



**Pattern of  
Invasion by  
*Adhatoda vasica*  
in Savannas  
of Sariska Tiger  
Reserve, Rajasthan,  
Western India**

## Abstract

As part of global experiments on Savanna vegetation, we examined the ecological characteristics of an important semiarid savanna in the Indian sub-continent i.e Sariska Tiger Reserve, Rajasthan, Western India during April 2009 to May 2011. 149 plots across five line transects were sampled for phyto-sociological interpretation in the Sariska-Kalighati valley which is the largest savanna valley habitat in the study area. Plots were segregated on the presence/absence of native invasive species *Adhatoda vasica* and community analysis revealed a total of eleven communities (five from infested plots and six from non-infested plots) and communities having similar composition were compared. Tree density, seedling density, species richness of shrubs and herbs and diversity and evenness of herbs was higher in non-infested plots. Sapling density did not follow a trend. Evenness of shrubs was lower in non-infested plots. Furthermore, mapping of *Adhatoda vasica* in the study area revealed that 5.22 km<sup>2</sup> (26.1%) of the Sariska-Kalighati valley was under infestation and three sites were compared following removal of this species which resulted in increased sapling density, shrub density and grass cover and decreased seedling density and herb density.

**Keywords:** *Adhatoda vasica*; invasion; Sariska Tiger Reserve; savanna; semi-arid.

## Introduction

The tropical and sub-tropical vegetation dominated by grasses, interspersed with a discontinuous cover of trees and shrubs is generally termed as savanna (Huntley and Walker, 1982; Frost et al., 1986). Although the term savanna is believed to have originated from an Arawak word which meant 'land without trees with much grass either tall or short' (Beerling and Osborne, 2006), now largely used to denote the land with both grasses and trees. This definition of savannas holds true for a wide range of climatic conditions i.e., 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. They cover about an eighth of the global land surface, covering over half the area of Africa and Australia, 45% of South America and 10% of India and Southeast Asia. The savanna vegetation in India is largely distributed in the semi-arid tracts of western, central and peninsular India and can be seen in a few protected areas (PAs) including Sariska Tiger Reserve in the state of Rajasthan.

Sariska Tiger Reserve (STR), located in the world's oldest hill ranges, i.e. Aravallis, its repository of serene forests, wide valleys and sprawling plateaus, was recently in the limelight due to local extinction of its flagship species i.e. tiger (*Panthera tigris*). This reserve happens to be the westernmost limit of tiger distribution in India. Very few areas in the tiger range have a typical semi-arid savannah vegetation. Across their range of occurrence, savannas are extremely variable in their physical and structural attributes. They encompass a gradient from nearly pure grasslands to closed woodlands, exhibit differences in the characteristics of dominant trees (fine-leaved and broad-leaved), herbaceous vegetation (tall to short grasses, vegetated and bare patches), plant life-history characteristics (deciduous to evergreen trees, annual to perennial grasses), tree spatial patterns (random, regular, or clumped) and plant and soil nutrient status (nutrient-poor or dystrophic savannas vs. nutrient-rich or eu-trophic savannas; House et al., 2003; Sankaran and Anderson, 2009). Today, savannas constitute the world's second largest biome, covering ~ 33 million km<sup>2</sup> or nearly 20% of the earth's land surface (Scholes and Walker, 1993; Ramankutty and Foley, 1999; Beerling and Osborne, 2006). They are widespread across Africa, Asia, South America and Australia, and cover more than half the area of the southern continents. They are host to approximately one-fifth of the world's population (Young and Solbrig, 1993) who are socio-

