FACTORS THAT SHAPE VEGETATION IN THE ARID ZONE OF INDIA

Dissertation submitted to Saurashtra University, Rajkot
in partial fulfilment of
Master’s Degree in Wildlife Science

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भारतीय वन्यजीव संस्थान
Wildlife Institute of India

Contents

List of boxes, tables and figures:

List of annexures and supplementary information:

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CERTIFICATE

This is to certify that **Ms. S. Aaranya Gayathri** has carried out an original piece of research in partial fulfilment of Master's Degree in Wildlife Science from the Saurashtra University, Rajkot, Gujarat. The topic of her dissertation is **"Factors that shape vegetation in the arid zone of India".** The study was carried out under our supervision from December 2018 to June 2019. We hereby certify that this work has not been submitted for any degree to any university

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-S. Aaranya Gayathri
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Executive Summary:

In the current era of Anthropocene, it has become increasingly important to make predictions in plant-animal distributions as a function of the predicted changing conditions. Thus, the need to determine what shapes different vegetation structures are recognised, but, the results are often scale specific and rarely single factor determined. We investigate what causes a vegetation structure shift from a grassland to savanna and their possible intermediate transitions in the Thar Desert, North-Western Rajasthan, India. We sampled for vegetation in 67 one km^2 grids spread across a 10,235 km^2 study area capturing heterogeneity in precipitation. We analysed soil samples collected from sampled grids for soil texture, water holding capacity, total organic carbon, rodded and loose bulk densities. We collared three types of livestock (n=28) to determine potential grazing pressure in the sampled grids as one of the determinants. We used generalized linear models and non-metric multidimensional scaling to determine the determinants of vegetation structure and community. Our results show a clear scale dependence on how the determinants act– precipitation defines the larger community attributes such as species richness (R^2=0.39, p= $1.029e^{-06}$); soil compaction under the precipitation umbrella defines the vegetation structure (and hence shift from grassland to savanna etc.) and grazing pressure (especially from the smaller livestock) defines the proportion of the life forms within each vegetation structure.

The role of environmental determinants in determine vegetation shifts assures that the transitions are going to be gradual. This precludes the frequent finding of grasslands shifting to a shrubland or forest due to livestock grazing. This could be attributed to our finding of livestock having no forage preference to any particular species (χ^2=25.76,df=18,p=0.1003) or life forms (χ^2= 5.1939, df = 2, p = 0.0745) or possibly due to the low variation in livestock grazing in this landscape. We also found that change in the environmental determinants, however, can lead to two or three possible structure types. A predictive modelling shows the presence of mixed grassland, soft grassland, tree savanna, and tree-shrub savanna in the study area. However, the map also indicates that 62.7% of it is already lost to agriculture/settlement. Enclosures of Desert National Park protects only one vegetation structure type and covers less than 1%. We emphasize the urgent need to delineate conservation areas based on requirements of faunal species of interest and its habitat requirements before a complete wipe-out of vegetation structure types occur.

1. INTRODUCTION

Grasslands, savannas and forests (refer to Box 1.1 for definitions) occur as alternative stable states (Da Silveira Lobo Sternberg, 2001; Warman and Moles, 2009), but the transitions are disturbance driven and are fine-lined (Hirota et al., 2011; but see Zak and Nippert, 2012). However, these vegetation structures have distinct significance and their distributions are not easily reversible (Staver et al., 2011). Percent cover is considered one of the important vegetation structure defining characteristic (Fig.1). The trimodal distribution of %tree cover distinguishes grasslands, savannas and forests and defines where the transition between two structure types would occur.

The %tree cover is considered, however, to be predominantly determined by precipitation (Lehmann et al., 2014). Lehmann et al. synthesized that the tree cover increases linearly with precipitation until a saturation point which differs between the sampled continents, namely, Africa, Australia and South America. Nevertheless, there are other factors, sometimes their interactive effects that have been attributed to determining the vegetation structure. For instance, in just the South-African grasslands, the transition between grassland and savanna is debated to be limited by fire (Smit et al., 2010), soil properties or nutrient availability (Pellegrini, 2016) or mega-herbivory (Skarpe, 1992) or excessive grazing (Staver et al., 2009), or may be CO_2 (Bond and Midgley, 2000). Failing to come to a consensus on what prevents a vegetation structure shift from the grassland to savanna is termed the grassland-savanna problem (Mills et al., 2006). A similar resistance prevails while solving the savanna-forest problem (Bond, 2008; Veldman, 2016). In both these cases, it is not unapparent that the responses might just be scale dependent and/or an adaptive feedback that is locally determined as suggested by Mills et al. (2006).

