000). Given the complexity of the interactions between the various deterministic factors, the question of how grasses and trees coexist over such a wide range of climatic, edaphic, biogeographical and historical circumstances is intriguing and it has been referred to as the 'savanna problem' (Scholes & Archer, 1997; Sarmiento, 1984). Early attempts to model the dynamics of tree–grass coexistence and explore the stability of savanna systems prescribed a competitive equilibrium centred on niche differentiation through the partitioning of soil resources (Walker *et al.*, 1981; Walker & Noy-Meir, 1982; Eagleson & Segarra, 1985; van Langevelde *et al.*, 2003). This approach is founded in classical competitive equilibrium theory whereby species can exist only if they occupy fundamentally different niches and thus avoid competitive exclusion (Hutchinson, 1959; MacArthur & Levins, 1967). However, the basic condition of effective niche partitioning between trees and grasses does not have unanimous empirical support, either spatially with respect to rooting patterns (Le Roux *et al.*, 1995; Jackson *et al.*, 1996; Mordelet *et al.*, 1997; Castro & Kaufmann, 1998), or temporally with respect to the phenology of growing seasons (Scholes & Archer, 1997; House *et al.*, 2003). Recent theoretical advances, models and empirical evidence indicate that early savanna models were also inadequate in their adherence to two other assumptions of equilibrium theory; spatial homogeneity and temporal stability in environmental determinants (e.g. Simoni *et al.*, 2000; Amarasekare, 2003; Fernandez-Illescas & Rodriguez-Iturbe, 2003). Although evidence against niche separation via rooting depth does not in principle preclude the possibility of another equilibrium explanation, experimental evidence suggests that inter-specific competition between grasses and trees is often stronger than intra-specific competition (Scholes & Archer, 1997), thus violating the equilibrium model's basic condition for stable coexistence.

There is a significant effect of trees on herbaceous layer and vice versa. Trees have a remarkably great influence due to the tree size and density, on herbaceous species composition and production. The effect of herbaceous vegetation on woody plant recruitment is variable, and multiple mechanisms can operate in various complex ways to influence germination and establishment (de Steven, 1991). Grasses may regulate woody plant recruitment directly (competition for light, water, nutrients) or indirectly (as fine fuel loads influence fire frequency and intensity). While grasses may reduce emergence, growth and survival of woody seedlings, the competitive reduction may not be large enough to cause high mortality or complete exclusion. As a result, the intensity of grass effects on trees will relax or intensify as grass composition changes in response to climatic fluctuation, succession or grazing. Environmental modifications caused by trees and shrubs have been widely investigated in arid and semi-arid systems (Haworth & McPherson, 1995). Since the strength of the modifications decrease with distance from the plant, a mixed tree-grass community consists of a spatial patchwork of different degrees of competition and facilitation (Dye *et al.*, 1995; Vetaas, 1992). The input of rainfall to the sub-canopy habitat via stemflow and through fall will depend on the size and intensity of rainfall events and the size and intensity of rainfall events and size, bark characteristics, canopy architecture and leaf area of the tree (Haworth & McPherson, 1995). Interception losses on the order of 5% to > 50% of gross annual rainfall have been reported, but stem flow can concentrate significant amounts of moisture near the base of the trees (Ko & Reich, 1993; Navar & Bryan, 1990; Thurow *et al.*, 1987; Pressland, 1973). As a result, measurements of soil moisture on transects from the stem outward into the between-canopy zone generally show peaks of wetness close to the stem (due to stem flow) and at the canopy perimeter (due to edge drip), with a drier area beneath the main canopy (Strang, 1969; Stuart-Hill *et al.*, 1987). The interspersion of grasses and woody plants also alters the hydrology of the savanna at a landscape scale by influencing horizontal patterns of water distribution (Joffre & Rambal, 1993). In addition to altering soil moisture and structure, both evergreen (Barth, 1980; Padien & Lajtha, 1992; Schlesinger *et al.*, 1996, Zinke, 1962) and deciduous trees typically enhance pools of soil nutrients and their fluxes beneath their canopies (Belsky *et al.*, 1989; Campbell *et al.*, 1994; Evans & Ehleringer, 1994; Frost & Edinger, 1991; Georgiadis, 1989; Isichei & Muoghalu, 1992; Jackson *et al.*, 1990; Kellman, 1979; Mordelet *et al.*, 1993; Tiedemann & Klemmedson, 1973,1977; Virginia, 1986; Weltzin & Coughenour, 1990). The semi-arid tropics where savannas predominate are among the sunniest places in the world, the amount of radiation reaching the place is maximum and the savanna tree canopy reduces direct and indirect solar radiation reaching the shaded area by 25-90% (Belsky *et al.*, 1989; Georgiadis, 1989; Jackson *et al.*, 1990; Ko & Reich, 1993; Tiedemann & Klemmedson, 1973). While trees and shrubs may build up tissue moisture storage to draw on during lean period, the savanna grasses succumb to the moisture stress (Misra, 1983). Low- growing, thorny trees may provide a refuge in which palatable grasses can persist in heavily grazed environments (O' Connor, 1995; Welsh & Beck, 1976). In some cases the tree seedlings associated with clumps of unpalatable grass may escape herbivory during this critical stage of their life cycle. High grass biomass can affect tree biomass by fuelling fires (Kauffman *et al.*, 1994), grazing reduces the fuel load and hence affects fire frequency, intensity or continuity of spread

(Baisan & Swetnam, 1990; Savage & Swetnam, 1990). Browsing, on the other hand, helps to keep woody plants within flame and conversely, fires keep woody plants browsable. Thus, a strong grazer-browser-fire interaction influences tree-grass mixtures. Recent savanna dynamics models have sought to take account of this inherent variability, recognizing savanna systems as being the result of complex, often nonlinear, interactions between climate, soil and disturbance (Sankaran *et al.*, 2004). These models, categorized as ‘demographic bottleneck models’ (Sankaran *et al.*, 2004) have been developed both to explore theoretical mechanisms of tree-grass coexistence (e.g. Menaut *et al.*, 1990; Jeltsch *et al.*, 1996, 1998; Higgins *et al.*, 2000; van Wijk & Rodriguez-Iturbe, 2002) and in seeking to provide management advice for policy makers (e.g. Gambiza *et al.*, 2000).

A critical factor for survival of savanna species is their ability to out-compete other species within the same niche. Due to high longevity and environmental resilience of adult trees, particular attention is paid to the seedling establishment phase, with establishment success being a combined function of: the maximum establishment opportunity, wet season drought and competition from the herbaceous layer. Tree seedling success in savannas and grasslands may be strongly influenced by the intensity of competition from herbaceous vegetation. An ecological explanation is therefore required in order to explain the structure and function of savanna systems in relation to existing environmental and biological determinants (Gardner, 2006). Many controlled-environment experiments and some field experiments suggest that grasslands dominated by productive, late seral species should be resistant to woody plant encroachment, even in the absence of fire, and that grazing promotes woody plant encroachment into grasslands by reducing the ability of grasses to competitively exclude woody seedlings (Van Auken, 2000). According to Belsky (1994), savanna trees competed more intensely with understory plants at wetter sites, where their roots terminated in or near crown zones, than at drier sites, where their roots extended farther into open grassland. Nutrients added by trees to crown zones in the form of tree litter and animal droppings increased understory productivity by fertilizing nutrient-limited soils. Shade contributed more to re-growth after severe defoliation than to growth under more normal conditions.

Protection from grazing and physical disturbance had greater impacts on species cover and diversity than removal of dominant species or fire. More species were significantly affected (positively and negatively) by disturbance and protection from grazing (50 - 100%) than by species removal and fire (< 41%). In most cases, the cover of tall, perennial species increased following protection from grazing while the cover of annual and short, perennial species decreased (Belsky, 1992). Across continents savanna types are distributed along rainfall gradients: woodlands are found under mesic conditions down to mean annual precipitations (MAPs) of about 500 mm, where they are gradually replaced by low tree and shrub savannas down to < 250 mm (Cole 1986; Sankaran *et al.* 2005), suggesting water availability limits the productivity of the environments and hence the ‘carrying capacity’ of trees. The role of light limitation on the distribution of species and genera is less clear. For instance there is evidence that tree seedlings in hot, arid areas may be facilitated by growing in the shade of adults (Weltzin & McPherson 1999; Barnes & Archer,

1999), probably because there is a lower water demand under tree canopies than in the open. However the growth of savanna trees in cooler, less water-stressed environments seems to be superior under trees than in the open (Davis *et al.*, 1998; Gordon & Rice, 2000; Siemann & Rogers, 2003; Dickie *et al.*, 2007), suggesting in this case, that tree shade facilitates seedlings by reducing the vigour of competitor grasses. Consequently shade may be facilitatory in both humid and arid regions but for very different reasons. That said it is possible that species differ in their ability to tolerate shading. The growth patterns of dominant species may also have been shaped by two biotic influences that vary cross-continently, namely competition with local grass species, and defoliation patterns by grazers. Competition with grasses would depend on the local species pool and hence the intensity of competition from grasses may be stronger or weaker in different environments. Evidence for this is provided by the manner in which African grass species have been able to invade Australian savannas (Rossiter *et al.*, 2003) and South American grasslands and savannas (Williams & Baruch, 2000). Grazing pressure may have influenced the growth patterns of tree seedlings on those continents where macro-herbivore species occur or have occurred in recent time, such that species growing in severely grazed environments may have adopted growth strategies designed to cope with grazing pressure, such as low stature and an emphasis on stored plant reserves at the expense of rapid growth. Factors affecting the establishment of dominant savanna species would be vital to understand the future course of succession and establishment of vegetation under varying soil resources *i. e.*, moisture and nutrients. Understanding the patterns of interaction between trees and grass will yield insights about the practical and management issues of savannas. Keeping these ecological questions in mind, a world-wide experiment on savanna tree seedlings was initiated by the University of Wageningen, the Netherlands in five continents. For Indian sub-continent, Sariska Tiger Reserve was selected as experimental site in the semi-arid region.

5.2 Materials and Methods

5.2.1 Study site selection

Sariska Tiger Reserve was selected as the dry savanna field experiment site owing to its status as protected grassland similar to the rangelands of African savannas. The rainfall and temperature parameters also complied with the desired environmental conditions. The prior knowledge about the study site was also an added advantage with regard to the logistics of the project. The experiment was carried on for two consecutive growing periods from April 2009- May 2011.

5.2.2 Study species selection

Six tree species and two grass species that were abundant in the semi-arid savanna region were selected for the experiment. The reason that species abundance was used as a criterion for species selection was to understand how the species which form the bulk or a substantial portion of the tree biomass in savannas,

responded to different treatments. Firstly because these species were presumably the best adapted to local conditions (hence their abundance), and secondly because as a result of their abundance, their responses to different environmental conditions would have substantial effects on the local savanna vegetation, relative to less-abundant species, and therefore it was important that they got priority. The species were *Acacia leucophloea* (Mimosoideae), *Anogeissus pendula* (Combretaceae), *Butea monosperma* (Faboideae), *Lannea coromandelica* (Anacardiaceae), *Ziziphus mauritiana* (Rhamnaceae), *Balanites aegyptiaca* (Balanitaceae), *Heteropogon contortus* (Poaceae) and *Chloris dolichostachya* (Poaceae).

5.2.3 Study Design

The experiment was set up in an area of 50 m X 50 m in a split plot design with a different water, light and defoliation conditions as in control plot (even water, sunlight, no defoliation), shade treatment (even water, 20% sunlight, no defoliation), defoliation/herbivory plot (even water, sunlight, defoliation) and natural plot (natural rainfall, sunlight, no defoliation) (Figure 5.1). The experimental plot was laid out and exclosed for major herbivores and 120 plots of 2.5 m X 2.5 m (Figure 5.2) with different treatments was laid out and tree seedlings were planted into treatments sub-plots consisting of different combinations of water, nutrient, light and grass in a factorial design (Figure 5.3). Each of the six (6) chosen tree species along with one (1) additional humid savanna tree species was planted in each treatment plots. For each year of data collected, 12 seedlings were required of each species per treatment combination. With an intention to collect 2 years of field data, 24 seedlings were planted per species per treatment combination, or 4 seedlings per species per treatment plot (4 seedlings in each species sub-square) (Figure 5.4).

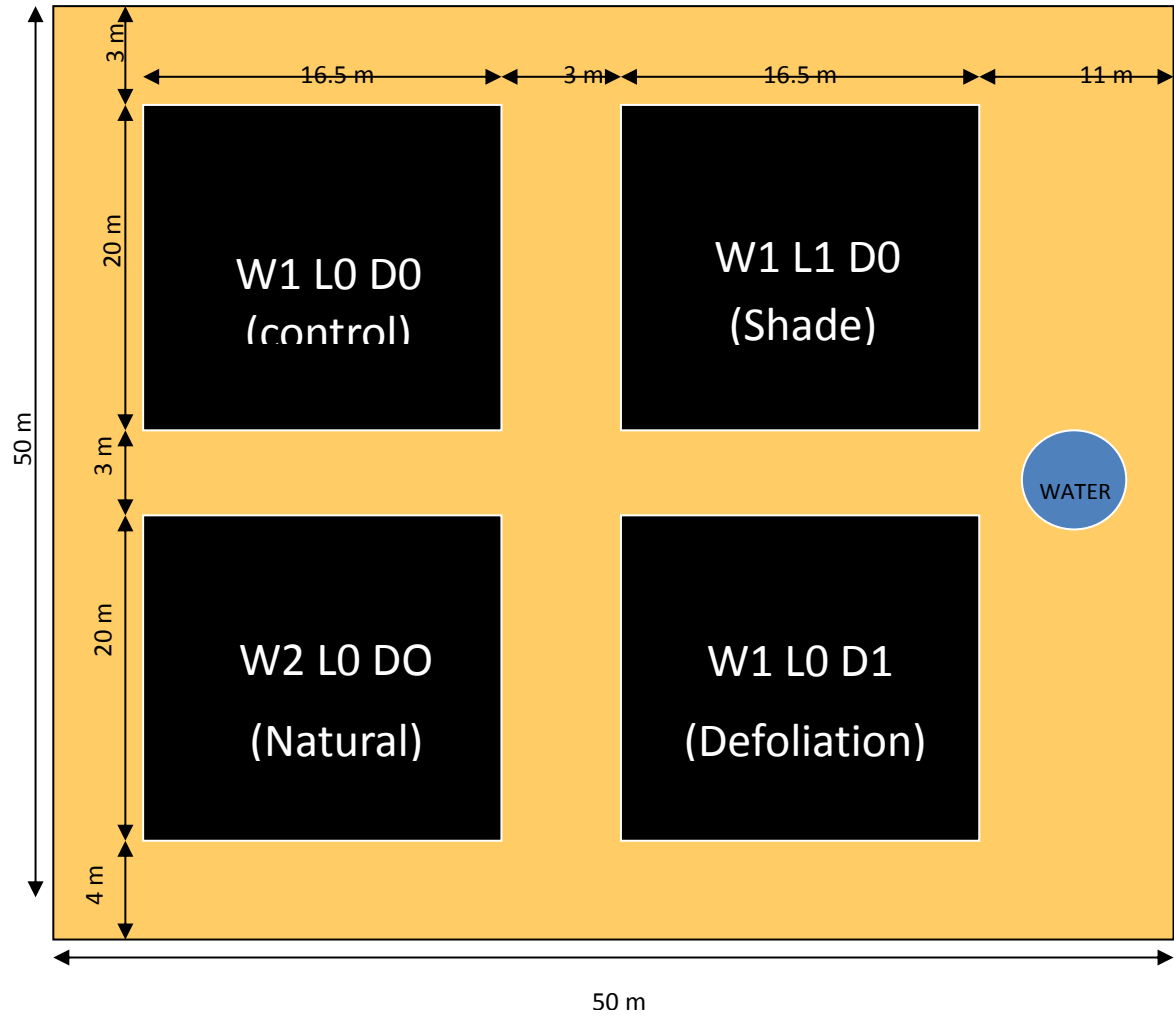


Figure 5.1: Schematic layout of the treatments for the field experiment. Water (W), Light (L) and Defoliation (D) were treated as whole plot treatments. Grass (G) and Nutrients (N) were treated as sub-plot treatments.