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economically dependent on savanna by enterprising in pastoralism or agriculture and wildlife reserves or tourism (Werner, 1990). Despite such an important holding in the nature's index they have been neglected in terms of ecological studies. Initial studies as late as 1967 were undertaken by Lamotte and associates in the Ivory Coast, followed by Medina in the Venezuelan llanos. American and British scientists in Tanzania, Kenya and Uganda contributed significantly in understanding the role of wild herbivores in tropical savannas thus being fruitful only to range managers or cattle ranchers (Huntley 1982). Savannas are comprised of interspersed life forms viz. herbaceous species and woody species that are competing plant types. To explain the coexistence of trees and grasses in savanna systems, Walter (1971) focused in his hypothesis of the separation of rooting niches on the competition for soil moisture in different soil horizons. According to Walter (1971), trees have access to water in deeper soil horizons, whereas grasses are superior competitors for water in the upper horizons (Walker and Noy-Meir 1982). Detailed field studies led to the rejection of the Walter hypothesis as the singular explanation for tree-grass coexistence (e.g., studies in West Africa: Le Roux et al., 1995; Seghier, 1995; Mordelet et al., 1997; Le Roux and Bariac 1998). This approach is also known as the "bottom up" model where a characteristic tree-grass ratio is expected for a given set of rainfall and soil conditions, with tree cover increasing as one moves from arid to mesic sites. Another polarized view is the "top down" model where primacy is given to the roles of disturbances such as herbivory and fire in regulating savanna structure. Both fire and grazing act to regulate tree cover in savannas by imposing demographic bottlenecks, or in some cases eliminating bottlenecks, to tree recruitment and establishment (Higgins et al., 2000; Sankaran et al., 2004; Bond, 2008).

In the 'bottom-up' perspective, savannas are viewed as 'stable' systems to the extent that disturbances such as fire and grazing, although capable of shifting the balance between trees and grasses, are not prerequisites for the persistence of both life-forms in the system. In the top-down view, savannas are essentially considered to be 'unstable' systems. Pure forests and grasslands are presumed to be the only stable states, and disturbances such as fire and grazing permit savannas to exist by 'buffering' the system against transitions to either extreme (Jeltsch et al., 1996, 1998, 2000; Higgins et al., 2000). Savannas exist because of factors that favor tree establishment at the arid end of the rainfall gradient, and factors that prevent canopy closure at the mesic end. Beside soil moisture, several other environmental parameters have been discussed to be important for the maintenance of savannas such as nutrient availability, fire, grazing and browsing, geology and geomorphology, soil, cultivation history, and termites (Frost et al., 1986; Furley et al., 1992; Furley, 1999; Scholes and Archer, 1997; van Langevelde et al. 2003) and however complexly these factors interact the degree may vary between different savanna types. Jeltsch et al. (2000) proposed in a unifying concept of tree-grass coexistence to focus on ecological buffering mechanisms which prevent the savanna system from crossing the boundaries to other vegetation systems, i.e. pure grassland and closed forest.

Historical evidence from India indicate that with the beginning of Pliocene period, deciduous trees replaced the evergreen vegetation over much of the country, while parts of Thar Desert came to be covered by desert scrub (Gadgil and 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). According to Gadgil and Meher-Homji (1985 in Saha, 2002) the practice of setting intentional fires has been in place for the past 50,000 years and is responsible for major modifications of the vegetation character (Pyne, 1994). According to Misra (1983), the tropical sub-humid and dry deciduous forests of India, which once covered large parts of the country, have been almost completely replaced by savannahs, a transformation most likely caused by fire. This paper deals with recent changes in structure and composition of savannah vegetation due to rapid spread by an unpalatable native shrub, *Adhatoda vasica* (Syn. *Justicia zeylanica*) in STR. Pattern of invasion by this species and management implications are discussed.

## Study Area

The study was conducted in STR, Rajasthan, India (**Figure 14.1**) which is situated between Longitudes 79°17'N to 76°34' N and Latitudes 27° 5' E to 27° 33' E. The area was a hunting reserve of the erstwhile princely state of Alwar before being declared as a Sanctuary in 1958 and later as a Tiger reserve in 1978. The altitude varies from 540 m to 777 m and 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). 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). 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 and Gupta, 2006).

Although, latitudinally the study area falls under sub-tropical zone, climatically it falls under hot arid steppe category (Kottek et al 2006). 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. The temperature varied from 52° C to 1° C during the study period. The relative