In this anthropocene era, where land-use changes and predicted climatic changes are multiple, there is a pressing need to address the grassland-savanna-forest problem. This holds true for India which a home to five different types of grasslands (Chandran et al., 2016), savanna, forest and their transitional stages. Even though, the grasslands support some of the last remaining populations of many threatened fauna (Rawat and Adhikari, 2016), the

Box 1.1: Recent stance on what differentiates a grassland, savanna and forest

Tropical grasslands: ‘grassland is defined as a non-wetland type with at least 10% vegetation cover, dominated or co-dominated by graminoid and forb growth forms, and where the trees form a single-layer canopy with less than 40% cover and 8 m height’ (Dixon et al., 2014).

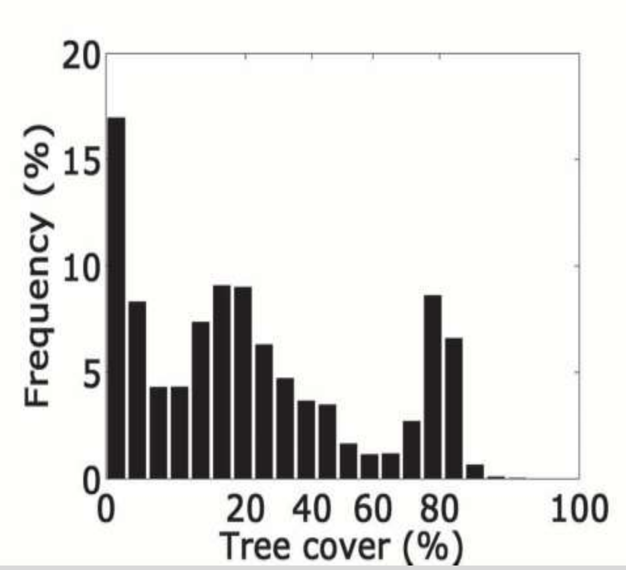
Tropical savannas: ‘savannah has tree canopy cover between 20 and 80% and above-ground grass biomass exceeds 0.5 tonnes ha−1’ (Moncrieff et al., 2016)

Tropical forests: ‘Forests are distinguished from savanna by having a tree cover of more than 80% with or without a continuous layer of grass’

Other similar terms:

Tropical grassy biomes: ‘ open grassland to densely canopied savanna with up to 80% tree cover. TGBs are distinguished from other tropical biomes principally through the presence of continuous C4 grass cover, widespread shade-intolerant plant species and the prevalence of fire (and frequently too, megaherbivory)’ (Parr et al., 2014).

Fig. 1.1: Defining vegetation structure type based on tree cover percent



Trimodal distribution in tree cover with three peaks indicating grasslands (0-5%), savanna (10-50%) and forests (>60%) in three continents Africa, Australia and South America. The intermediate bands (5-10% and 50-60%) are the tipping points where transitions between two vegetation structure types would occur (Hirota et al., 2011). Note the definitions are region specific as it differs from the global definitions in Box 1.1

grasslands along with savanna are one of the most neglected ecosystems in the country (Singh et al., 2006). Owing to their less tree cover, they are often excluded from the ‘forest’ management policies in the country. A 50% wipe out of grasslands (including shrublands and pasturelands) is predicted to have occurred in India in the last 130 years (Tian et al., 2014). On the other hand, while a vegetation structure shift from grassland to savanna to forest could occur, Misra (1983) reported a reverse vegetation structure shift with the dry deciduous forests shifting to savanna due to excessive human-induced fires. A thorough description and map of the distinct vegetation structures are available for India (Gaussen et al., 1972, Roy et al., 2015). However, a few studies recognised the need to determine the factors that shape the diverse and distinct vegetation structures of India, though few in the light of preventing vegetation structures shifts.

Dabadghao and Shankarnarayan (1973) detailed in great depth the environmental conditions in which the graminoid communities in India exist, though not pertaining to any specific vegetation structure. Meher-Homji (1975) recognized the close relationship between the number of species and the aridity index while delineating the arid zones of India. This was further bolstered by the findings of Reddy et al., (2011) which indicate an apparent increase in tree species as precipitation increases in Rajasthan. With regard to vegetation structure shift, from wetland, tree-savanna, shrub-savanna to scrub-woodland, Perennou and Ramesh (1987) reported that salinity and moisture were major drivers causing ecosystem transitions in Keoladeo National Park, Rajasthan.