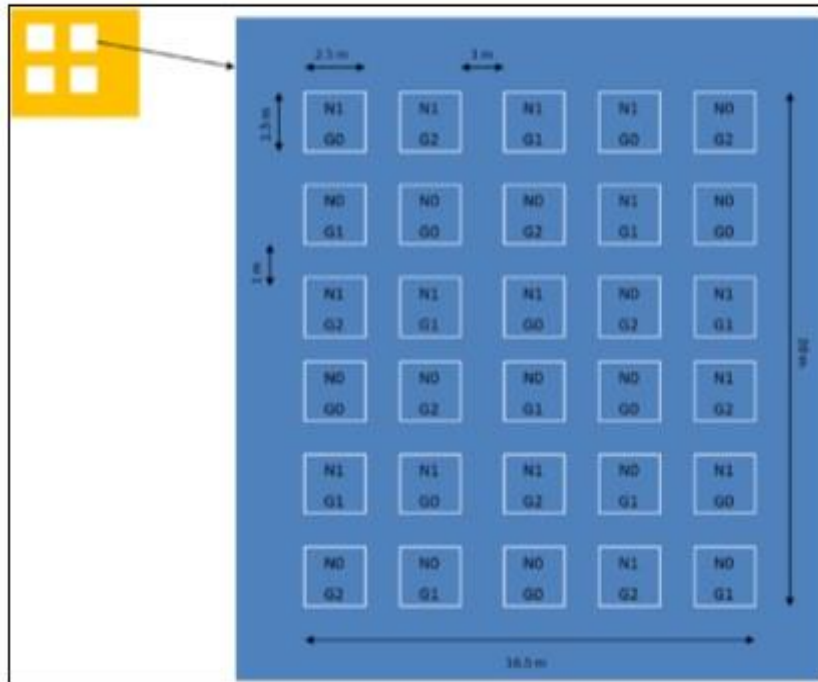


Figure 5.2 . Layout of plots in each whole plot (block)

The treatment combinations were as follows:

1. **Grass (G):** Three treatments: absence (G0), presence of *Heteropogon contortus* (G1), presence of *Chloris dolichostachya* (G2).

The grassed plots were designed to consider the effects of grass competition on the growth of tree seedlings. Therefore the experiment included three grass treatments: grasses G1 or G2 present or grasses absent.

2. **Nutrients (N):** Two treatments: no fertiliser added (N0), fertiliser added (N1).

Two fertilizer treatments were applied. The one treatment had no fertilizer added (N0) and the second treatment had fertilizer added (N1) to increase the availability to the trees and grass seedlings. Four applications of Urea (NH_2CONH_2) were administered monthly following rates applied by Kraaij & Ward (2006) and by Tilman (1987) so that 4gm^{-2} of Nitrogen was available for absorption to each treated plot. The treatment combinations were Nutrient absent and grass absent (N0G0), Nutrient absent and *Heteropogon contortus* (N0G1), Nutrient absent and *Chloris dolichostachya* (N0G2), Nutrient present and grass absent (N1G0), Nutrient present and *Heteropogon contortus* (N1G1), Nutrient present and *Chloris dolichostachya* (N1G2).

3. **Water (W):** Two treatments at each site: Even (W1), Natural rainfall (W0).

To demonstrate how differently the species grow under abundant and low water availability, the rule for even water application as applied to the Even Water Treatment (W1), that is proposed here was based on the water deficit rules as defined in the Köppen-Geiger system.

4. **Light (L):** Two light treatments: natural light (L0), 20% light (L1).

Two light treatments were applied. The one treatment had natural light and the other treatment had 20% natural light, mimicking the level of shading found under closed canopies of some savanna tree species (Kanegae *et al.*, 2000; Bauhus *et al.*, 2004).

5. **Defoliation (D):** Two defoliation treatments: no defoliation (D0), defoliation (D1).

Defoliation treatments were applied to tree seedlings growing with and without grass competitors and high and low N, under even water conditions (W1), to observe how the species respond to defoliation and how this response was modified by competitor grasses. The treatment combinations were Nutrient absent and grass absent (N0G0), Nutrient absent and *Heteropogon contortus* (N0G1), Nutrient absent and *Chloris dolichostachya* (N0G2), Nutrient present and grass absent (N1G0), Nutrient present and *Heteropogon contortus* (N1G1), Nutrient present and *Chloris dolichostachya* (N1G2).

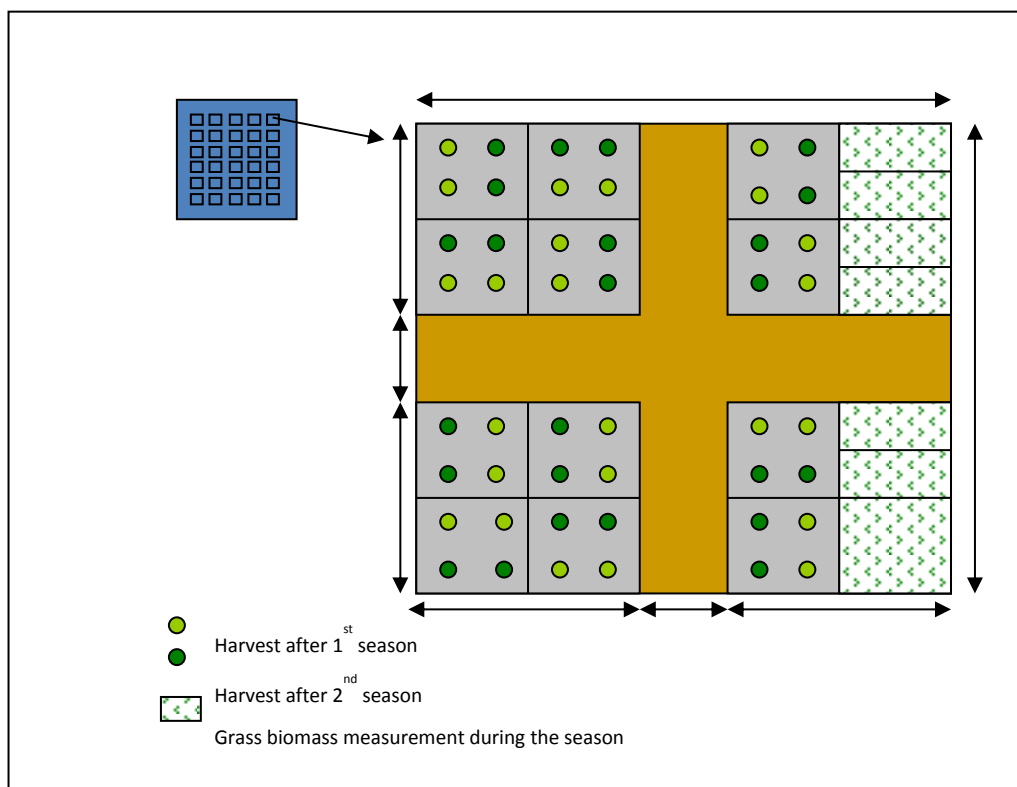


Figure 5.3 Layout of each sub-plot

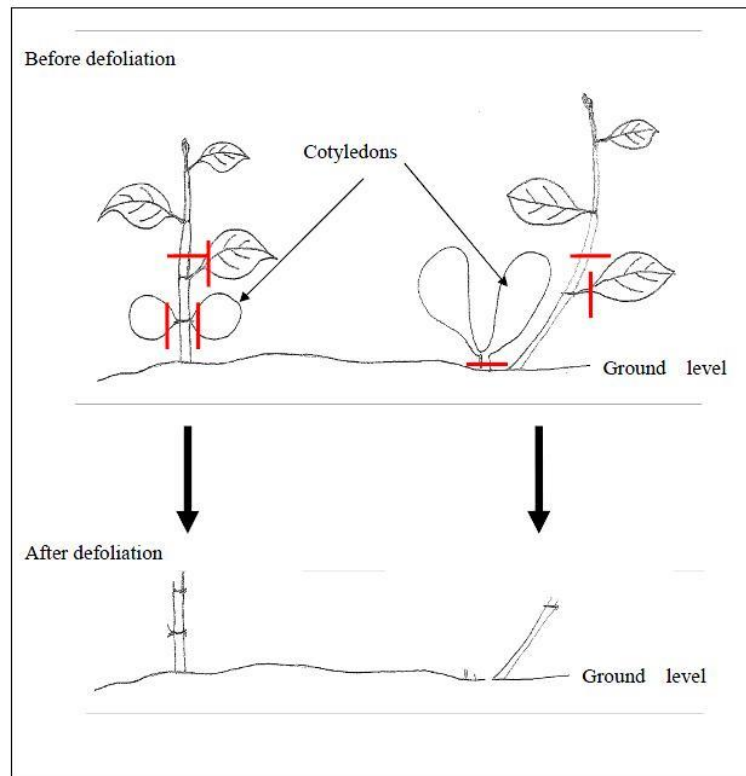


Figure 5.4 Defoliation treatment of tree seedlings. Bold lines represent positions where seedlings were cut (GEST design)

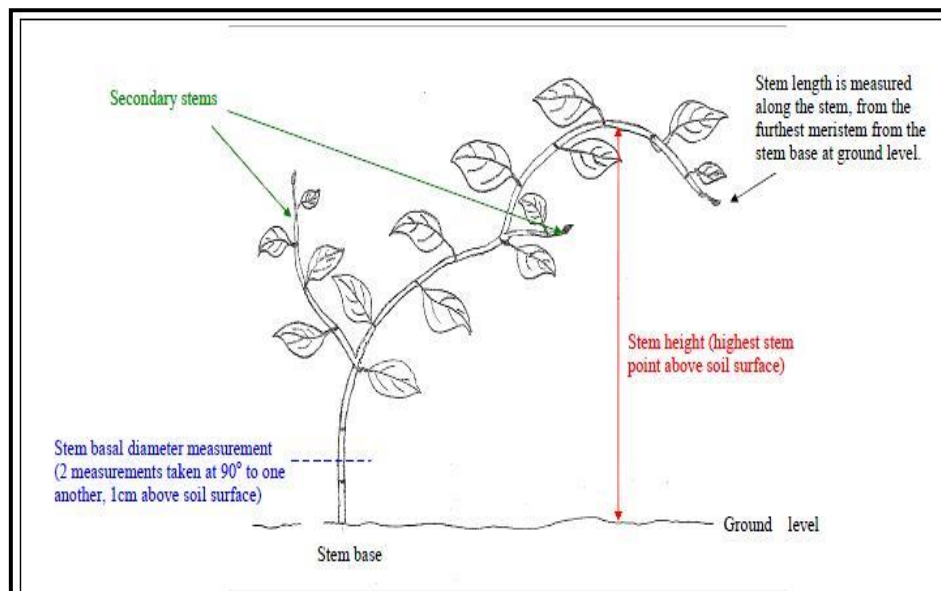


Figure 5.5 Various Measurements to be taken on each tree seedling

5.2.4 Methods

The field experiment was conducted in Karnakawas beat of Sariska range in Sariska Tiger Reserve (STR), Rajasthan. The geographical location of the plot was 27°22'20.09'' N and 76°23'45.09'' E. It was initiated in April 2009 and the setup was established according to the project design. The tree species and grass species selected for the experiment were *Acacia leucophloea*, *Anogeissus pendula*, *Balanites aegyptiaca*, *Butea monosperma*, *Lannaea corromandolica*, *Zizyphus mauritiana*, *Chloris dolychostachya* and *Heteropogon contortus*. The seeds for these species were collected locally in the preceding season of the initiation of the experiment. These seedlings were raised in the green house that was constructed near the enclosure site. A 50 m X 50 m plot was chosen and prepared for the field experiment by clearing the native vegetation by uprooting of trees, shrubs and grasses and the plot was enclosed for macro herbivores on all the sides by wire mesh fencing. A 200 m pipeline was laid down from the nearby well for water treatments. The plot was marked and pegged and the 120 plots of 2.5 m X 2.5 m subplots were laid out. The rain sheds and light sheds were constructed on the individual plots. Grass was planted on their respective plots and watered regularly to facilitate their establishment beforehand. Once the grass was established, four seedlings of all the seven target tree species were transferred from the greenhouse to the subplots only after the onset of the monsoon (rainy season) and initial measurements like seedling height, length, basal diameter, number of leaves and condition of cotyledon were recorded for all the seedlings (Figure 5.5) (Plate 5.2 to 5.14). The seedlings were planted in August 2009. They were subjected to various nutrient, water, grass, light and defoliation treatments as per the requirements of the experiment (Figure 5.6). Data on seedling parameters with respect to growth was collected while continuing the specified treatments for a period of six months. The youngest fully grown leaf of each individual was scanned at the start and end of the experiment. At the end of the experiment all the seedlings were clipped at ground level, bagged, and oven dried at 70°C for 48 hrs and weighed for dry mass.

Twelve of the 24 seedlings were marked and monitored in the first season (two out of four per plot). They were harvested at the end of the first season, providing data on 0-1 year old seedlings. The second set of 12 seedlings was marked prior to the beginning of the second season and they were also monitored during the second season in order to obtain data on 1-2-year old seedling growth. The 12 seedlings harvested per species per treatment combination at the start of the first season were replaced at the start of the second season, in order to collect a second set of data on first-year growth. The data was collected every 4 weeks, unless specified at a longer interval, in weeks 0, 4, 8, 12, 16, 20 and 24. The following data was collected on each seedling in each treatment sub-plot:

- stem length & stem height (4 weeks)
- basal stem diameter (2 measurements, 1 cm above ground, 4 weeks)
- number of leaves (4 weeks)
- leaf area (start and end of the growing season)

- Indirect estimate of grass biomass (4 weeks)
- number of live seedlings and number of live leaves on these seedlings at beginning of the second growing season

Biomass accumulation of grass plots was estimated every 4 weeks during the growing season. There were 4 sub-squares per treatment sub-plot. 1 sub-square was set aside in each sub-plot to be harvested at the end of the season. The remaining 3 sub-squares were each divided in half, giving a total of 6 sub-rectangles, each 0.25 X 0.5 m². Since the grass was clipped down to 2 cm during the planting week, no monitoring measurements were taken during Week 0. Measurements were taken in Weeks 4, 8, 12, 16, 20, and 24. At each of these dates, one of the 6 grass sub-rectangles was selected and all grass material was clipped to 2 cm, bagged, oven-dried and weighed. After the completion of the first year of the experiment, the plots were left undisturbed and the enclosure was prepared for the second year of experimentation. The seeds that were collected in April-May 2010 were sown in seedling bags in the greenhouse nearby the experimental site. The rain sheds and light sheds were repaired and the soil was manually cleared for weeds, undesirable grasses and seedlings during May-June 2010. After the onset of monsoon in first week of July, the germinated seedlings were planted at the experimental site in a design oriented manner in which 2 seedlings of all species were planted in each treatment plot. In this second year, 2 new seedlings and 2 previous year seedlings of each target species were monitored for 0-1 year and 1-2 year data on seedling growth parameters respectively. The youngest fully grown leaf of each individual was scanned using Canolide Scanner (Plate 5.14) at the start and end of the experiment. Data with respect to growth was collected every 4 weeks while continuing the specified treatments for a period of six months. At the end of the experiment all the seedlings were clipped at ground level, bagged, and oven dried at 70°C for 48 hrs and weighed for dry mass (Plate 5.13).



Plate 5.1 A typical savanna landscape in Sariska Tiger Reserve



Figure 5.6 Layout of the savanna experiment (Top View) in Sariska Tiger Reserve, India



Plate 5.2. Clearing out vegetation manually for the site



Plate 5.3. Laying the experimental plots



Plate 5.4. Exclosing the site for macro herbivores by fencing



Plate 5.5. Greenhouse for germination of seedlings



**Plate 5.6. *Butea monosperma* seedling
alongwith *Chloris dolichostachya***



**Plate 5.7. Shade plots showing subdued
grass growth**



**Plate 5.8 The experimental plot with rain
sheds and light sheds**



**Plate 5.9 Planting *Butea monosperma*
seedling in the plot**



(a)



(b)

Plate 5.10 Measurement of Basal Diameter (a) and height (b) of a seedling



Plate 5.11 Defoliation treatment on
Anogeissus pendula seedling



Plate 5.12 Measuring the fresh weight
for *Balanites aegyptiaca* after
Defoliation treatment



(a)



(b)

Plate 5.13 Weighing of *Balanites aegyptiaca* (leaf (b) and stem (a) separately) after oven drying at 70 °C for 48 hours



Plate 5.14. Scanning the leaf of *Butea monosperma* for leaf area

5.3 Data Analysis

Differences among treatments in seedling survival and growth rates were tested for significance by analysis of variance (ANOVA) (Lindaman 1992). Grass above ground biomass was analysed on a per plot basis and compared using ANOVA using SPSS 16.0 software. All statistical tests were at the 0.05 significance level. The treatments blocks were compared with the control block for significant differences in treatments considering water, defoliation, shade and block as fixed factors and including all 2 way and 3 way interaction terms.