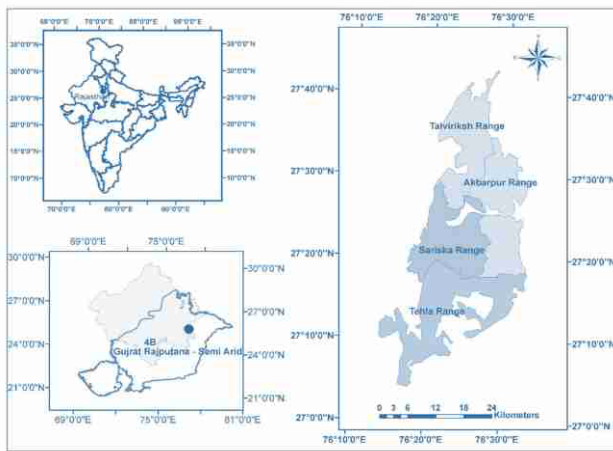


Figure 14.1 The Study Area

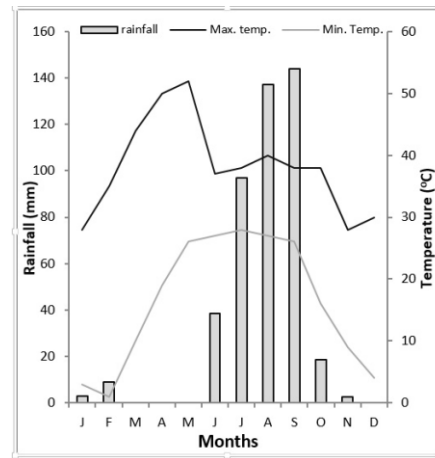


Figure 14.2 Ombrothermic diagram for the study area Sariska Tiger Reserve, Rajasthan during June 2009- May 2010

humidity is high during monsoon and ranged from 52% to 2% (Figure 14.2). The annual rainfall recorded for the study period (June 2009-July 2010) was 735.1 mm. The park supports carnivore species such as reintroduced tigers (*Panthera tigris*), leopard (*Panthera pardus*) and striped hyena (*Hyaena hyaena*) alongwith wild herbivores such as chital (*Axis axis*), sambar (*Rusa unicolor*) and nilgai (*Boselaphus tragocamelus*). Omnivores found are wild pig (*Sus scrofa*) and golden jackal (*Canis aureus*). Rhesus macaque (*Macaca mulatta*) and common langur (*Semnopithecus entellus*) are the two primates found here. 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. There are 32 villages within the Tiger Reserve and of them ten are situated in the notified National Park. 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. 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 livestock grazing, local people commonly collect grasses and lop trees for their livestock and fuelwood requirements (Kumar and Shahabuddin, 2005).

According to Champion and Seth (1968), the forests of STR fall within Northern Tropical Dry deciduous (Group V) and Northern Tropical Thorn Forests (Group VI). Although, Vyas (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 this park exclusively. In 2008, Sankar et al. studied vegetation composition and structure and mapped vegetation types of the entire STR. The Sariska-Kalighati 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 of Sariska.

Subsequently, Sankar (1984) also 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. 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. This study was conducted during 2009-2011.

## Methodology

Five line transects of 1.5 km each was laid in the Sariska-Kalighati valley which is the largest valley habitat in STR and a 10 m radial plot was laid at every 50 m for trees, 5 m concentric plot for shrubs and 6, 1m X 1m for herbs and grass cover for enumeration of tree, shrub and ground layers. Density, frequency and basal area of each species in each plot were calculated to seek importance value index (IVI). Importance Value Index (IVI) is the sum of relative density, relative dominance and relative frequency for a species (Curtis and McIntosh, 1950). The data collected was subjected to multivariate analysis; using TWINSpan (Hill, 1979). Species richness (a-diversity) of the vegetation cluster was

calculated as the average number of species per stand and Shannon–Wiener index for the relative evenness and Diversity (Pielou, 1975; Magurran, 1988). Population structure of 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.

For mapping the invasion of *Adhatoda vasica*, 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. 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 and vegetation parameters were recorded following aforementioned methods. These were compared to locations where no removal had been done.

## Results

Of the 149 plots sampled, *Adhatoda* was present in 73 plots. TWINSpan dendrogram divided the data set into 11 communities, five were identified for *Adhatoda* present area (Table 14.1) and six from *Adhatoda* absent area (Table 14.2). We compared the differences in sapling and seedling densities, diversity indices for effect of *Adhatoda* infestation in similar communities and four communities were 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 (Figure 14.3). By contrast in *Prosopis juliflora* scrubland, *Adhatoda* infestation facilitates the sapling and seedling establishment and no seedling and sapling occurrence was observed in non-infested area. In *Acacia-Grewia* scrubland, seedling numbers were greater in non-infested area whereas saplings were more in *Adhatoda* infested area. In case of scrubland, *Adhatoda* infestation did not seem to have a significant effect on grass cover (Figure 14.4), however, grass cover for *Acacia-Zizyphus* woodland was decreased by the infestation of *Adhatoda*. Species count for shrubs was found to be higher in *Adhatoda* absent areas for all the communities however (Figure 14.5). 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 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 (Figure 14.6).