In Thar desert grasslands, many studies have highlighted that the climax graminoid, *Lasiurus sindicus* are declining (Krishna et al., 2014; Mertia et al., 2006; Roy and Roy, 1996) and is gradually being supplanted by the shrub *Aerva pseudotomentosa* (Wada et al., 1995) due to excessive livestock grazing.

In this study, we address a part of the grassland-savanna problem. We investigate the relative importance of factors that shape the grassland, savanna and their transitional stages in the Thar desert of India with the following questions:

i) What determines vegetation composition in the arid grassland-savanna regions of India?

a) How do species richness and species composition change with climatic and edaphic factors, and livestock grazing?

ii) What determines vegetation structure in the arid grassland-savanna regions of India?

a) How do proportion of different life forms i.e. grass, shrub, tree, etc. change with climatic and edaphic factors, and livestock grazing?

b) How do vegetation structure i.e. grassland, savanna etc. change with climatic and edaphic factors, and livestock grazing?

Considering that livestock grazing is fairly a recent phenomenon in the landscape occurring rampantly only in the last three decades, we assume livestock grazing to have a negative impact on the grasslands. We assume the livestock grazing to be specific to some species or life-forms and hence reduce species richness and subsequently increase compositional similarity. Alternatively, we expect a positive relationship for richness and a negative relationship for compositional similarity as precipitation or the gradient in edaphic factors increase.

We expect grass density to decrease with increase in livestock grazing intensity, but, we expect an increase for shrubs and trees. We expect a similar relationship with soil rodded and loose bulk densities which determine soil compaction. We expect grass and tree to have a positive relationship and shrubs to have a negative with soil water holding capacity and precipitation. But we expect grass and shrub to have a positive relationship and tree to have negative with total organic carbon. We expect a coarse soil texture (i.e., more %sand) to support more shrub than grass or trees. Based on this we hypothesise the outcome of the interactions to give different vegetation structures (Table 1.1).

Table 1.1: Hypothesis for the vegetation structure we expect as a result of the interactive effect of the considered covariates

Vegetation structure type	Precipitation	Water holding capacity	%sand	Soil total organic carbon	Grazing intensity	Soil bulk density
Grassland	+	+	-	-	-	-
Shrubland	-	-	+	-	+	+
Forest	+	+	-	+	+	+

*We expect every other combination to result in a savanna. The savanna could be a shrub-savanna or a tree-savanna depending on the weightage of covariates that satisfies shrub density or tree density. eg., if grazing intensity and bulk density increases in a grassland, it satisfies two more criteria for becoming a forest, hence yielding a tree-savanna instead.

2. STUDY AREA

2.1. Study area

The study was conducted in the Thar desert grasslands of the North-Western Rajasthan, India. The Thar experiences 0 - 300 mm rainfall with temperatures ranging from 0°C in winter to 51°C in summer. A five year drought cycle is prevalent in this region. It is reported to have a floral diversity of 628 species belonging to 87 families (Bhandari et al., 1995). The region supports two dominant grassland communities, a climax *Lasiurus sindicus – Panicum turgidum* (Roy et al., 2015; Reddy et al., 2011) and a non-climax *Dactylotenium* sp.– *Cenchrus* sp. (Roy et al., 2015). Some of the distinct fauna this region supports include chinkara (*Gazella bennettii*), Indian hedgehog (*Paraechinus micropus*), spiny tailed lizard (*Saara hardwickii*) and a considerable population of the great Indian bustard (*Ardeotis nigriceps*) (Dutta et al., 2010). However, only 7.45% of the Thar Desert is under the protected-area network of India, all being wildlife sanctuaries. Among these, the 'Desert National Park' is the largest wildlife sanctuary (3162 km^2), of which a small fraction of 170.25 km^2 of area is protected as enclosures and is technically inviolate.