The 3 models that were used for the analysis were:

For water: $y = B_0 + B_1 * \text{Water} + B_2 * \text{Grass} + B_3 * \text{Nutrient} + \text{Interactions}$

For Shade: $y = B_0 + B_1 * \text{Shade} + B_2 * \text{Grass} + B_3 * \text{Nutrient} + \text{Interactions}$

For Defoliation: $y = B_0 + B_1 * \text{Defoliation} + B_2 * \text{Grass} + B_3 * \text{Nutrient} + \text{Interactions}$

Here y is the independent variable and it is explained as the sum of other dependant factors and B0, B1, etc. are the constant factor of each dependant variable. Each of the six species were analysed for different treatments for parameters such as stem length, stem height, stem basal diameter, total leaves, total mass and leaf mass fraction.

The Kaplan-Meier plots were used for survival analysis for each species in each block. The survival models for each treatment block were:

For water: $\ln \frac{1-p}{p} = B_0 + B_1 * \text{Water} + B_2 * \text{Grass} + B_3 * \text{Nutrient} + \text{Interactions}$

$1-p$

For Shade: $\ln \frac{1-p}{p} = B_0 + B_1 * \text{Shade} + B_2 * \text{Grass} + B_3 * \text{Nutrient} + \text{Interactions}$

$1-p$

For Defoliation: $\ln \frac{1-p}{p} = B_0 + B_1 * \text{Defoliation} + B_2 * \text{Grass} + B_3 * \text{Nutrient} + \text{Interactions}$

$1-p$

The 0-1 yr seedling data for second year of the experiment was not grouped with the data of first year of the experiment because time was considered to be a fixed factor so the results for both years are given separately.

5.4 Results

The mean height of the individuals of each species in each treatment were compared and differences were observed (Figure 5.7, 5.8, 5.9). The detailed results species wise are given as following.

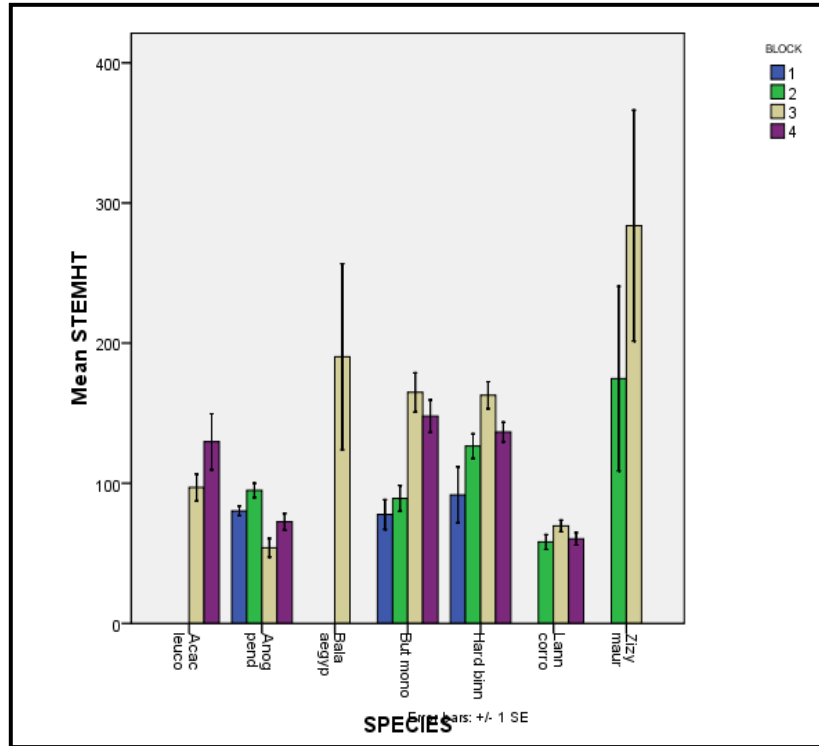


Figure 5.7 Differences in growth in tree species in four treatment blocks (Control (Block 1), Shade (Block 2), Defoliation (Block 3), Natural (Block 4) in first year experiment (2009-2010)

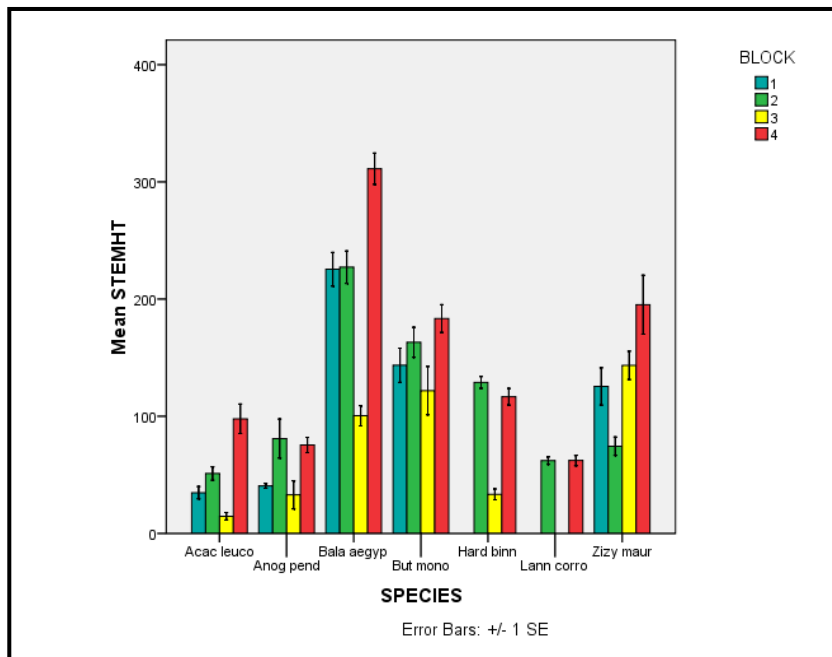


Figure 5.8 Differences in growth in tree species in four treatment blocks (Control (Block 1), Shade (Block 2), Defoliation (Block 3), Natural (Block 4)) in 0-1 year seedling in second year experiment (2010- 2011)

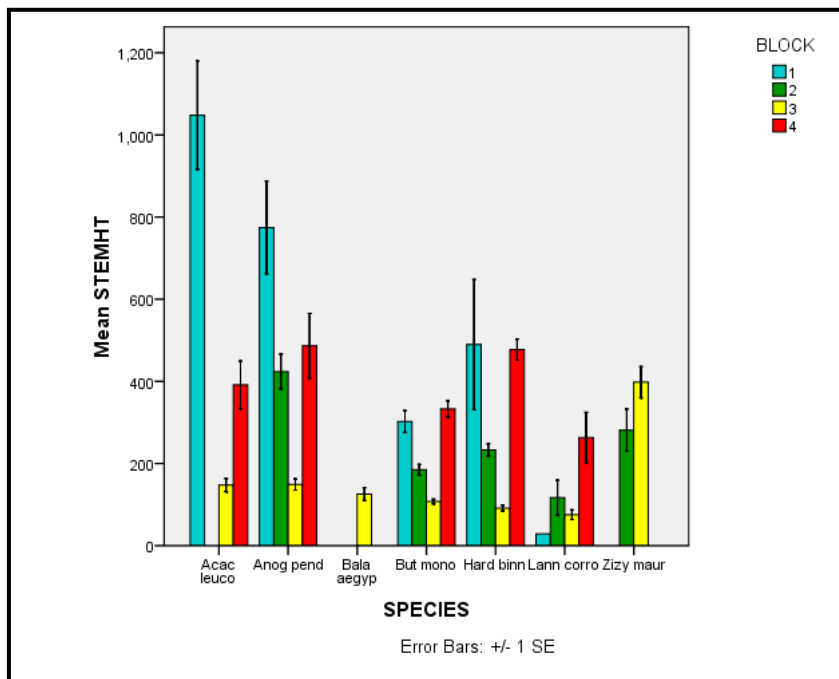


Figure 5. 9 Differences in growth in tree species in treatment blocks (Control (Block 1), Shade (Block 2), Defoliation (Block 3), Natural (Block 4)) in 1-2 year seedling in second year experiment (2010-2011)

5.4.1 Tree seedling

5.4.1.1 *Acacia leucophloea*

In the first year of experiment, for *Acacia leucophloea*, the defoliation treatment did not have enough cases to give significant results but the growth was significantly higher in nutrient rich conditions ($p=0.003$). It had a significant biomass factor with nutrient supplementation ($p=0.016$) and *Chloris barbata* as grass species followed by *Heteropogon contortus* and empty plots.

In the second experimental year, the first year seedling showed higher growth in control conditions and the leaf number was significantly influenced by grass treatment ($p=0.029$) with a significant interaction with nutrients ($p=0.018$) such that the nutrients also facilitated the number of leaves in grassed (*Heteropogon contortus*) plots. These seedlings had significantly higher growth in natural rainwater conditions ($p=0.003$). The second year seedling showed a significant stem height growth, biomass and leaf mass fraction in

control conditions ($p < 0.001$). They had higher growth in even water treatment ($p = 0.01$), nutrient supplemented and grass absent conditions.

5.4.1.2 *Anogeissus pendula*

In the first experimental year, *Anogeissus pendula* was significantly affected by shade treatment ($p = 0.019$) and the response of variables was better explained in shade condition thus proving it to be a shade loving species and the nutrient supplemented plots had a higher average growth. It had a higher growth in no defoliation and nutrient rich condition with a significant grass ($p = 0.041$), nutrient ($p = 0.049$) and defoliation treatment ($p = 0.036$) and these factors significantly interacted with each other ($p_{\text{nutrient} * \text{defoliation}} = 0.016$, $p_{\text{nutrient} * \text{grass} * \text{defoliation}} = 0.003$). It was significantly affected by even water treatment ($p = 0.027$) having higher growth in the treatment, slightly increased growth was observed in nutrient rich conditions and plots with grass as compared to empty plots.

For second year, the first year seedling and the second year seedling showed a higher growth in no defoliation or controlled treatment and grass absent plots ($p = 0.005$, $p < 0.001$). The first year seedlings were significantly affected by shade ($p < 0.001$) and it proved to be a shade loving species by having a higher growth in these conditions. It also had significant effect by even water treatment ($p < 0.001$) such that growth was better in rainwater treatment.

5.4.1.3 *Balanites aegyptiaca*

There was no germination for this species in the first year of experiment hence there were no results obtained for the first year. However, for the second year, the first year seedling showed higher growth in nutrient supplemented conditions, control ($p < 0.001$) and grass absent plots. Seedling growth was significantly affected by shade treatment ($p = 0.016$) having longer length in shade treatment. The leaves and biomass was significantly more in sunlight conditions ($p = 0.005$, $p = 0.044$). The first year seedling also had significantly higher growth ($p < 0.001$) in natural rain and grass absent condition.

5.4.1.4 *Butea monosperma*

In the first experimental year, *Butea monosperma* was significantly affected by grass treatment ($p=0.048$) and the absence of grass increased the mean height and there was a slight improvement in the growth rate with addition of nutrient. The biomass ($p<0.001$) however had a higher value in sunlight treatment as the leaves ($p<0.001$) were more hence contributing solely to the biomass. The shade treatment also had a significant interaction with the nutrient treatment ($p=0.047$). There was a significant effect of defoliation treatment on the stem height ($p<0.001$), stem length ($p=0.001$), stem basal area ($p=0.001$) and biomass ($p=0.007$). The species performed better in defoliated conditions and slightly better in nutrient richer conditions. The grass treatment was however reversed in this case. Water treatment was significant ($p<0.001$) and the species performed well in natural rainfall conditions and natural nutrient conditions and along with grasses. Biomass was however greater in nutrient rich and grass absent conditions.

For second experimental year, the first year seedling had improved growth in nutrient supplemented plots and no defoliation plots ($p=0.001$) and significantly higher basal area in grass absent conditions. They had significantly higher basal area in grass absent conditions. The first and the second year seedling were found to have significantly higher stem basal area ($p<0.001$), leaves ($p=0.057$) and biomass ($p=0.009$) in sunlight conditions. The second year seedling showed significantly higher growth in no defoliation treatment ($p<0.001$) and nutrient supplemented plots, with a significant interaction between grass and nutrients ($p=0.057$) and nutrients and defoliation ($p=0.034$) and a 3 way interaction between grass, nutrient and defoliation ($p=0.012$). The second year seedling had significantly higher biomass ($p<0.001$) in natural rainfall treatment, but higher leaf numbers in even water treatment ($p=0.006$) and grass absent plots ($p=0.009$).

5.4.1.5 *Lannea coromandelica*

In the first experimental year, *Lannea coromandelica* had no surviving individuals in the sunlight conditions thus suggesting its shade tolerant characteristic. Slightly higher growth in nutrient supplemented conditions and very slight difference between grass treatments were observed for this species. There was not enough cases for *Lannea coromandelica* to test the significance of the defoliation as a main treatment but within this treatment the growth was slightly higher for nutrient rich plots and no grass plots. For water treated plots, this species had better growth in nutrient rich and grassed conditions.

In the second experimental year, the first year seedling had higher growth ($p=0.025$) and biomass ($p=0.01$) in nutrient supplemented conditions.

5.4.1.6 *Zizyphus mauritiana*

There were no germination for seedlings in the first experimental year hence there were no results for the second year seedlings too, but in the second year, the first year seedling stem length and stem basal area were significant in defoliation treatment ($p < 0.001$), having higher basal area in defoliated individuals and higher length in controlled individuals. Presence of grass in the plot significantly decreased the number of leaves ($p = 0.014$). The seedlings were significantly affected by shade treatment ($p = 0.003$) having higher growth in sunlight conditions. They were also found to be significantly affected by grass ($p = 0.017$), with higher growth in grass absent plots and rainfall conditions. It was also found that the seedlings had higher biomass in grass absent plots ($p = 0.002$) and nutrient supplemented plots

5.4.2 Grass biomass

The grass sub-plots containing *Chloris dolichostachya* and *Heteropogon contortus* were clipped monthly after the start of the experiment, the grass was bagged and oven dried for 48 hrs at 70 oC and dry weight was measured. The dry weight revealed an interesting pattern with time depending upon the treatment blocks. The grass died down in shade treatment due to lack of sunlight, in the even water treatment (Figure 5.10) the grass biomass increased with time until the 6th month while in the defoliation treatment (Figure 5.11) it decreased when the first clipping was done and then increased again until fifth month and decreased by a marginal amount. In the natural rainfall treatment it reached maximum in 3rd month and then decreased after turning brown and losing most of its moisture in winter (Figure 5.12). The different shades in the graphs depict the sub- treatments within a block treatment and since we are not comparing the data between these sub treatment plots within a water, shade or defoliation block treatment, the legend for different shades is not mentioned here.