Population structure for 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, *Anogeissus pendula* had higher number of seedlings but they were unable to survive due to anthropogenic pressures such as lopping and grazing. 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 *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. Presence of *Adhatoda* limited the sapling and seedling density in most communities but it increased the species count and diversity for shrubs and herbs and species evenness in herbs. In case of scrubland, *Adhatoda* infestation did not seem to have a significant effect on grass cover however grass cover for *Acacia-Zizyphus* woodland was significantly decreased by the infestation of *Adhatoda*.

The following map (Figure 14.7) shows the extent of invasion of *Adhatoda vasica* along the 20 km<sup>2</sup> valley of Sariska-Kalighati. The area under invasion was calculated to be 5.22 km<sup>2</sup> which is 26.1 % of the area that was studied. Plate 14.1 depicts the invasion in a *Butea monosperma-Acacia catechu* woodland within the study area. Within one 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. *Adhatoda vasica* was found to have maximum density (29058.82 ind/ha.) followed by *Grewia flavescens* (3529.41 ind/ha.) in shrubs and *Elytraria acaulis* (21666.37 ind/ha.) in herbs. Species richness for herbs was found to be 8. Grass cover was found to be 16% within a year of removal.



**Table 14.1.** Communities with *Adhatoda* infestation

Communities	Tree sapling			Density seedling			Basal area			Diversity			Species richness			Evenness		
	Tree	sapling	Herb	seedling	Shrub	Herb	Tree	Shrub	Herb	Tree	Shrub	Herb	Tree	Shrub	Herb	Tree	Shrub	Herb
<i>Adhatoda-Balanites aegyptiaca</i>	66.6	469.0	10*104	256.8	2406.4	10*104	1.127	0	1.58	2.04	17	1	12	17	0	0.63	0.72	0.72
<i>Adhatoda- Acacia leucophloea</i>	47.7	441.9	8.4*104	346.3	1973.8	8.4*104	1.273	1.30	1.32	1.72	16	5	13	16	0.81	0.51	0.62	0.62
<i>Adhatoda-Acacia leucophloea-Butea monosperma</i>	52.6	272.8	5.8*104	325.3	7109.9	5.8*104	4	1.59	0.68	2.22	20	6	10	20	2.85	0.29	0.74	0.74
<i>Adhatoda-Acacia catechu-Zizyphus mauritiana</i>	86.1	43.09	6.5*104	277.2	865	6.5*104	1.574	1.31	0.59	1.98	18	6	9	18	0.73	0.26	0.68	0.68
<i>Adhatoda-Prosopis juliflora</i>	23.8	652.9	9.8*104	684.7	705.8	9.8*104	0.699	0.64	1.16	1.77	12	2	8	12	0.92	0.56	0.71	0.71

**Table 14.2.** Communities without *Adhatoda* infestation

Communities	Tree sapling			Density seedling			Basal area			Diversity			Species richness			Evenness		
	Tree	sapling	Herb	seedling	Shrub	Herb	Tree	Shrub	Herb	Tree	Shrub	Herb	Tree	Shrub	Herb	Tree	Shrub	Herb
<i>Zizyphus mauritiana-Butea monosperma</i>	65.02	113.4	7.7*104	85.4	414.1	7.7*104	3.05	0.80	0.97	1.63	18	4	5	18	1.11	0.60	0.56	0.56
<i>Acacia catechu-Zizyphus mauritiana</i>	62.1	285.0	7.6*104	406.1	735.2	7.6*104	2.018	0.90	1.29	1.71	14	4	7	14	0.65	0.66	0.65	0.65
<i>Prosopis juliflora-Lantana camara scrubland</i>	115.4	955.4	9.9*104	298.6	1073.5	9.9*104	5.462	1.06	1.49	0.83	11	5	8	11	1.7	0.72	0.34	0.34
<i>Acacia-Grewia flavescens</i>	59.7	441.9	8*104	346.3	1779.4	8*104	1.798	1.18	1.94	2.43	17	4	12	17	0.85	0.78	0.85	0.85
<i>Acacia leucophloea-Zizyphus nummularia-Prosopis juliflora- scrubland</i>	24.8	127.4	8*104	60.16	2300.7	8*104	0.928	1.28	0.58	2.21	16	4	8	16	1.77	0.28	0.79	0.79
<i>Prosopis juliflora</i>	47.7	5.31	3.6*104	5.31	215.6	3.6*104	2.535	0.34	0.75	0.92	8	2	3	8	0.5	0.69	0.44	0.44