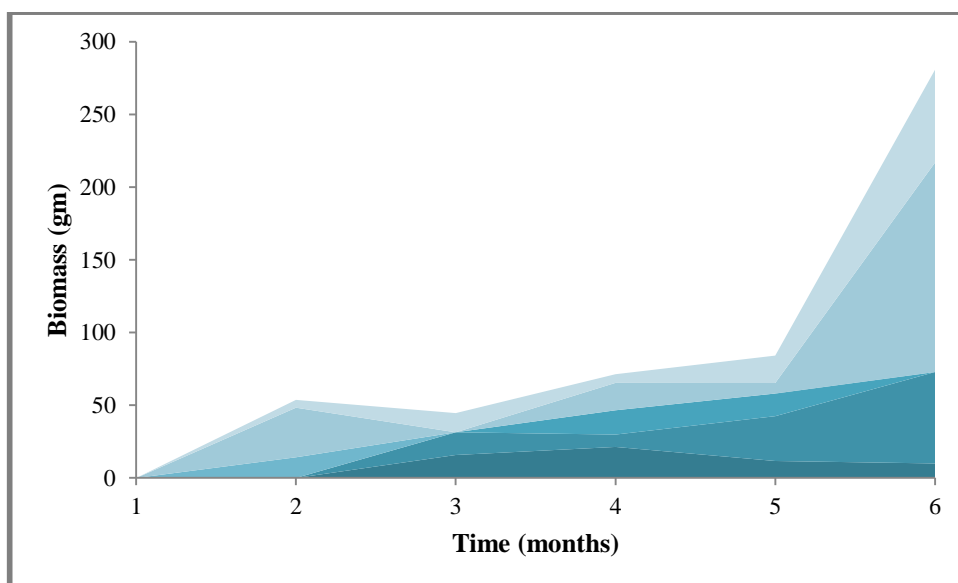


Figure 5.10 Grass Biomass in Even water treatment

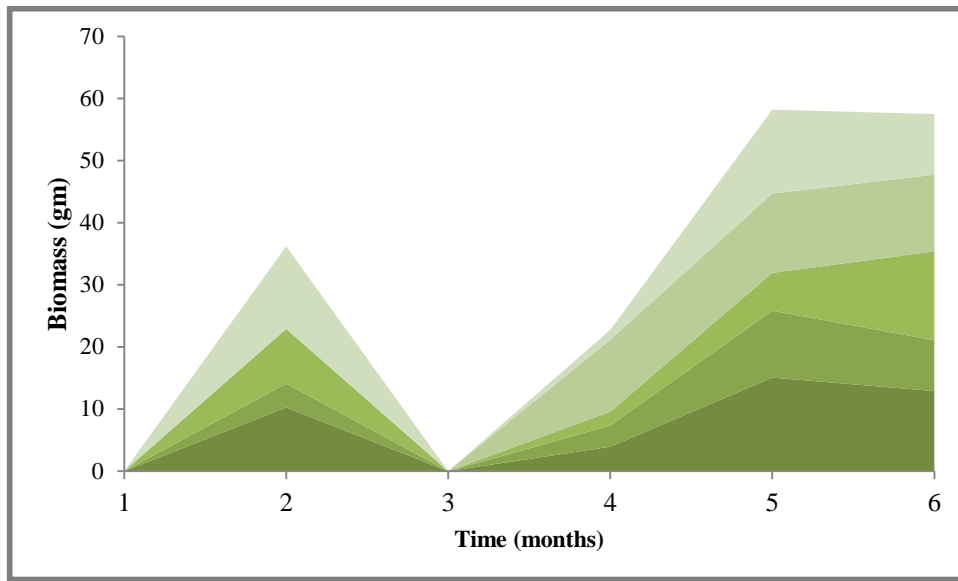


Figure 5.11 Grass Biomass in Defoliation treatment

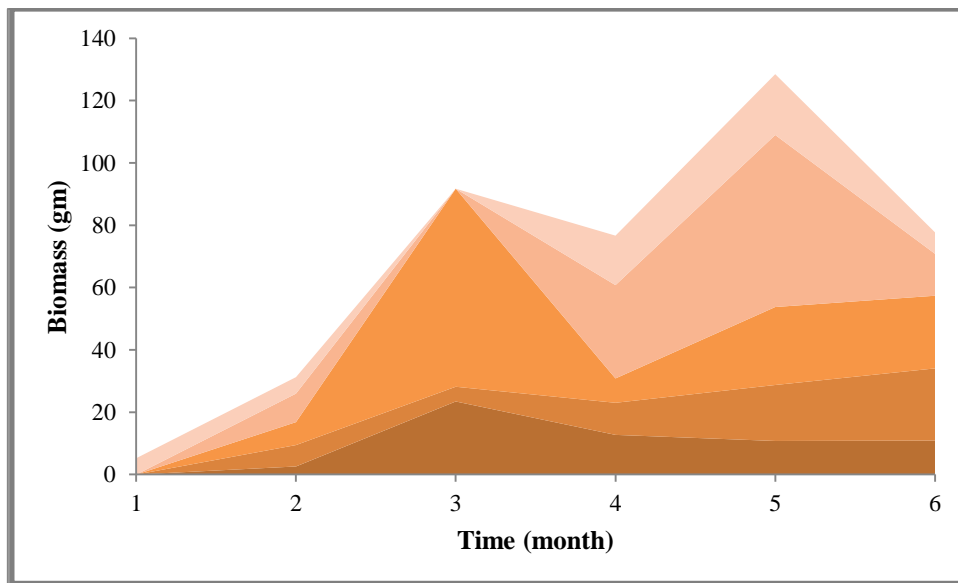


Figure 5.12 Grass Biomass in Natural rainfall treatment

5.4.3 Seedling Survival analysis

The data was analysed for survival of seedlings under various treatment combinations for each species in each block. In the first experimental year, 95% of *Anogeissus pendula* seedlings survived in the shade and control plots but only 41% in defoliation and natural plots. *Butea monosperma* showed highest survival of 87.7% in natural plots followed by 70% in defoliated condition, 62.5% in shaded plots and 56% in control plots (Figure 5.13). *Lannea coromandelica* had highest survival in shade plots (64.8%), 40% in defoliation, 34% in natural plot and 20% in control plots. The rest of the species could not be germinated successfully due to the poor quality of seeds collected. Another feature was evident that 90% of 1-2 year seedlings survived the treatments, the 10% deaths were caused by damage due to rats or common langurs.

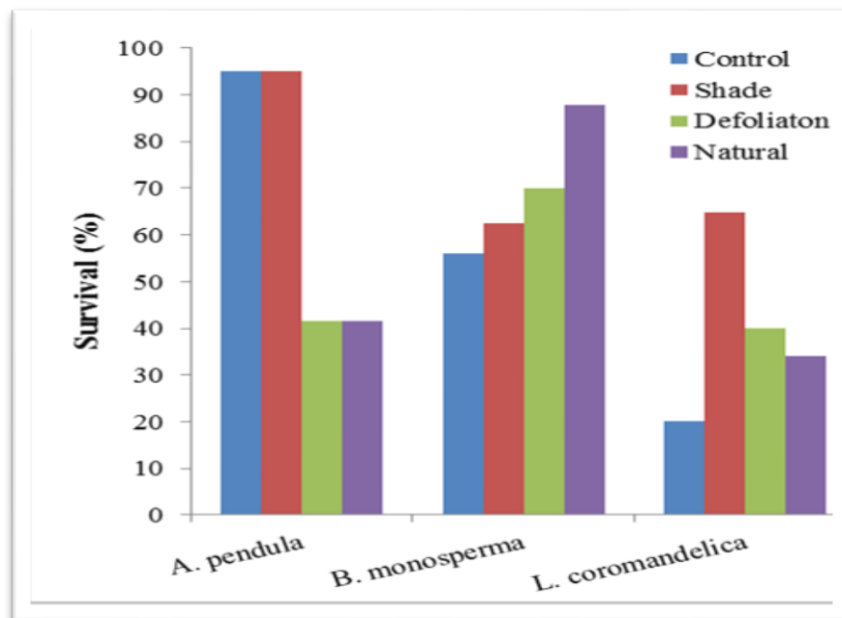


Figure 5.13 Survival of tree species in the four treatment blocks

5.5 Discussion

The experiment results helped us to understand the behaviour of seedlings in their first 2 year of growth pattern under various treatments. Each of the six target species responded differentially when subjected to these treatments. *Zizyphus mauritiana* seedlings showed a strong intra-specific competition such that only one out of the two planted seedlings in 30% of the plots survived. Both the grass species *Chloris barbata* and *Heteropogon contortus* were unable to survive in the shade plots. The grass although is a tough competitor for resources but still provided protection to the seedlings from scorching sun in the summer

and biting frost which were the two major contributors for seedling mortality. *Anogesissus pendula* showed best growth results in shade treatment followed by even water conditions and defoliation treatment in the first year. In the second year, however both the new (0-1 year) and the 1 year old seedlings had performed best in even water treatment followed by shade treatment and proving to be worst hit species by defoliation. *Butea monosperma* although had better growth with the supplementation of nutrients, yet performed the best after defoliation treatment followed by natural conditions, shade treatment and even water treatment in the first year, but in the second year of experiment the best results were obtained for natural treatment and worst in defoliated conditions. The expected results conform to the unpublished results for some species from the GEST site at Brazil. *Lannea coromandelica* did not show significant differences in the treatments but did slightly better in defoliated conditions in the first year and second year followed by rainfall and shade treatment. Shade treatment provided the best survival conditions for this species. *Zizyphus mauritiana* performed the best in natural plots followed by defoliation, even water and shade plots. In natural conditions, the grassed plots showed poorer growth pattern as compared to empty plots. *Balanites aegyptiaca* also had the best results in natural conditions, followed by shade and control and worst in defoliated conditions.



(a)



(b)

Plate 5.15 Seedling in open (a) and grassed plots (b) (open plot seedling burnt by frost but grass acted as a barrier for the seedlings within them)

5.6 Management Recommendations

- *Acacia leucophloea* and *Zizyphus mauritiana* shows best growth without any treatment. Removal of grass however improves the survival and growth. The seedlings of *Acacia leucophloea*, *Butea monosperma* and *Zizyphus mauritiana* were found to be drought resistant and hence can be planted at low moisture areas but for better survival, grazing should be regulated. The *in-situ* germination for *Butea monosperma* does not require any treatment but for *Acacia leucophloea* the germination was improved if the seed coat was given a small cut from the side with some moisture. *Zizyphus mauritiana* showed high germination when the seeds were soaked in water and drained and sun dried such that the seed coat developed some cracks.
- *Balanites aegyptiaca* showed 100% germination in nursery conditions after washing and sun drying the seeds. Although the species had best survival and growth without any treatment but it tends to succumb to grazing pressure hence protection to the juvenile seedling is recommended and since water is not a limiting factor for the species hence can be planted at low moisture areas.
- Experimental studies on *Anogeissus pendula* and *Lannea coromandelica* resulted that the species had best survival and growth in shade treatment thus depicting to be shade lovers and hence if planted in shady areas will lead to a better growth and survival of the species. Sowing of seeds in a 3 inch seed bed resulted in germination of *Anogeissus pendula* in nursery condition.
- Awareness amongst local inhabitants should be made by the Forest Department for practise of rotational closure of grasslands for establishment of “Sanctum sanctorum” for grazing and fodder collection so that the grasslands can cope up with the natural grazing pressure with time. Such closure may also help in regulating grazing by ungulates and domestic cattle thus in turn providing protection from herbivory.

Chapter 6

INVASIVE SPECIES

6.1 Introduction

Invasive plants are non-native species that have successfully spread outside their native range (Richardson, *et al.*, 2000; Williamson, 1996). Most invasions over the past several centuries have involved species transported directly or indirectly by humans. Their effects are pervasive and varied, depending upon genetics and population size of individual species, diversity and structure of communities, disturbance regimes and biogeochemical cycles. Most biological invasions over the past several centuries have involved species transported directly or indirectly by humans (McKinney & Lockwood, 1999; Pyšek *et al.*, 2002). It is well established that invasive species severely effect native biodiversity, cause hundreds of billions of dollars in economic damages and complicate the management of natural ecosystems around the world (Cox, 2004; Mooney, 2005). Among all the invasive organisms, alien invasive plants (AIP's) have been major cause for concern since long time because of their economic costs as weeds in agricultural fields (Pimentel, 2002), their ability to colonize rapidly in natural habitats and thereby affecting regeneration of native plants (Daehler & Strong, 1994; Wilcove *et al.*, 1998) and alter ecosystem functions (D'Antonio & Vitousek, 1992; Vitousek, 1990). According to the [Nature Conservancy](#) (Pimentel *et al.*, 2001), the estimated damage from invasive species worldwide totals over \$1.4 trillion, five percent of the global economy.

Biological invasions affect virtually all ecosystems on earth, but the degree to which different regions and biomes are invaded, and the quality of information from different regions, varies greatly. A large body of literature exists on the invasion of savannas in the Neotropics and northern Australia where invasive plants, especially African grasses, have had major impacts. As savannas cover about 60% of the continent, with tens of millions of people relying on the services they provide, it is timely to assess the current status of invasions as a threat to these ecosystems. A number of drivers and explanatory factors of plant invasions in

savannas have been described, mostly from the Neotropics and Australia. These include herbivore presence, residence time, intentional introductions for pasture improvements, fire regimes, the physiology of the introduced species, and anthropogenic disturbance. Therefore savannas are subject to many kinds of anthropogenic disturbances, as well as periodic natural disturbances (fire, drought, floods, mega-herbivores; Walker & Noy-Meir, 1982; Scholes, 1997). Anthropogenic disturbances create habitats and conditions suitable for invasions by alien plants, thus forming multiple sources for further invasions into savanna systems (van Wilgen *et al.*, 2001). According to Turpie (2004a), the grassland and savanna biomes are extensively invaded by AIPs, but mostly in the moister regions and particularly along river courses. The relative performance of native and invasive species could vary depending on the amount of environmental stress. Other environmental variables such as disturbance regime could also differentially increase the performance of native plants relative to co-occurring invaders (Alpert *et al.*, 2000; Hobbs & Huenneke, 1992; Mueller-Dombois & Loope, 1990).

Several ecosystems around the world are also dominated by native invasive plants (NIPs). NIPs are opportunistic and extremely adapted to exploit diverse habitats, generally less palatable and regenerate profusely, often in response to disturbance of the land, such as clearing, fire or overgrazing. According to Horvitz *et al.* (1998), high levels of biotic disturbance within communities was the only reason for an increase in the invisibility of the area. However, recent studies have indicated that the spatial scale of disturbance and local species diversity are as important as the degree of disturbance in understanding invasibility (Levine, 2000). Selective removal of palatable species may also lead to over abundance of NIPs. Overgrazing is one of the major disturbing factors in invasion and it leads to inability of the palatable native grasses to regenerate thus reducing the carrying capacity of the property for the domestic stock dramatically. Unpalatable or less palatable, species of native plants are favoured because of the lack of competition from palatable species. The grazing animals on site would not act as control agents for the invasive natives because of their un-palatability. Since increasingly large numbers of species are being imported by humans to areas far from their native geo-graphic ranges, and because some of these species have huge ecological and economic impacts on the native communities to which they are introduced, the ability to predict which species are likely to have large impacts becomes paramount. Preserving "intact" natural systems is an obvious priority for many conservation biologists. From the perspective of invasion biology, natural areas that have experienced minimal human disturbance have long been noted to be less invaded than areas that have been directly disturbed by humans (Allan, 1936; Rejmànek, 1989). Establishment in a natural community may require different traits than those required upon entering a human-disturbed habitat (Horvitz *et al.*, 1998), and features essential for establishment may not be consistent across taxa. Reichard & Hamilton (1997) conducted a retrospective analysis of traits of introduced woody plants to distinguish invaders and non invaders. Discriminant analysis models could correctly classify 86% of invaders; high risk of invasiveness was related to vegetative reproduction

(Daehler, 1998), lack of pre-germination seed treatment requirements, perfect (hermaphroditic) flowers and a long period of time in which the fruit was on the plant. Competitive ability is another trait that may confer an advantage for invasive species during establishment. Many studies have documented invaders that show a superior ability to exploit local resources when compared with native residents (Melgoza *et al.*, 1990, Petren & Case, 1996, Kupferberg, 1997, Holway, 1999, Byers, 2000) or when compared with non-invading introduced species (Thebaud *et al.*, 1996). Few communities are impenetrable to invasion by exotic species (Usher, 1988; Lodge, 1993a; Gordon, 1998), and communities differ in their susceptibility to invasion as well as in their ecological and evolutionary responses to these invasions. Within communities, invasibility is determined by the properties of the invasive species, the native species (e.g., relative competitive abilities, ability to resist disturbance) (Lonsdale, 1999) and the community. A species may be invasive either because it shares traits with resident native species or, alternatively, because it possesses traits different from those of native species and thus can occupy "empty niches" (Mack, 1996; Levine & D'Antonio, 1999).

Prosopis juliflora had been a favourite species, in the past, in Rajasthan for afforestation activities to meet the fuelwood requirements (Mathur & Saxena, 1968). It was planted around Sariska Tiger Reserve (STR) during 1968-1977, which has posed a serious problem within the Tiger Reserve. It is estimated that as much as 5000 ha. of STR has been infested by *P. juliflora*. It is also not a palatable species, therefore, it has not helped in reducing pressure on forests for the demand of fodder or small timber for agricultural implements (Sharma, 1983).

Along with *Prosopis juliflora*, *Adhatoda vasica*, *Cassia tora*, *Parthenium* sp. and *Lantana camara* also have spread within the landscape (plate 6.1) and are known to pose an allelopathic effect on the native palatable vegetation. Molisch (1937) coined the term 'allelopathy' which refers to all stimulatory and inhibitory biochemical interactions between the plants including microbes. The allelopathic plants control the environment in which they live. It is a negative factor in the formation of associations and communities. Low species diversity due to exclusion of the susceptible species from the common habitat is also attributed to allelopathy.

A case study of *Adhatoda vasica*. It can be classified under native invasive species as *Adhatoda vasica* was originated in India, Nepal and South Asia. It was introduced to Florida and the Caribbean (Cuba, Curacao), where it is called La Vasaca, Castana de Malabar, or Malabar nut tree. The shrub is bushy, branchy and commonly grows to 2.5 meters. The plant grows rapidly and coppices well (National Academy of Sciences, 1980). It regenerates through seeds as well as root suckers and grows well within the rainfall range of 500 to 1600 mm. Leaves are long and dark green in colour and cattle do not eat this plant as the leaves emit an unpleasant smell (Sampath Kumar *et al.*, 2010). It survives prolonged drought and tolerates infertile as well as alkaline soils. However, Geilfus (1989) warned that because it grew vigorously, *Adhatoda vasica* could invade uncultivated areas, such as pastures.



Plate 6. 1. Germination of weeds such as *Cassia tora* in gregarious numbers gives tough competition to local tree seedlings

Sankar (1984) observed that *A. vasica* had assumed the status of “weed” in STR and reported that the ungulates such as chital and sambar were using patches of *Adhatoda* only for cover but these species were not found feeding on it. The working plan records of the forest division indicated that *Adhatoda* was always considered as a shrub more so for its numerous medicinal properties and hence there was never a need for it to be considered as an invasive species. But recent observations in the study area have highlighted the fact that the species being unpalatable has increased manifold and replaced the native palatable vegetation. *Adhatoda* directly alters the growth of other plant species by forming its own monocultures. The park authorities have started a manual eradication of this species from the study area. Sankar *et al.* (2008) also mentioned that *Adhatoda* was a native understory species but had become common in disturbed and over grazed areas and appeared to suppress grass and other native herbaceous species but at the same time the eradication should be such that cover for predators is not lost completely (Sankar *et al.*, 2012). This study deals with the study of extent of invasion and the vegetation composition of ground layer after the eradication of *A. vasica*.

6.2 Methodology:

6.2.1 Mapping the extent:

The mapping was done by walking across the intensive study area. A hand held GPS was used to locate the geographical coordinates of the path walked with a distance of 5-10 m between two consecutive points. The infested area was delineated and the boundary was walked so as to enclose the infested area in the polygon. Effort was made to cover all the infested areas into polygons. These points were plotted in ArcGIS 9.2 (ESRI, 2006) to estimate the invasion, along with the major roads, villages, chowkis and drainage pattern and also the area under invasion was calculated.

6.2.2 Vegetation composition:

Two locations were randomly selected where *A. vasica* had been manually removed, one location where eradication was done within 1 year and at another where it was done before 2 years. Ten plots of 10 m radius were laid randomly in each of the two locations. Trees were counted in the 10 m plot and their GBH was also measured, shrubs were counted in 5 m concentric radial plot and six 1mX1m quadrats were laid inside the plot and herbs and ground cover was measured. This data was analysed for density, frequency, IVI, evenness indices. These were compared to locations where no removal had been done.

6.3 Results

6.3.1 Mapping the extent

The following map (Figure 6.1) shows the extent of invasion of *Adhatoda vasica* along the 20 km² valley of Sariska. The area under invasion was calculated to be 5.22 km² which is 26.1 % of the area that was studied.

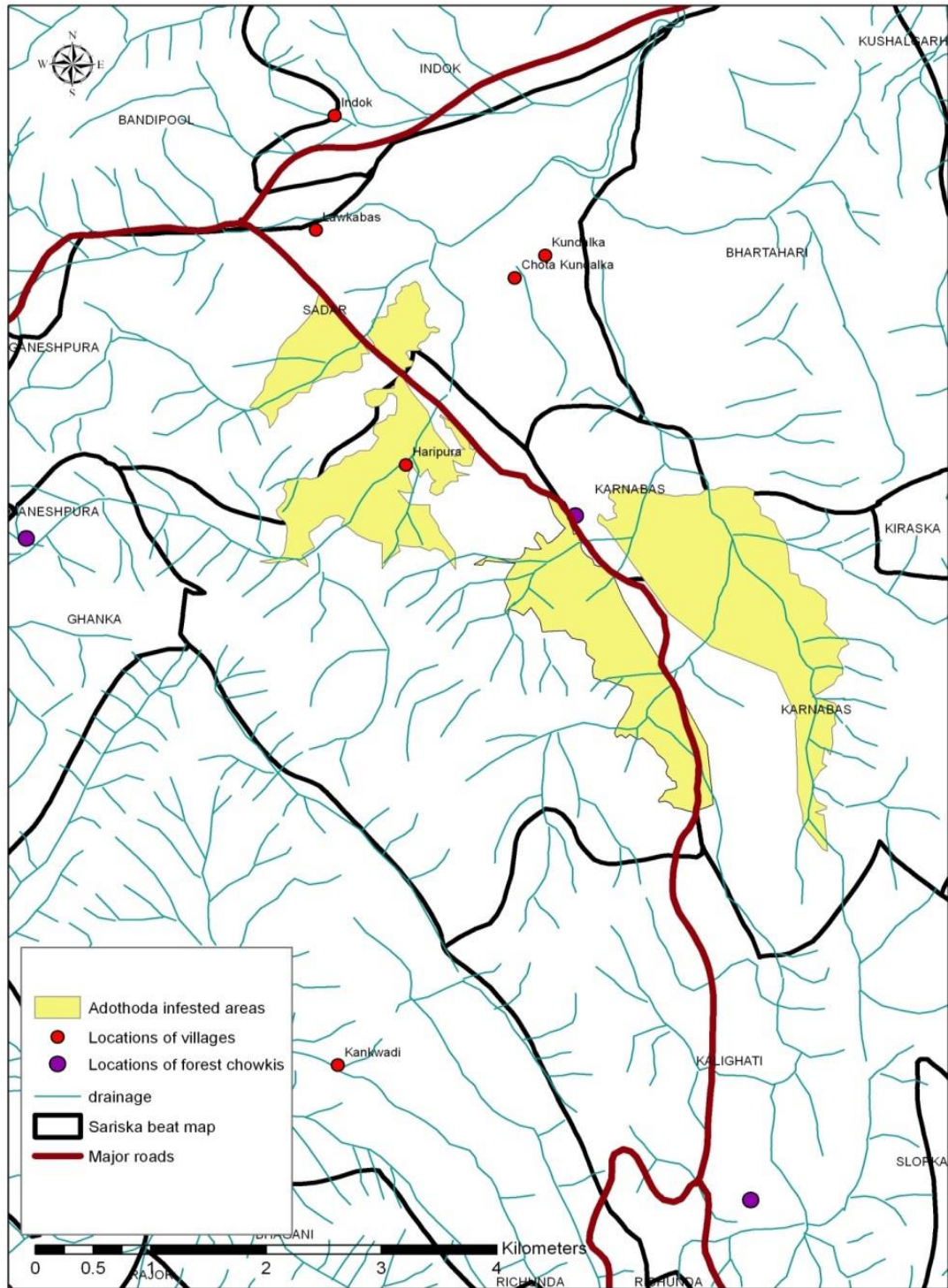


Figure 6.1 Extent of *A. vasica* invasion along the Sariska valley



Plate 6.2 *A. vasica* invasion in a *B. monosperma*-*A. catechu* woodland



Plate 6.3 Un-supressed growth of *A. vasica*



Plate 6.4 A. *vasica* growing along the state highway #29



Plate 6.5 A. *vasica* growing along forest roads



Plate 6.6 Manual uprooting of *A. vasica* in the study area

6.3.2 Vegetation composition

The various vegetation parameters were calculated for two locations: one within 1 year of removal of *Adhatoda vasica* and other within 2 years of removal of the same species. A parallel control (invaded with *Adhatoda*) was also selected to compare the species richness, diversity and composition of vegetation in the invaded and restored areas. An assumption was made to exclude bigger trees from any calculations as uprooting was supposed to not affect trees but alter the ground cover for changes in seedling, sapling, shrubs, herbs and grass. Another hypothesis was made that the three sites for comparison were not different in terms of soil composition, moisture availability and disturbance as these sites were not far enough from each other and hence any changes at the three sites could be purely attributed to effects of *Adhatoda* invasion on native vegetation.

a) Within 1 year of removal

The total seedling and sapling density was found to be 334.39 ind/ha and 25.48 ind/ha. *Anogeissus pendula* was the only species in seedling stage with 50% frequency. It was also found to have maximum sapling density (Table 6.1). Among shrubs, *Adhatoda vasica* was found to have maximum density (29058.82 ind/ha) followed by *Grewia flavescens* (3529.41 ind/ha) and *Capparis sepiaria* (470.59 ind/ha). For herbs, *Elytraria acaulis* (21666.37 ind/ha) had the maximum density, followed by *Dicliptera verticillata* (19999.37 ind/ha) and *Sida*

acuta (5000 ind/ha). Species richness for herbs was found to be 8. Grass cover was found to be 16% within a year of removal.

Table 6.1 Various parameters from site 1

Species	Habit	Density/ha	Freq (%)	Abundance
<i>Anogeissus pendula</i>	seedling	334.39	50	21
<i>Anogeissus pendula</i>	sapling	12.74	20	2
<i>Zizyphus mauritiana</i>	sapling	9.55	10	3
<i>Butea monosperma</i>	sapling	3.18	10	1
<i>Grewia flavescens</i>	shrub	3529.41	80	3.75
<i>Adhatoda vasica</i>	shrub	290588.2	100	24.7
<i>Capparis decidua</i>	shrub	117.65	10	1
<i>Securinega leucopyrus</i>	shrub	117.65	10	1
<i>Capparis sepiaria</i>	shrub	470.59	40	1
<i>Dicliptera verticillata</i>	herb	19999.37	50	0.40
<i>Boerhavia diffusa</i>	herb	1666.7	10	0.17
<i>Sida cordifolia</i>	herb	1666.7	10	0.17
<i>Abutilon indicum</i>	herb	1666.7	10	0.17
<i>Puppalia lappacea</i>	herb	1666.7	10	0.17
<i>Elytraria acaulis</i>	herb	21666.3	60	0.37
<i>Solanum nigrum</i>	herb	3333.4	20	0.17
<i>Sida acuta</i>	herb	5000	10	0.5
<i>Chloris dolichostachya</i>	grass	13.61%		
<i>Setaria pumila</i>	grass	0.25%		
<i>Heteropogon contortus</i>	grass	1.08%		
<i>Dichanthium annulatum</i>	grass	0.16%		
<i>Tragus roxburghii</i>	grass	0.08%		
<i>Cenchrus setigerus</i>	grass	0.05%		
<i>Sporobolus coromandelianus</i>	grass	0.66%		

b) Within 2 years of removal

The total seedling and sapling density at this site was found to be 57.32 ind/ha and 203.82 ind/ha. *Balanites aegyptiaca* was found to have highest seedling and sapling density among

others (Table 6.2). Density for shrubs was found to be 24588.24 ind/ha and *Adhatoda vasica* had maximum density (14941.18 ind/ha) and *Capparis decidua* had the minimum density (352.94 ind/ha). Herb density was found to be 288332.5 ind/ha, where, *Dicliptera verticillata* (116666.8 ind/ha) was highest with *Cassia tora* (66666.8 ind/ha), *Sida acuta* (54999.4 ind/ha) and *Elytraria acaulis* (18333.04 ind/ha) in the decreasing order. Species richness for herbs was found to be 12. Grass cover was found to be 52.58% at this site.

Table 6.2 Various parameters from site 2

Species	Habit	Density/ha	Freq (%)	Abundance
<i>Butea monosperma</i>	seedling	3.18	10	1
<i>Zizyphus mauritiana</i>	seedling	12.74	20	2
<i>Balanites aegyptiaca</i>	seedling	41.4	40	3.25
<i>Zizyphus mauritiana</i>	sapling	19.11	30	2
<i>Butea monosperma</i>	sapling	6.37	10	2
<i>Balanites aegyptiaca</i>	sapling	178.34	70	8
<i>Grewia flavescens</i>	shrub	6470.59	90	6.11
<i>Adhatoda vasica</i>	shrub	14941.18	100	12.7
<i>Capparis decidua</i>	shrub	351.94	30	1
<i>Dichrostachys cinerea</i>	shrub	1176.47	20	5
<i>Capparis sepiaria</i>	shrub	1647.06	90	1.55
<i>Dicliptera verticillata</i>	herb	116666.7	80	0.42
<i>Boerhavia diffusa</i>	herb	8332.6	30	0.28
<i>Cassia tora</i>	herb	66666.8	90	0.74
<i>Achyranthus aspera</i>	herb	5000	20	0.25
<i>Puppalia lappacae</i>	herb	1666.7	10	0.17
<i>Elytraria acaulis</i>	herb	18333.04	60	0.31
<i>Peristrophe bicalyculata</i>	herb	1666.7	10	0.17
<i>Sida acuta</i>	herb	54999.4	80	0.69
<i>Maerua arenaria</i>	herb	1666.7	10	0.17
<i>Abutilon indicum</i>	herb	1666.7	10	0.17
<i>Barleria cristata</i>	herb	3333.3	10	0.33
<i>Chloris dolichostachya</i>	grass	30.66%		
<i>Setaria pumila</i>	grass	5.16%		
<i>Heteropogon contortus</i>	grass	2.91%		
<i>Sporobolus coromandelianus</i>	grass	0.33%		

<i>Cynodon dactylon</i>	grass	12.58%
<i>Digitaria ciliaris</i>	grass	0.08%
<i>Eleusine indica</i>	grass	0.58%
<i>Aristida adscensionis</i>	grass	0.25%

6.4 Discussion

The study revealed that manual removal of *Adhatoda* resulted in increased sapling density, shrub density (Figure 6.2) and grass cover (Figure 6.3) and decreased seedling density and herb density. Grass cover showed an inversely proportional relationship to seedling and herb density, one of the possible explanations could be the increased competition imposed on seedling and herb establishment by grass. Population regeneration for *Adhatoda vasica* indicated that mature individuals and seedlings decreased by uprooting within 1 year of removal and further decreased within 2 years of removal (Figure 6.4). Increase in individuals of middle aged category was observed over time. The absence of seedlings of tree species like *Butea monosperma*, *Zizyphus mauritiana*, *Acacia leucophloea* and *Acacia catechu* in the invaded areas showed that it inhibited their seedling growth. *Anogeissus pendula* was the lone species that was observed to produce seedlings within the invaded areas as it finds conducive shade ample environment under the thick canopy of *Adhatoda*.