Pattern of Invasion by *Adhatoda vasica* in Savannas of Sariska Tiger Reserve, Rajasthan, Western India

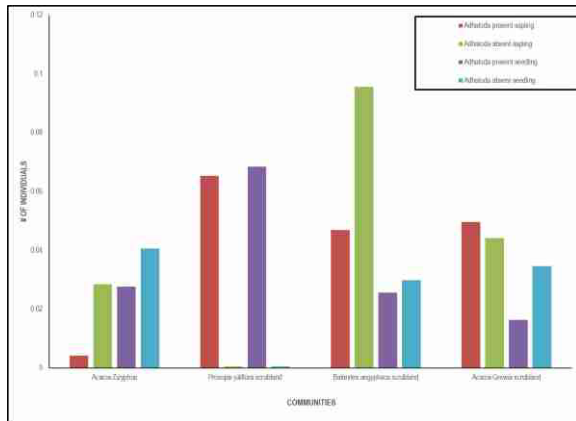


Figure 14.3 Seedling and sapling population for various communities under presence and absence of *Adhatoda*

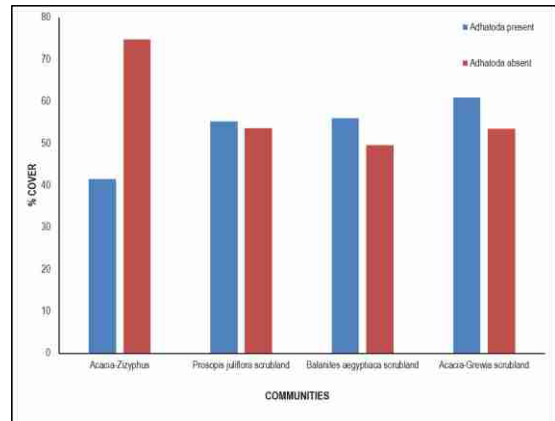


Figure 14.4 Grass cover in *Adhatoda* infested and non-infested communities

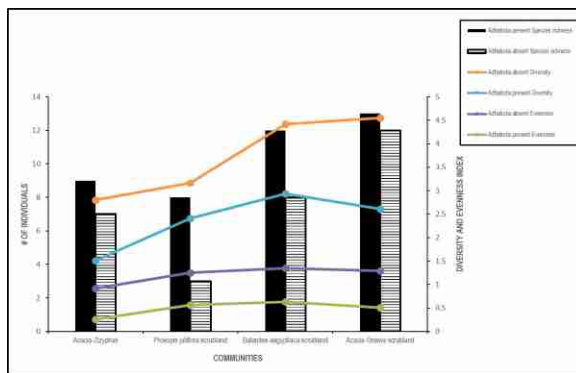


Figure 14.5 Variation in Richness, Evenness and Diversity for herbs in different plant communities

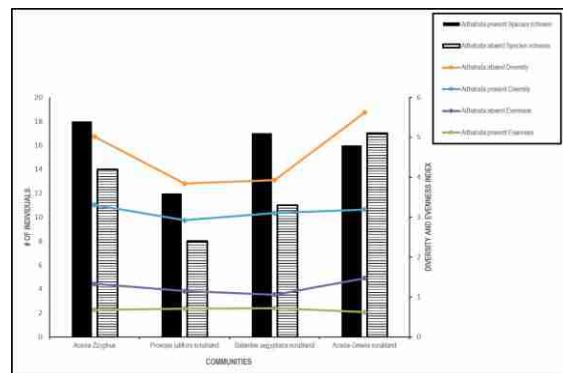


Figure 14.6 Variation in Richness, Evenness and indices diversity for shrubs in different