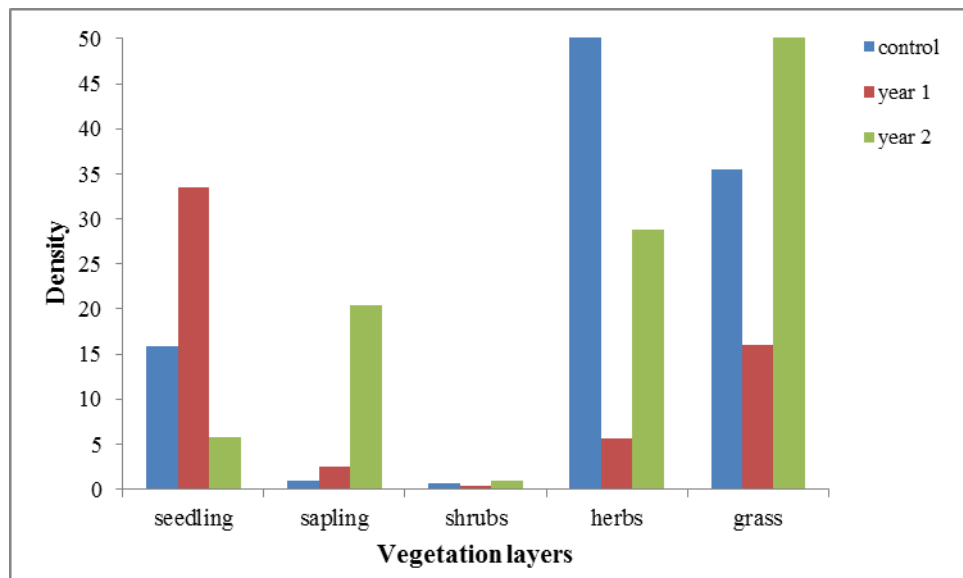


Figure 6.2 Observed densities for different vegetative layers

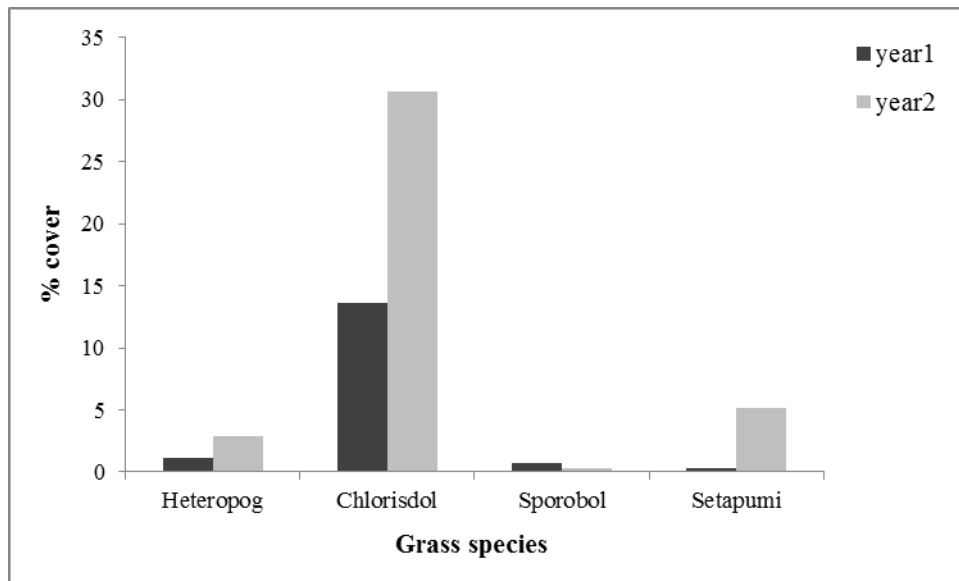


Figure 6.3 Changes in grass cover after removal of *Adhatoda vasica*

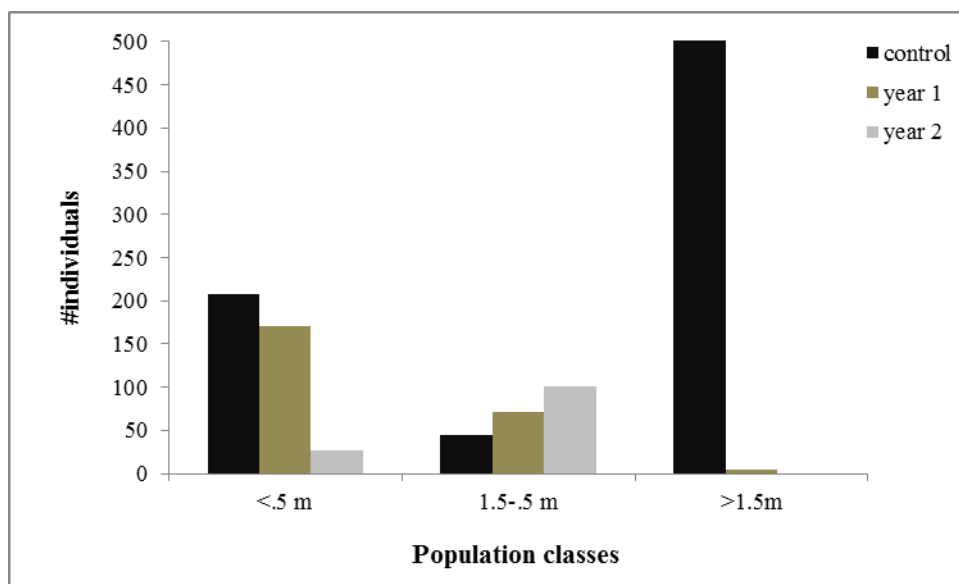


Figure 6.4 Regeneration of *Adhatoda vasica* population after removal

Many conceptual and mathematical models have suggested that increases in resource availability (including space, created by physical disturbance) can increase community susceptibility to invasion (Davis *et al.*, 2000; Fox & Fox, 1986; Hobbs, 1989; Shea & Chesson, 2002; Sher & Hyatt, 1999; Tilman, 1999). Researches in southern Arizona has shown that *Prosopis juliflora var. velutina* competes strongly with perennial and annual grasses for soil moisture, and the grass production increased when the mesquite is killed (Cable & Tschirley, 1961). It is unlikely that one approach alone will overcome problems of dense native plant invasion. Rather, a combination of two or more approaches - fire, mechanical control and

grazing management need to be considered together as part of a comprehensive paddock or property plan. The eradication process should be followed up every year to reduce the invasive effects to a minimum. Hence, a more rational approach such as thinning or uprooting of *Adhatoda* over a large span of time with additional facilitation of grass species such as *Cynodon dactylon*, *Heteropogon contortus* and *Chloris dolichostachya* might be useful to create equal survival opportunities for both tree and grass layer in such a landscape.

Eradication of NIP alone might not allow ecosystems to recover, because some invaders change the condition of the habitat so as to render it unsuitable for native species. Successful eradications can also have undesired effects resulting from a fertile gap being created in the landscape and establishment or increase of one or more other invasive species which were suppressed earlier in comparison to the main invasive species in that area.

Invasive species eradication is an increasingly important component of the conservation and management of natural ecosystems. However, in natural systems, a shift in emphasis from strict invasive management towards broader ecosystem restoration goals is required. This will place more emphasis on the full diagnosis of causal factors and the desired ecological outcomes of eradications (Hobbs, 1999). Benefits (reduced weed pressure) are realized after at least 1-3 seasons or years of growing cover crops, depending on location, type of cover crop, and cover crop accession (Chikoye *et al.*, 2002). Labour investments for weeding subsequent crops may be reduced by up to 50 percent (Akobundu *et al.*, 2000).

Finally, removal of invasive plant species can reduce habitat or resources available for native fauna if the removal is not accompanied by further restoration measures. The type of species being removed, the degree to which it has replaced native taxa, and the presence of other non-native species can affect the eventual impacts of removal of an invasive species. Post-eradication monitoring is also extremely valuable, not least because it allows managers to document the positive outcomes of eradication successes. It also provides the opportunity to learn from mistakes and gives managers the chance to curtail negative effects before they become severe. More frequent ecological studies that take advantage of eradication programs as being large-scale ecosystem experiments will speed the accumulation of knowledge about system responses to exotic species removals. As knowledge about effective eradication methods accumulates, attention should turn to combining such methods with broader ecological principles to form cost-effective removal strategies that accomplish overall restoration goals (Zavaleta *et al.*, 2001).

Human disturbance of natural communities may have broadened the range of characteristics leading to successful colonization and thus increased the frequency of invasion into existing communities (Vitousek *et al.*, 1996). In turn, research on the ecology, genetics and evolutionary biology of invasive species may eventually provide the practical information that will be essential for preventing the homogenization of the world's flora and fauna (Sakai *et al.*, 2001).

Effective policy and management strategies aimed at reducing the considerable ecological, economic, and human health risks of invasions depend upon a solid understanding of transfer mechanisms (vectors). In short, a scientific understanding of why, how, when and where species are transported provides a critical foundation for vector management (Ruiz & Carlton, 2003).

6.6 Management recommendations

- a) **Management of Total Grazing Pressure:** Ensuring that total grazing pressure is at a low enough level so that palatable native grasses such as *Cynodon dactylon*, *Heteropogon contortus* and *Chloris dolichostachya* can regenerate. This could include spelling paddocks when seasonal conditions are appropriate and careful placement of watering points, fences and saltlicks. Dense regeneration of invasive native plants may be a symptom of changes associated with grazing management. Any permanent solution requires changes in grazing management. Appropriate grazing management depends on setting management objectives for individual paddocks, working out and implementing the management required to achieve those objectives, and monitoring the effects. Consider 'total grazing pressure' - the effect not only of wild ungulates, but domestic stock as well.
- b) **Minimal disturbance:** The native vegetation on site should be kept free from disturbance as much as possible. Baring of the soil surface, constructing tracks or fence-lines through areas of existing native vegetation, or unnecessary clearing could all lead to re-colonisation.
- c) **Monitoring:** Carefully monitor for invasion, respond early and follow up regularly.
- d) **Managing VDC:** The weeds can be removed by the village development committees (VDC) and put to ethno-medicinal use. *Adhatoda vasica* is known to possess wide spectrum of medicinal properties including positive effects on inflammatory diseases (Chakraborty & Brantner, 2001) therefore, it can be used as an alternate source of income generation by VDC's.
- e) **Supplementation:** Removal of *Adhatoda* should be followed by external supplementation of grass species such as *Cynodon dactylon*, *Heteropogon contortus* and *Chloris dolichostachya* which may increase the chances of restoration of the area rather than increase of other suppressed opportunistic invasive species.

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Appendix 1 List of plant species identified during study period 2009-2011. Nomenclature follows Parmar (1985).

Family	species	local name
Adiantaceae	<i>Adiantum capillus-veneris</i> L.	
Pteridaceae	<i>Actinopteris radiata</i> (J. Koenig ex Sw.) Link	
Pinaceae	<i>Pinus roxburghii</i> Sarg.	
Menispermaceae.	<i>Cissampelos pareira</i> L	chidi ka laddu
	<i>Cocculus hirsutus</i> (L.) Diels	
	<i>Tinospora cordifolia</i> (Thunb.) Miers	dilwali bel
Nelumbonaceae	<i>Nelumbo nucifera</i> Gaertn.	
Papaveraceae	<i>Argemone Mexicana</i> L.	peeli kateli
	<i>A. ochroleuca</i> Sweet	

Capparaceae	<i>Capparis decidua</i> (Forssk.) Edgew.	kair
	<i>C. sepiaria</i> L.	jaal
	<i>Cleome viscosa</i> L.	kukarbhawra
	<i>Crataeva adansonii</i> D.C. Prodr	
	<i>Maerua arenaria</i> (DC.) Hook. f. & Thorns.	hari bel
Flacourtiaceae	<i>Flacourtia indica</i> (Burm. f.) Merr.	kakon
Caryophyllaceae	<i>Polycarpaea corymbosa</i> (L.) Lam.	
	<i>Spergula arvensis</i> L.	
Portulacaceae	<i>Portulaca suffruticosa</i> Thwaites	luniya
Malvaceae	<i>Abutilon bidentatum</i> A. Rich.	san
	<i>A. indicum</i> (L.) Sweet	jungli san
	<i>Hibiscus lobatus</i> (J. A. Murray) Kuntze	
	<i>Pavonia zeylanica</i> Cav.	
	<i>Sida acuta</i> Burm. f.	krashti
	<i>S. cordifolia</i> L.	dilkrashti
	<i>S. cordata</i> (Burm. f.) Borssum.	dilkrashti
	<i>S. mysorensis</i> Wight & Arn.	
	<i>S. rhombifolia</i> L.	
	<i>S. veronicaefolia</i> Lam.	
Bombacaceae	<i>Bombax ceiba</i> L.	semal
Sterculiaceae	<i>Helicteres isora</i> L.	baincha
	<i>Melhania futtyporensis</i> Munro ex Mast.	
	<i>Sterculia urens</i> Roxb	
	<i>Waltheria indica</i> Linn.	
Tiliaceae	<i>Corchorus aestuans</i> L.	
	<i>C. olitorius</i> L.	
	<i>C. trilocularis</i> L.	
	<i>Grewia villosa</i> Willd	kaimer
	<i>G. flavescens</i> A. Juss.	chapoon
	<i>G. tenax</i> (Forsk) Fiori	ganger
	<i>Triumfetta pentandra</i> A. Rich.	chichdi
	<i>G. tiliifolia</i> Vahl.	dhaman
Zygophyllaceae	<i>Tribulus terrestris</i> L.	gokhru
Oxalidaceae L	<i>Oxalis corniculata</i>	
Rutaceae Corr.	<i>Aegle marmelos</i> (L.)	beel
	<i>Limonia acidissima</i> L.	
	<i>Naringi crenulata</i> (Roxb.) Nicolson	
Balanitaceae	<i>Balanites aegyptiaca</i> (L.) Del.	hingot
Burseraceae	<i>Boswellia serrata</i> Roxb. ex Coleb.	Saalar
	<i>Commiphora wightii</i> (Arn.) Bhandari	guggal
Meliaceae	<i>Azadirachta indica</i> A. Juss.	neem
	<i>Melia azedarach</i> L.	bakain
Celastraceae	<i>Maytenus emarginatus</i> (Willd.) Ding Hou	kakoda
Rhamnaceae	<i>Ziziphus mauritiana</i> Lam.	ber
	<i>Z. nummularia</i> (Burm. f.) Wight & Arn.	jhadberi
Vitaceae	<i>Ampelocissus latifolia</i> (Roxb.) Planch	
Sapindaceae	<i>Cardiospermum halicacabum</i> L	doda bel
Anacardiaceae	<i>Lannea coromandelica</i> (Houtt.) Merr.	gurjan
	<i>Mangifera indica</i> L.	aam
	<i>Rhus mysorensis</i> G. Don	daansra
Moringaceae	<i>Moringa pterygosperma</i> Gaertn.	sehjan
Faboideae	<i>Abrus precatorius</i> L.	ratti
	<i>Alysicarpus</i> spp	

	<i>Butea monosperma</i> (Lam.) Taub.	chilla
	<i>B. superba</i> Roxb.	
	<i>Crotolaria medicagenia</i> Lam.	dhaniya jhojhru
	<i>C. hispida</i> Schinz	
	<i>Dalbergia sissoo</i> Roxb.	shisham
	<i>Desmodium gangeticum</i> (L.) DC.	
	<i>D. repandum</i> (Vahl.) DC.	
	<i>Delonix regia</i> (Boj. ex Hook.) Raf.	gulmohar
	<i>Erythrina suberosa</i> Roxb.	
	<i>Indigofera cordifolia</i> Heyne ex Roth	
	<i>I. coerulea</i> Roxb.	
	<i>I. linnaei</i> Ali	bufdi
	<i>I. tinctoria</i> L.	
	<i>I. trita</i> L. f.	
	<i>Inga dulcis</i> (Roxb.) Willd.	jungli jalebi
	<i>Mucuna pruriens</i> (L.) DC.	conch
	<i>Pongamia pinnata</i> L.	karanj
	<i>Rhynchosia minima</i> L. DC. var. <i>laxiflora</i> (Camb.) Baker	
	<i>Sesbania sesban</i> (L.) Merr.	
	<i>Tephrosia pumila</i> (Lam.) Pers.	
	<i>T. purpurea</i> (L.) Pers.	jhojhru
	<i>T. strigosa</i> (Dalz.) Sant. & Mahesh.	
	<i>Vigna radiata</i> (L.) Wilczek	moongbel
	<i>Zornia gibbosa</i> Span.	
Caesalpinoideae	<i>Bauhinia racemosa</i> Lam.	jhinjha
	<i>Cassia alata</i> L.	
	<i>C. fistula</i> L.	kaudiyala
	<i>C. mimosaefolia</i>	
	<i>C. obtusifolia</i> L.	badi pawad
	<i>C. pumila</i> Lam.	
	<i>C. tora</i> L.	pawad
	<i>Parkinsonia aculeata</i> L.	
	<i>Tamarindus indica</i> L.	imli
Mimosoideae	<i>Acacia catechu</i> (L. f.) Willd.	kattha
	<i>A. leucophloea</i> (Roxb.) Willd	ronj
	<i>A. nilotica</i> L. Del.	desi kikar
	<i>A. senegal</i> (L.) Willd.	dhauli khair
	<i>Albizia lebbeck</i> (L.) Benth.	siris
	<i>Dichrostachys cinerea</i> (L.) Wight & Arn.	barbara
	<i>Mimosa himalayana</i> Gamble	
	<i>Propolis cineraria</i> (L.) Druce	khejri
	<i>P. juliflora</i> (Sw.) DC.	vilayti kikar
Rosaceae	<i>Potentilla supina</i> L.	chinkni
Combretaceae	<i>Anogeissus pendula</i> Edgew.	dhok
	<i>Terminalia arjuna</i> (Roxb. ex DC.) Wight & Arn.	tal
	<i>T. bellerica</i> (Gaertn.) Roxb.	behera
Myrtaceae	<i>Syzygium cumini</i> (L.) Skeels	jamun
Lythraceae	<i>Ammannia baccifera</i> L.	
	<i>Lawsonia inermis</i> Lam.	mehendi
	<i>Woodfordia fruticosa</i> (L.) Kurz	