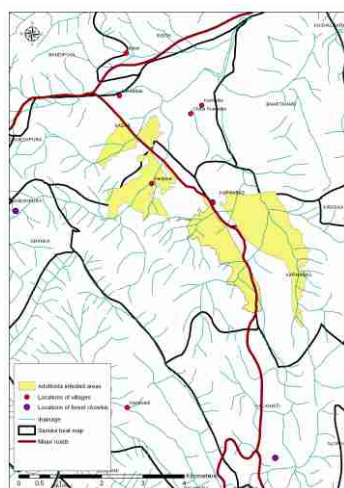


Figure 14.7 Extent of *A. vasica* invasion along the Sariska valley



Plate 14.1 *A. vasica* invasion in a *B. monosperma*-*A. catechu* woodland

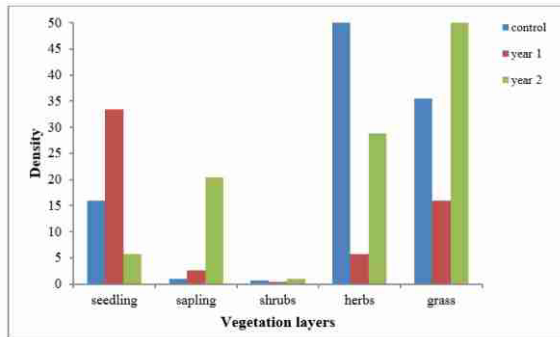


Figure 14.8 Observed densities for different vegetative layers

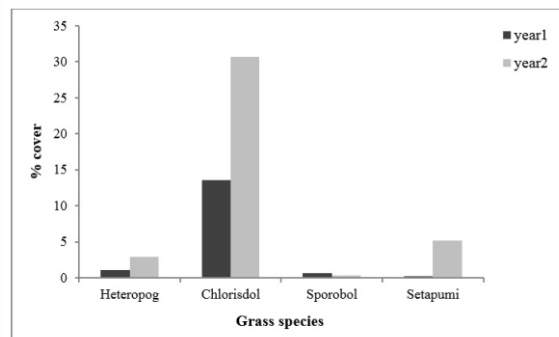


Figure 14.9 Changes in grass cover after removal of *Adhatoda vasica*

Within two 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 (41.4 ind/ha and 178.34 ind/ha). In shrubs, *Adhatoda vasica* had maximum density (14941.18 ind/ha) and *Capparis decidua* had the minimum density (352.94 ind/ha). For herbs, *Dicliptera verticillata* (116666.8 ind/ha) had highest density. Species richness for herbs was found to be 12. Grass cover was found to be 52.58% at this site (Figure 14.8 & 14.9).

## Discussion

The savanna mosaic of Sariska was formed by interspersed layers of tree savanna and shrub savanna or scrubland savanna. Tree savanna was dominated by *Acacia leucophloea*, *Butea monosperma*, *Acacia catechu* and *Zizyphus mauritiana* interspersed throughout the landscape. The common grasses were *Chloris dolichostachya*, *Heteropogon contortus* and *Desmostachya bipinnata* which were approximately 1-1.5 m high. These grasses also suppressed young seedlings by blocking 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.

Scrub savanna was characterized by presence of *Balanites aegyptiaca* and *Zizyphus nummularia* alongwith dominant grass species that were short in height including *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 from frost. 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. Fodder for wild ungulates was majorly provided by shrubs such as *Grewia flavescens* and *Capparis sepiaria* and *Acacia* spp. *Capparis sepiaria* fulfilled fodder requirements during dry season when all other species had lost their green matter (Rodgers, 1990a). It was found that *Adhatoda vasica* was more prevalent in relatively moist areas. This implies that available soil moisture was used by perennial shrubs such as *A. vasica* 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 dry cold and hot seasons, a partial or absolute status quo is maintained in the soil moisture mainly in the open. Transpiration is eliminated by shedding of leaves. Leaflessness is a characteristic physiognomic feature of the Indian arid zone vegetation (Sen, 1973). There was a distinct seasonal behavior 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 grouped near artificial and supplemented water resources.

The study reveals that manual removal of *Adhatoda* resulted in increased sapling density, shrub density and grass cover and decreased seedling density and herb density (Figure 14.8 & 14.9). 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. 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*.

## Management recommendations

- a. Management of grazing pressure: It would be desirable to keep grazing pressure by domestic livestock at low 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. "Total grazing pressure" should be considered as the effect not only of wild ungulates, but domestic stock as well.
- b. Monitoring: Regular monitoring for invasion, early response and regular follow up would help in planning management action.
- c. Managing VDC: The weeds can be removed by the village development committees (VDC) and put to ethno-medicinal use. Since *Adhatoda vasica* is known to possess wide spectrum of medicinal properties including positive effects on inflammatory diseases (Chakraborty and Brantner, 2001) therefore, it can be used as an alternate source of income generation by VDC's.
- d. 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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## References

- Chakraborty, A. and Brantner, A. H. (2001). Study of Alkaloids from *Adhatoda vasica* Nees on their anti-inflammatory activity. *Physiotherapy Research*, 15: 532-534.
- Champion, H. G. and Seth, S. K. (1968). Revised Survey of the Forest Types of India, pp 404. Manager of Publications, New Delhi.
- Curtis, J. T. and McIntosh, R. P. (1950). An upland forest continuum in the Prairie-Forest border region of Wisconsin. *Ecology*, 32: 476-496
- Dixit, A. M. (1997). Ecological evaluation of dry tropical forest vegetation: an approach to environmental impact assessment. *Tropical Ecology*, 38: 87-99
- Frost, P., Medina, E., Menaut, J. C., Solbrig, O., Swift, M. and Walker, B. (1986). Responses of Savannas to Stress and Disturbance. *IUBS Special Issue no. 10*: 1-82.
- Furley, P. A. (1999). The nature and diversity of neotropical savanna vegetation with particular reference to the Brazilian cerrados. *Global Ecology and Biogeography*, 8: 223-241.
- Furley, P. A., Proctor, J. and Ratter, J. A. (eds.) (1992). *Nature and dynamics of forest-savanna boundaries*. Chapman and Hall, London
- Gadgil, M. and Meher-Homji, V. M. (1985). Land use and productive potential of Indian savannas. In : *Ecology and Management of world's savannas* by J. C. Tothill and J. J. Matt (Eds.). CSIRO, Division of Tropical crops and pastures: Queensland, Australia. The Australian Academy of Sciences, Canberra.
- Hill, M. O. (1979). TWINSpan - A FORTRAN Program for Arranging Multivariate Data in an Ordered Two-Way Table by Classification of the Individuals and Attributes. Cornell University, Ithaca, NY.
- Huntley, B. J. and Walker, B. H. (1982). *Ecology of Tropical Savannas*. Springer, New York.
- Jeltsch, F., Weber, G.E. and Grimm, V. (2000). Ecological buffering mechanisms in savannas: a unifying theory of long term tree-grass coexistence. *Plant Ecology*, 161: 161-171.
- Khan, J. A. (1996). Analysis of woody vegetation of Gir Lion sanctuary and national Park, Gujarat, India. *Tropical Ecology*, 37: 247-256.
- Le Roux, X. and Bariac, T. (1998). Seasonal variation in soil, grass and shrub water status in a west African humid savanna. *Oecologia*, 113: 456-466.
- Le Roux, X., Bariac, T. and Mariotti, A. (1995). Spatial partitioning of soil water resources between coexisting species. *American Naturalist*, 101: 377-385.
- Magurran, A. E. (1988). *Ecological Diversity and its Measurement*. London. Croom Helm.
- Medina, E. 1983. Adaptations of tropical trees to moisture stress. In *Tropical Trees as living systems*. P. B. Tomlinson and M. H. Zimmermann (eds.) pp. 225-37. Cambridge University Press, Cambridge.
- Mordelet, P., Menaut, J. C. and Mariotti, A. (1997). Tree and grass rooting patterns in an African humid Savanna. *Journal of Vegetation Science*, 8: 65-70.
- Parmar, P. J. (1985). A contribution of the flora of Sariska Tiger Reserve, Alwar District, Rajasthan. *Botanical Survey of India*, 27(1-4): 29-40.