Onagraceae	<i>Ludwigia perennis</i> L.	
Cucurbitaceae	<i>Coccinia grandis</i> (L.) Voigt	
	<i>Luffa acutangula</i> (L.) Roxb. var. <i>amara</i> Cl.	jungli tori
	<i>Momordica charantia</i> L. var. <i>muricata</i> (Willd.) Chakravarty	karela bel
	<i>Trichosanthus cucumerina</i> L.	
	<i>T. tricuspidata</i> Lour.	
	<i>Mukia maderaspatana</i> (L.) M.Roem.	kachribel
Cactaceae	<i>Opuntia elatior</i> Mill.	
Aizoaceae	<i>Zaleya govindia</i> (Buch. Ham. ex D. Don) Nair	
Molluginaceae	<i>Glinus lotoides</i> L.	
	<i>Mollugo cerviana</i> Ser.	chidiya ka dhaniya
Rubiaceae	<i>Borreria articularis</i> (Linn. f.) F. N. Williams.	
	<i>B. stricta</i> G. Mey.	
	<i>Mitragyna parvifolia</i> (Roxb.) Korth	kadamb
	<i>Oldenlandia corymbosa</i> L.	
Asteraceae	<i>Acanthospermum hispidum</i> DC.	dukatta
	<i>Ageratum conyzoides</i> L.	
	<i>Bidens biternata</i> (Lour.) Merr. & Sherrf	
	<i>Blainvillea acmella</i> (L.) Philip.	jungli kaalajeeri
	<i>Blumea lacera</i> (Burm. f.) DC.	
	<i>Cyathocline purpurea</i> (D. Don) Kuntze	
	<i>Eclipta alba</i> (L.) Hassk.	
	<i>E. prostrata</i> L.	
	<i>Emilia sonchifolia</i> (L.) DC.	
	<i>Grangea maderaspatana</i> Poir.	
	<i>Launaea procumbens</i> (Roxb.) Ramayya & Rajgopal	
	<i>Tridax procumbens</i> L.	khoon chusni rokdi
	<i>Verbesina encelioides</i> (Cav.) Benth. & Hook. f. ex A. Gray	
	<i>Vernonia cinerea</i> (L.) Less.	
	<i>Xanthium strumarium</i> L.	
Plumbaginaceae	<i>Plumbago zeylanica</i> L.	chitrawal
Ebenaceae	<i>Diospyros melanoxylon</i> Roxb.	tendu
Oleaceae	<i>Nyctanthes arbortristis</i> L.	harshingar
Apocynaceae	<i>Carissa carandas</i> L.	karonda
	<i>Holarrhena antidysenterica</i> (L.) Wall.	kaner
	<i>Nerium indicum</i> Mill.	
	<i>Wrightia tinctoria</i> R. Br.	dudhi
	<i>W. tomentosa</i> Roem. & Schult.	dudhi
Asclepiadaceae	<i>Calotropis procera</i> (Ait.) R. Br.	aakda
	<i>Pergularia daemia</i> (Forssk.) Chiov.	
	<i>Wattakaka volubilis</i> (L. f.) Stapf	
Boraginaceae.	<i>Heliotropium merifolium</i> Retz	
Ehretiaceae	<i>Cordia dichotoma</i> Forst. F.	lasoda
	<i>Ehretia laevis</i> Roxb.	chamrod
Convolvulaceae	<i>Convolvulus prostratus</i> Forssk.	
	<i>Evolvulus alsinoides</i> Linn.	
	<i>Ipomoea nil</i> (L.) Roth	
	<i>I. muricata</i> (L.) Jacq.	
	<i>I. pes-tigridis</i> L.	dhakdhela bel

	<i>I. eriocarpa</i> R. Br.	
	<i>Merremia gangetica</i> Cufod.	
	<i>Rivea hypocrateriformis</i> Choisy	
Cuscutaceae	<i>Cuscuta reflexa</i> Roxb.	amarbel
Solanaceae	<i>Datura innoxia</i> Mill.	dhatura
	<i>Nicotiana plubaginifolia</i> Viv.	tambaku
	<i>Solanum incanum</i> L.	jungli baingan
	<i>S. nigrum</i> L.	
Scrophulariaceae	<i>Kickxia ramosissima</i> (Wall.) Janch.	
	<i>Lindenbergia muraria</i> (L. ex D. Don) Bruehl	
	<i>Lindernia ciliata</i> (Colsm.) Pennell	
	<i>L. crustacea</i> (L.) F. Muell.	
	<i>L. multiflora</i> (Roxb.) Mukherjee	
Bignoniaceae	<i>Tecomella undulata</i> (Seem) Sm.	roheda
	<i>Jacaranda mimosifolia</i> D. Don	
Pedaliaceae	<i>Sesamum mulayanum</i> Nair	jungli til
Martyniaceae	<i>Martynia annua</i> L.	billayi
Acanthaceae	<i>Adhatoda zeylanica</i> Medie.	adushta
	<i>Barleria cristata</i> L.	
	<i>B. prionitis</i> L. var. <i>prionitis</i>	vajradanti
	<i>Blepharis madaraspatensis</i> (L.) Roth	
	<i>Dicliptera verticillata</i> (Forssk.) Chirst	kaagler
	<i>Dipteracanthus patulus</i> (Jacq.) Nees	
	<i>Elytraria acaulis</i> (L. f.) Linden	moriya ki tambaku
	<i>Lepidagathis cristata</i> Willd.	
	<i>Peristrophe bicalyculata</i> (Retz.) Nees	kaksa
	<i>Rostellularia procumbens</i> L.	
	<i>Rungia parviflora</i> Nees	
Verbenaceae	<i>Clerodendrum phlomidis</i> L. f.	aernia
	<i>Lantana camara</i> L. var. <i>aculeata</i> (L.) Mold. salvifolia Jacq.	Lalten
Lamiaceae	<i>Anisomeles indica</i> (L.) Kuntze	
	<i>Leucas urticaefolia</i> (Vahl) R.Br	
	<i>Ocimum canum</i> Sims.	manbabchi
	<i>Salvia aegyptiaca</i> Linn.	
Nyctaginaceae	<i>Boerhavia diffusa</i> L.	saati
	<i>B. chinensis</i> (L.) Rottb.	
Amaranthaceae	<i>Achyranthus aspera</i> L. var. <i>aspera</i>	unga
	<i>Alternanthera pungens</i> Kunth	
	<i>A. sessilis</i> (L.) DC.	
	<i>Amaranthus spinosus</i> L.	
	<i>Celosia argentea</i> L.	
	<i>Digera muricata</i> (L.) Matt.	lusuwa
	<i>Pupalia lappacea</i> (L.) Juss.	barbut
Polygonaceae	<i>Antigonon leptopus</i> Hook. & Arn.	jhumki bel
	<i>Polygonum plebium</i> R. Br.	
Proteaceae	<i>Grevillea robusta</i> Cunn. ex R. Br.	
Euphorbiaceae	<i>Emblica officinalis</i> Gaertn.	amla
	<i>Euphorbia clarkaeana</i> Hook. f.	dudhi
	<i>E. hirta</i> L.	dudhi rokdi
	<i>E. neriifolia</i> L.	dandathor
	<i>E. prostata</i> Ait.	
	<i>Kirganelia villosa</i> Blanco	

	<i>Mallotus philippensis</i> (Lam.) Muell. Arg.	rohini
	<i>Phyllanthus amarus</i> Schum. & Thonn	
	<i>P. niruri</i> L.	
	<i>Ricinus communis</i> L.	
	<i>Securinega leucopyrus</i> Willd.	dholaan
Ulmaceae	<i>Holoptelea integrifolia</i> (Roxb.) Planch.	papdi
Moraceae	<i>Ficus benghalensis</i> L.	bad
	<i>F. glomerata</i> Roxb.	gular
	<i>F. palmata</i> Forssk.	
	<i>F. religiosa</i> L.	peepal
	<i>Morus alba</i> L.	shehtoot
Liliaceae	<i>Urginea indica</i> (Roxb.) Kunth	kolikanda
	<i>Asparagus racemosus</i> Willd.	naharkanta
Commelinaceae	<i>Commelina benghalensis</i> L.	bokna
	<i>C. forsklii</i> Vahl.	
	<i>C. obliqua</i> Vahl.	
Pandanaceae	<i>Pandanus odoratissimus</i> L. f.	kewda
Arecaceae Roxb.	<i>Pheonix sylvestris</i> (L.)	khajur
	<i>Borassus flabellifer</i> L.	taad
Typhaceae	<i>Typha domingensis</i> Pers.	
Cyperaceae	<i>Cyperus pangorei</i> Rottb.	
	<i>C. rotendus</i> L.	mothinga
	<i>Fimbristylis dichotoma</i> (L.) Vahl.	
Poaceae	<i>Apluda mutica</i> L.	gawan
	<i>Aristida adscensionis</i> L.	laapda
	<i>Arthraxon lancifolius</i> (Trinn.) Hochst.	bugdha
	<i>Cenchrus setigerus</i> Vahl	aajan
	<i>Chloris barbata</i> Sw.	
	<i>C. dolichostachya</i> Lagasca	baansi
	<i>C. virgata</i> Sw.	phool waali ghaas
	<i>Chrysopogon fulvus</i> (Spreng.) Chiov.	
	<i>Cynodon dactylon</i> (L.) Pers.	doob
	<i>Dendrocalamus strictus</i> (Roxb.) Nees	baans
	<i>Desmostachya bipinnata</i> (L.) Stapf	daab
	<i>Dichanthium annulatum</i> (Forssk.) Stapf	kaid
	<i>Digitaria ciliaris</i> (Retz.) Koeler	koori
	<i>Echinochloa colona</i> (L.) Link	
	<i>Eragrostis ciliaris</i> (L.) R. Br.	
	<i>E. tenella</i> (L.) P. Beauv. Ex Roem. & Schult.	
	<i>Eleusine indica</i> (L.) Gaertn.	moti taadi
	<i>Heteropogon contortus</i> (L.) P. Beauv. Ex Roem. & Schult.	surbala
	<i>Imperata cylindrica</i> (L.) Racuschel	
	<i>Oplismenus burmanii</i> (Retz.) P. Beauv.	
	<i>Paspalum distichum</i> L.	
	<i>Paspalidium flavidum</i> (Retz.) A. Camus	
	<i>Pennisetum orientale</i> L. C. Rich.	jungli bajra
	<i>Saccharum bengalense</i> Retz.	munja
	<i>S. spontaneum</i> L.	kaans
	<i>Setaria intermedia</i> Roem. & Schult.	
	<i>S. pumila</i> (Poir) Roem. & Schult.	chaproda
	<i>Sorghum halepense</i> (L.) Pers.	baru
	<i>Sporobolus coromandelianus</i> (Retz.) Kunth	chidibajra

	<i>Themeda quadrivalvis</i> (L.) Kuntze	
	<i>Tragus roxburghii</i> Panigrahi	susiyachoti
	<i>Vetiveria ziznioides</i> (L.) Nash	khus
	<i>Sehima nervosum</i> (Rottl.) Stapf	seran
	<i>Brachiaria ramosa</i> (L.) Stapf.	
	<i>Dactyloctenium aegyptium</i> (L.) Willd.	mukda
Sapotaceae	<i>Mimusops elengi</i> L.	molishree

Appendix 2 Results for ANOVA on treatments for each factor of target species for first year of experimental study 2009-2010 at Sariska Tiger Reserve, Rajasthan

Treatment	Defoliation		Year	0-1 yr			
	Grass (G)	Nutrient (N)		Treatment(T)	G*N	G*T	N*T
<i>Acacia leucophloea</i>	0.816	0.084		0.275			
<i>Anogeissus pendula</i>	0.041*	0.049*	0.036*	0.188	0.057*	0.016*	0.003*
<i>Butea monosperma</i>	0.203	0.76	<0.001*	0.89	0.792	0.28	0.087
<i>Lannea coromandelica</i>	0.078	0.471		0.106			

Species (Stem length)	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Acacia leucophloea</i>	0.528	0.003*		0.694			
<i>Anogeissus pendula</i>	0.058*	0.319	0.002*	0.593	0.129	0.122	0.035*

<i>Butea monosperma</i>	0.326	0.577	0.001*	0.879	0.935	0.385	0.07
<i>Lannea coromandelica</i>	0.093	0.409		0.089			

Species (Stem basal area(Ln))	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Acacia leucophloea</i>	0.328	0.216		0.131			
<i>Anogeissus pendula</i>	0.087	0.274	<0.001*	0.586	0.046*	0.069	0.051*
<i>Butea monosperma</i>	0.552	0.39	0.001*	0.757	0.966	0.781	0.174
<i>Lannea coromandelica</i>	0.361	0.827		0.97			

Species (Total leaves (Ln))	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Acacia leucophloea</i>	0.883	0.041*		0.977			
<i>Anogeissus pendula</i>	0.493	0.059	0.076	0.678	0.506	0.362	0.197
<i>Butea monosperma</i>	0.211	0.945	0.099	0.539	0.854	0.889	0.371
<i>Lannea coromandelica</i>	0.358	0.851		0.993			

Species (Total mass (Ln))	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Acacia leucophloea</i>	0.964	0.008*	0.944	0.687			
<i>Anogeissus pendula</i>	0.111	0.121	0.112	0.183	0.543	0.941	0.508
<i>Butea monosperma</i>	0.753	0.35	0.007*	0.905	0.925	0.889	0.208
<i>Lannea coromandelica</i>	0.061	0.084		0.176			

Species (Leaf mass fraction(Ln))	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Acacia leucophloea</i>	0.39	0.558	0.631	0.572		0.811	
<i>Anogeissus pendula</i>	0.874	0.699	0.095	0.676	0.81	0.314	0.849
<i>Butea monosperma</i>	0.066	0.126	0.102	0.231	0.566	0.825	0.694
<i>Lannea coromandelica</i>	0.092	0.258		0.569			

Treatment	Shade		Year 0-1 yr				
Species (Stem height)	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Anogeissus pendula</i>	0.61	0.153	0.019*	0.177	0.856	0.046*	0.545

<i>Butea monosperma</i>	0.048*	0.402	0.599	0.461	0.13	0.047*	0.277
<i>Lannea coromandelica</i>	0.914	0.913		0.271			

Species (Stem length)	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Anogeissus pendula</i>	0.531	0.309	0.138	0.131	0.858	0.088	0.846
<i>Butea monosperma</i>	0.064	0.998	0.005*	0.217	0.724	0.718	0.775
<i>Lannea coromandelica</i>	0.498	0.519		0.878			

Species (Stem basal area (Ln))	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Anogeissus pendula</i>	0.169	0.022*	0.824	0.946	0.984	0.842	0.31
<i>Butea monosperma</i>	0.842	0.82	0.009*	0.295	0.61	0.413	0.559
<i>Lannea coromandelica</i>	0.669	0.634		0.455			

Species (Total leaves (Ln))	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Anogeissus pendula</i>	0.692	0.099	0.98	0.948	0.728	0.727	0.444
<i>Butea monosperma</i>	0.507	0.295	<0.001*	0.715	0.394	0.419	0.039*

Species (Total mass (Ln))	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Anogeissus pendula</i>	0.372	0.027*	0.279	0.502	0.486	0.853	0.874
<i>Butea monosperma</i>	0.923	0.453	<0.001*	0.202	0.855	0.812	0.465
<i>Lannea coromandelica</i>	0.771	0.483		0.336			

Species (Leaf mass fraction(Ln))	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Anogeissus pendula</i>	0.311	0.544	0.072	0.333	0.869	0.189	0.87
<i>Butea monosperma</i>	0.552	0.892	0.008*	0.686	0.401	0.207	0.091

Treatment	Water		Year	0-1 yr			
Species (Stem height)	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T

<i>Acacia leucophloea</i>	0.602						
<i>Anogeissus pendula</i>	0.449	0.628	0.193	0.077	0.78	0.323	0.999
<i>Butea monosperma</i>	0.016*	0.129	<.001*	0.153	0.797	0.543	0.412
<i>Lannea coromandelica</i>	0.854	0.417		0.251			

Species (Stem length)	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Acacia leucophloea</i>	0.242						
<i>Anogeissus pendula</i>	0.579	0.95	0.021*	0.268	0.985	0.611	0.863
<i>Butea monosperma</i>	0.342	0.95	<0.001*	0.506	0.833	0.193	0.298
<i>Lannea coromandelica</i>	0.311	0.18		0.065			