- Parthasarthy, N. and Sethi, P. (1997). Trees and lianas species diversity and population structure in a tropical dry evergreen forest in south India. *Tropical Ecology*, 38: 19-30.
- Pascoe, E. H. (1950). A manual of the geology of India and Burma. 3 vols. Govt. of India press. Nasik.
- Pauline, R., Sundarapandian, S., Chandrasekaran, S., Swamy, P. S. and Rajan, P. (1996). Vegetation structure and regeneration potential of a deciduous forest at Alagar Hills Madurai. *Environment and Ecology*, 14: 182-188.
- Pielou, E. C. (1975). *Ecological Diversity*. New York. Wiley.
- Pyne, S.J. (1994). Nataraja: India's cycle of fire. *Environmental History Review*, 18: 1-20.
- Rodgers, W. A. (1990a). *Capparis sepiaria* L.: An important dry season fodder plant for wildlife. *Range Management and Agroforestry*, 11(2): 199-206.
- Saha, S. (2002). Anthropogenic fire regime in a deciduous forest of central India. *Current Science*, 82: 101 – 104.
- Sankar, K. (1994). Ecology of three large sympatric herbivores (chital, sambar, nilgai) with special Reference to the reserve management in Sariska Tiger Reserve, Rajasthan. Ph.D., Thesis. University of Rajasthan, Jaipur, India.
- Sankar, K., Qureshi, Q., Mondal, K., Worah, D., Srivastava, T., Gupta, S. and Basu, S. (2008). Ecological studies in Sariska Tiger Reserve, Rajasthan. Final Report. pp 11. Wildlife Institute of India, Dehra Dun.
- Scholes, R. J. and Archer, S. R., (1997). Tree-grass interactions in savannas. *Annual Review of Ecology, Evolution and Systematics*, 28: 517–544.
- Scholes, R. J. and Hall, D. O. (1996). The carbon budget of tropical savannas, woodlands, and grasslands. In *Modelling Terrestrial Ecosystems*, ed A Breymeyer, D Hall, J Melillo, G Agren, pp. 69-100. Wiley, Chichester.
- Seghier, J., Floret, C. and Pontanier, R. (1995). Plant Phenology in relation to water availability: Herbaceous and Woody species in the savannas of northern Cameroon. *Journal of Tropical Ecology*, 11(2): 237-254.
- Sen, D. N. (1973). Ecology of Indian Desert III. Survival adaptations of vegetation in dry environment. *Vegetation*, 27 (4/6): 201-265.
- Sharma, V. D. (1983). Management plan of Sariska Tiger Reserve for 1983-1988. Wildlife Wing. Forest Department, Govt. of Rajasthan, Jaipur.
- Singh, K. P. and Misra, R. (1978). Structure and functioning of natural, modified and silvicultural ecosystems in eastern Uttar Pradesh. Final Technical Report (1975-1978). MAB Research Project 1. Banaras Hindu University.
- Van Langevelde, F., van de Vijver, C., Kumar, L., van de Koppel, J., de Ridder, N., van Andel, J., Skidmore, A.K., Hearne, J.W., Stroosnijder, L., Bond, W.J., Prins, H.H.T. and Rietkerk, M. (2003). Effects of fire and herbivory on the stability of savanna ecosystems. *Ecology*, 84: 337–350.
- Vasanthy, G., Caratini, C. and Delibrias, G. (1980). Palynological studies on clayey peats of Palni and Nilgiri hills. Paleocological significance. Vth International Palynological Conference Cambridge.
- Vyas, L. N. (1967). Contribution of flora of North-east Rajasthan. Alwar district. *Journal of Bombay Natural History Society*, 63: 191-231.
- Walker, B. H. and Noy-Meir, I. (1982). Aspects of stability and resilience in savanna ecosystems. *Ecology of tropical savannas* (ed. by B.J. Huntley and B.H. Walker), pp. 556-590. Springer-Verlag, Berlin.
- Walter, H. (1971). *Ecology of Tropical and Subtropical Vegetation* (Ed. By J H. Burnett, Translated by D. Mueller-Dombois). Oliver and Boyd, Edinburgh.
- Werner, P. A. (1991). *Savanna Ecology and Management: Australian Perspectives and Intercontinental Comparisons*. London: Blackwell Sci.
- Werner, P. A. (1990). Savanna Management for Pastoral Industries [Introduction]. *Savanna Ecology and Management: Australian Perspectives and Intercontinental Comparisons*, *Journal of Biogeography*, 17 (4/5): 501-502.
- Whyte, R. O. (1980). The graminologist must know his forests. *Indian Journal of Forestry*, 3: 1-5.
- Yadav, A. S. and Gupta, S. K. (2006). Effect of micro-environment and human disturbance on the diversity of woody species in the Sariska Tiger Project in India. *Forest Ecology and Management*, 225: 178-189.
- Young, M. D. and Solbrig, O. T. (1993). Providing an environmentally sustainable, economically profitable, and socially equitable future for the world's savannas. *The world's savannas: policy options for sustainable land use* (ed. by M.D. Young and O.T. Solbrig), MAB Vol. 12. UNESCO, pp. 321-344. Paris and The Panthenon Publishing Group, New York.