Species(Stem basal area (Ln))	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Acacia leucophloea</i>	0.53						
<i>Anogeissus pendula</i>	0.614	0.572	0.01*	0.091	0.774	0.147	0.974
<i>Butea monosperma</i>	0.364	0.58	<0.001*	0.343	0.99	0.226	0.226
<i>Lannea coromandelica</i>	0.371	0.178		0.054*			

Species (Total leaves (Ln))	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Acacia leucophloea</i>	0.239						
<i>Anogeissus pendula</i>	0.313	0.271	0.027*	0.685	0.392	0.803	0.639
<i>Butea monosperma</i>	0.005*	0.922	0.631	0.648	0.783	0.871	0.238
<i>Lannea coromandelica</i>	<0.001*						

Species (Total mass (Ln))	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Acacia leucophloea</i>	0.085	0.016*		0.451			
<i>Anogeissus pendula</i>	0.654	0.125	0.07	0.241	0.52	0.917	0.357
<i>Butea monosperma</i>	0.597	0.934	0.689	0.478	0.826	0.3	0.967
<i>Lannea coromandelica</i>	0.863	0.409		0.409			

Species(Leaf mass fraction (Ln))	Grass (G)	Nutrient (N)	Treatment(T)	G*N	G*T	N*T	G*N*T
<i>Acacia leucophloea</i>	0.646	0.718	0.19			0.399	
<i>Anogeissus pendula</i>	0.7	0.682	0.769	0.445	0.708	0.447	0.913
<i>Butea monosperma</i>	0.206	0.146	0.004*	0.351	0.538	0.924	0.945

p<0.05 was used as the significance level

Appendix 3 Results for ANOVA on treatments for each factor of target species for second year of experimental study in 2010-2011 in Sariska Tiger Reserve, Rajasthan

Treatment	Defoliation							Defoliation						
	0-1 yr							1-2 yr						
Year	0-1 yr							1-2 yr						
Species (Stem height)	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.774	0.465	0.259	0.281				0.078	0.888	<0.001*	0.577	0.063		
<i>Anogeissus pendula</i>	0.005*	0.253	0.77	0.879				0.216	0.48	<0.001*	0.774	0.269	0.444	
<i>Balanites aegyptiaca</i>	0.478	0.52	<0.001*	0.403	0.25	0.983	0.819							
<i>Butea monosperma</i>	0.887	0.39	0.409	0.453	0.083	0.24	0.133	0.951	0.308	<0.001*	0.1	0.863	0.489	0.0
<i>Lansea coromandelica</i>								0.945	0.15	0.245				
<i>Zizyphus mauritiana</i>	0.246	0.94	0.588	0.99	0.812	0.207	0.316							

Species (Stem length)	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.54	0.94	0.249	0.455				0.449	0.252	<0.001*	0.207	0.665		
<i>Anogeissus pendula</i>	0.109	0.448	0.228	0.884				0.081	0.5	<0.001*	0.793	0.156	0.497	
<i>Balanites aegyptiaca</i>	0.136	0.689	<0.001*	0.826	0.033*	0.24	0.403							

<i>Butea monosperma</i>	0.824	0.827	0.001*	0.393	0.365	0.421	0.72	0.428	0.012*	<0.001*	0.057*	0.824	0.034*	0.0
<i>Lannea coromandelica</i>								0.899	0.146	0.234				
<i>Zizyphus mauritiana</i>	0.151	0.19	<0.001*	0.031*	0.476	0.85	0.599							

Species (Stem basal area(Ln))	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.923	0.808	0.498	0.187				0.038*	0.374	0.045*	0.343	0.721		
<i>Anogeissus pendula</i>	0.321	0.443	0.631	0.149				0.006*	0.731	0.702	0.699	0.993	0.562	
<i>Balanites aegyptiaca</i>	0.01*	0.086	<0.001*	0.671	0.79	0.271	0.604							
<i>Butea monosperma</i>	0.272	0.374	0.022*	0.267	0.652	0.372	0.341	0.142	0.84	0.469	0.382	0.538	0.144	0.3
<i>Lannea coromandelica</i>								0.257	0.429	0.362				
<i>Zizyphus mauritiana</i>	0.322	0.408	<0.001*	0.03*	0.342	0.474	0.871							

Species (Total leaves (Ln))	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.029*	0.875	0.152	0.018*				0.258	0.667	0.228	0.369	0.183		
<i>Anogeissus pendula</i>	0.249	0.528	0.086	0.21				0.492	0.539	0.872	0.885	0.147	0.735	
<i>Balanites aegyptiaca</i>	0.542	0.858	<0.001*	0.577	0.037*	0.596	0.721							

<i>Butea monosperma</i>	0.969	0.411	0.426	0.295	0.801	0.833		0.678	0.259	<0.001*	0.922	0.01*	0.902	0.9
<i>Lannea coromandelica</i>								0.466						
<i>Zizyphus mauritiana</i>	0.014*	0.883	0.924	0.082	0.796	0.754	0.212							

Species (Total mass (Ln))	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.283	0.894	0.968	0.253				0.404	0.077	0.004*	0.149	0.974		
<i>Anogeissus pendula</i>	0.497	0.145		0.752				0.046*	0.645	0.015*	0.806	0.642	0.781	
<i>Balanites aegyptiaca</i>	0.018*	0.615	0.001*	0.201	0.326	0.257	0.831							
<i>Butea monosperma</i>	0.646	0.128	0.48	0.507	0.523	0.785	0.255	0.566	0.727	0.414	0.824	0.35	0.41	0.8
<i>Lannea coromandelica</i>								0.732	0.692		0.291			
<i>Zizyphus mauritiana</i>	0.015*	0.877	0.443	0.081	0.508	0.297	0.646							

Species (Leaf mass fraction(Ln))	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.057*	0.373	0.746	0.984				0.085	0.936	0.001*	0.117	0.291		
<i>Anogeissus pendula</i>	0.097	0.042*		0.283				0.026*	0.587	<0.001*	0.48	0.542	0.291	
<i>Balanites aegyptiaca</i>	0.111	0.669	0.34	0.215	0.472	0.774	0.049*							

<i>Butea monosperma</i>	0.663	0.11	0.924	0.397	0.23	0.773	0.85	0.715	0.055	0.694	0.019*	0.974	0.006*	0.3
<i>Lannea coromandelica</i>								0.102	0.061		0.036*			
<i>Zizyphus mauritiana</i>	0.014*	0.937	0.225	0.269	0.522	0.843	0.672							

Treatment	Shade							Shade						
	0-1 yr							1-2 yr						
Species (Stem height)	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.958	0.416	0.348	0.473	0.878	0.929	0.975							
<i>Anogeissus pendula</i>	0.002*	0.619	<0.001*	0.939	<0.001*	0.851		0.173	0.356	0.072	0.31	0.154	0.723	
<i>Balanites aegyptiaca</i>	0.685	0.246	0.978	0.975	0.098	0.575	0.172							
<i>Butea monosperma</i>	0.638	0.318	0.344	0.626	0.269	0.08	0.697	0.316	0.5	<0.001*	0.091	0.473	0.479	0.2
<i>Lannea coromandelica</i>	0.654	0.196		0.213				0.093	0.025*	0.931	0.092			
<i>Zizyphus mauritiana</i>	0.399	0.268	0.003*	0.653	0.345	0.596	0.598							

Species (Stem length)	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.944	0.629	0.464	0.661	0.695	0.74	0.933							
<i>Anogeissus pendula</i>	0.029*	0.683	<0.001*	0.957	0.001*	0.417		0.044*	0.612	0.241	0.33	0.283	0.878	

<i>Balanites aegyptiaca</i>	0.105	0.209	0.016*	0.465	0.182	0.953	0.964							
<i>Butea monosperma</i>	0.458	0.622	0.806	0.959	0.164	0.28	0.518	0.323	0.129	0.005*	0.011*	0.64	0.137	0.6
<i>Lannea coromandelica</i>	0.82	0.269		0.201				0.98	0.027*	0.911	0.089			
<i>Zizyphus mauritiana</i>	0.523	0.475	0.022*	0.218	0.014*	0.087	0.246							

Species (Stem basal area (Ln))	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.879	0.923	0.759	0.166	0.898	0.761	0.836							
<i>Anogeissus pendula</i>	0.598	0.455	0.083	0.178	0.081	0.699		0.009*	0.965	0.691	0.173	0.228	0.407	
<i>Balanites aegyptiaca</i>	0.31	0.007*	0.44	0.44	0.116	0.355	0.733							
<i>Butea monosperma</i>	0.435	0.258	<0.001*	0.954	0.014*	0.255	0.997	0.296	0.204	<0.001*	0.154	0.498	0.329	0.0
<i>Lannea coromandelica</i>	0.788	0.929		0.474				0.086	0.043*	0.871	0.339			
<i>Zizyphus mauritiana</i>	0.47	0.395	0.316	0.332	0.036*	0.15	0.099							

Species (Total leaves (Ln))	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.045*	0.104	0.76	0.187	0.987	0.156	0.464							
<i>Anogeissus pendula</i>	0.249	0.528	0.618	0.21				0.245	0.745	0.955	0.141	0.693	0.283	

<i>Balanites aegyptiaca</i>	0.13	0.368	0.005*	0.233	0.271	0.724	0.4							
<i>Butea monosperma</i>	0.989	0.579	0.057	0.676	0.959	0.404	0.441	0.05*	0.087	<0.001*	0.134	0.704	0.865	0.1
<i>Lannea coromandelica</i>								0.723	0.262		0.368			
<i>Zizyphus mauritiana</i>	0.019*	0.647	0.176	0.082	0.55	0.776	0.113							

Species (Total mass (Ln))	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.228	0.149	0.245	0.394	0.606	0.213	0.552							
<i>Anogeissus pendula</i>	0.9	0.145	0.668	0.752				0.03*	0.911	0.116	0.054*	0.227	0.275	
<i>Balanites aegyptiaca</i>	0.093	0.055*	0.044*	0.156	0.007*	0.739	0.107							
<i>Butea monosperma</i>	0.786	0.034*	0.009*	0.672	0.695	0.427	0.789	0.356	0.972	0.001*	0.296	0.144	0.638	0.4
<i>Lannea coromandelica</i>	0.683	0.339		0.297				0.477	0.01*		0.594			
<i>Zizyphus mauritiana</i>	0.107	0.242	0.005*	0.148	0.752	0.667	0.081							

Species (Leaf mass fraction (Ln))	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.211	0.694	0.324	0.706	0.062	0.483	0.431							
<i>Anogeissus pendula</i>	0.567	0.042*	0.566	0.283				0.3	0.95	0.866	0.288	0.33	0.488	

<i>Balanites aegyptiaca</i>	0.112	0.702	0.718	0.947	0.485	0.615	0.004*							
<i>Butea monosperma</i>	0.184	0.008*	0.487	0.733	0.736	0.556	0.412	0.162	0.038*	0.003*	0.36	0.657	0.151	0.1
<i>Lannea coromandelica</i>	0.681	1		0.391				1	0.086		0.978			
<i>Zizyphus mauritiana</i>	0.106	0.739	0.677	0.901	0.447	0.513	0.509							
Treatment	Water							Water						
Year	0-1 yr							1-2 yr						
Species (Stem height)	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.21	0.667	0.007*	0.048*	0.216	0.231	0.385	0.628	0.377	0.01*		0.42		
<i>Anogeissus pendula</i>	0.061	0.425	<0.001*	0.904	0.004*	0.985	0.993	0.253	0.886	0.313	0.438	0.575	0.283	
<i>Balanites aegyptiaca</i>	0.296	0.944	<0.001*	0.714	0.446	0.504	0.639							
<i>Butea monosperma</i>	0.501	0.235	0.078	0.337	0.073	0.101	0.62	0.97	0.364	0.594	0.228	0.917	0.765	0.1
<i>Lannea coromandelica</i>	0.395	0.753		0.529				0.616	0.4	0.451	0.976			
<i>Zizyphus mauritiana</i>	0.017*	0.359	0.065	0.417	0.412	0.962	0.556							

Species (Stem length)	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
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<i>Acacia leucophloea</i>	0.116	0.807	0.003*	0.03*	0.094	0.172	0.227	0.753	0.455	0.006*		0.998		
<i>Anogeissus pendula</i>	0.267	0.928	<0.001*	0.455	0.036*	0.578	0.431	0.107	0.826	0.096	0.309	0.623	0.252	
<i>Balanites aegyptiaca</i>	0.002*	0.188	0.002*	0.045*	0.058*	0.921	0.749							
<i>Butea monosperma</i>	0.661	0.394	0.625	0.345	0.835	0.46	0.677	0.693	0.037*	0.118	0.13	0.92	0.326	0.2
<i>Lannea coromandelica</i>	0.245	0.581		0.618				0.671	0.376	0.461	0.95			
<i>Zizyphus mauritiana</i>	0.104	0.72	0.436	0.622	0.09	0.825	0.161							
Species (Stem basal area (Ln))	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.002*	0.557	<0.001*	0.031*	0.26	0.717	0.082	0.77	0.723	0.023*		0.547		
<i>Anogeissus pendula</i>	0.891	0.438	<0.001*	0.408	0.472	0.933	0.577	0.105	0.681	0.878	0.404	0.826	0.522	
<i>Balanites aegyptiaca</i>	0.002*	0.007*	<0.001*	0.284	0.023*	0.766	0.594							
<i>Butea monosperma</i>	<0.001*	0.666	0.446	0.786	0.151	0.662	0.825	0.156	0.183	0.224	0.463	0.858	0.474	0.0
<i>Lannea coromandelica</i>	0.035*	0.564		0.08				0.843	0.887	0.32	0.849			
<i>Zizyphus mauritiana</i>	0.248	0.317	0.128	0.308	0.098	0.641	0.311							

Species (Total leaves (Ln))	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
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<i>Acacia leucophloea</i>	0.98	0.579	0.001*	0.085	0.046*	0.412	0.094	0.493	0.969	0.347		0.144		
<i>Anogeissus pendula</i>	0.184	0.672	0.012*	0.782	0.909	0.337	0.176	0.63	0.958	0.166	0.295	0.448	0.777	
<i>Balanites aegyptiaca</i>	0.033*	0.129	<0.001*	<0.001*	0.004*	0.033*	<0.001*							
<i>Butea monosperma</i>	0.364	0.992	0.636	0.316	0.398	0.235	0.725	0.009*	0.768	0.006*	0.52	0.174	0.217	0.5
<i>Lannea coromandelica</i>														
<i>Zizyphus mauritiana</i>	0.002*	0.777	0.614	0.182	0.59	0.674	0.065							
Species (Total mass (Ln))	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.276	0.312	0.145	0.114	0.221	0.986	0.715	0.565	0.908	0.048*		0.405		
<i>Anogeissus pendula</i>	0.315	0.112	0.165	0.752				0.091	0.983	0.419	0.263	0.469	0.361	
<i>Balanites aegyptiaca</i>	<0.001*	0.035*	<0.001*	0.011*	0.002*	0.974	0.51							
<i>Butea monosperma</i>	0.617	0.774	0.372	0.657	0.226	0.296	0.183	0.236	0.994	<0.001*	0.541	0.66	0.595	0.
<i>Lannea coromandelica</i>								0.725	0.713	0.098	0.665			
<i>Zizyphus mauritiana</i>	0.002*	0.226	0.661	0.314	0.15	0.911	0.441							

Species (Leaf mass fraction (Ln))	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N*T	Grass (G)	Nutrient (N)	Treatment (T)	G*N	G*T	N*T	G*N
<i>Acacia leucophloea</i>	0.544	0.763	0.428	0.655	0.429	0.773	0.897	0.685	0.712	0.062		0.978		
<i>Anogeissus pendula</i>	0.101	0.169	1	0.283				0.923	0.266	0.874	0.119	0.963	0.58	

<i>Balanites aegyptiaca</i>	0.287	0.44	<0.001*	0.008*	0.083	0.359	0.654							
<i>Butea monosperma</i>	0.244	0.935	0.556	0.41	0.894	0.045*	0.508	0.477	0.027*	0.001*	0.261	0.637	0.05*	0.1
<i>Lannea coromandelica</i>								0.776	0.697	0.47	0.468			
<i>Zizyphus mauritiana</i>	0.217	0.309	0.109	0.756	0.508	0.224	0.638							

p<0.05 was used as the significance level