2.2. Land-use changes in the region

In Jaisalmer alone there has been a 602% increase in croplands in 40 years from 1972-2012 (Status of Agriculture, 1974). This has especially been drastic in the recent years post the establishment of the Indira Gandhi Canal (IGC) which aimed at irrigating 9.5 lac ha of land in 7 districts of Rajasthan (Shrivastava et al., 2013). The consequences are however, not few. A combined effect of the canal and subsequent agricultural expansion has reportedly caused severe fluctuations in the ground water table (Santra et al., 2014; Tyagi, 2004 in Jaisalmer district, Rajasthan) and possibly increased precipitation (Rao, 1996 in Ganganagar district, Rajasthan). It has also been reported to have changed the soil properties from sandy to alluvial type in the Thar landscape (Tyagi, 2004) and accelerated plant encroachment especially by the planted *Prosopis* species. Further, due to reduced recognition of the grasslands as distinct vegetation structures, large scale plantations of *Vachellia tortilis* have been practiced in this landscape (Mohan et al., 2016). Solanki (1990), in an account of Jaisalmer, reported that

“..agriculture is rudimentary..”, with pastoralism being the only economy with about 2000 livestock constituting the migratory herds. However, the 2012 livestock census reported of a density of 83 livestock per km^2 in Jaisalmer. More than half of India’s livestock is dependent on natural fodder (Roy and Singh, 2013).

With rampant land-use changes occurring in this landscape, there are a few pressing concerns that need to be addressed i) with edaphic properties changing due to the IGC, which vegetation structures will shift and to what? ii) with the supposed severe increase in livestock grazing, will the grasslands incline to becoming a shrubland or a forest, a process termed as shrub invasion or woody plant encroachment (Bestelmeyer, 2005)?

3. METHODS AND ANALYSIS

3.1. Study Design

To obtain an optimal sampling block that provides a gradient in the environmental factors as well as be logistically less intensive, we chose a 10,235 km^2 (~150 x 90 km) area stretching from the IGC in the north to the Desert National Park in the south, henceforth intensive study area (26° 04’ - 27° 34’ N and 70° 10’ – 71° 02’ E) (Fig. 3. 1). We gridded the study block into 1 km^2 grids. Grids that overlapped with the 50 m buffer around croplands and settlements from the LULC map available were excluded from the intensive study area leaving 3186 potential grids for sampling (non-empty grids in Fig. 3.1(c)). We then extracted soil texture and precipitation indices for the centroids of these grids from the available maps using QGIS (QGIS, 2014) and RStudio (RStudio, 2019). Soil texture maps were obtained from Rajasthan NRSC website at 1 sq. km resolution (NRSC, 2016) while, precipitation data for August month (averaged across 30 years 1970-2000) was obtained from WorldClim at 2.5 km^2 resolution (Fick and Hijmans, 2017). We then performed a two factorial clustering of the grids, first by soil texture and then by precipitation (see supplementary information S1 for details on the procedure). This resulted in 53 unique soil texture-precipitation clusters. We then randomly selected a proportional sample of grids from each of the clusters to sample, keeping total required sampling grids as 70 and minimum for each soil texture-precipitation clusters as one. Four grids were sampled inside the enclosures of the Desert National Park which are expected to have regulated grazing. Grids with plantations were eliminated on visit and the closest possible adjoining grid from the same cluster were chosen for sampling.

In each of the grid, four 1 hectare plots of 50 x 200 m each were laid. A complete sampling was adopted for trees within the 1 hectare cell (henceforth ha). Shrubs were sampled at 5 x 5 m and grasses at 1 x 1 m with 5 spatial replicates within each 1 ha plot. Within each 1 ha plot we recorded data on species identity, girth (GBH for trees taller than 1.34 m and at base for otherwise), height from ground to the lower margin of the crown as well as min and max diameter of the crown using a 3 m measuring tape. The total height was estimated by keeping a reference stick of 1 m. The shrub and grass plots were made by creating a frame using PVC pipes of desired dimensions joined in the corners using elbow connectors. Within the 5 x 5 m shrub plots we recorded species identity, min and max diameter and total height using a 3 m measuring tape, while for grasses we recorded species identity, dominant height and a visual estimation of the percentage cover (a visual representation of the sampling design is given in supplementary information S2). Visual estimation was carried out by visually dividing the 1 m^2 plot into 4 quarters and fitting all the grasses in these quadrats and estimating the total percent cover, i.e. if the grasses would fit into one quadrat completely it is taken as 25% cover. Species that tend to grow more than 2 m in height in this landscape and obtain a GBH of more than 10 cm were considered as trees, while the otherwise were considered as shrubs. Soil was collected up to a depth of 15 cm at five locations within each of the cells. Soil collected was sun-dried and labelled for later analysis.

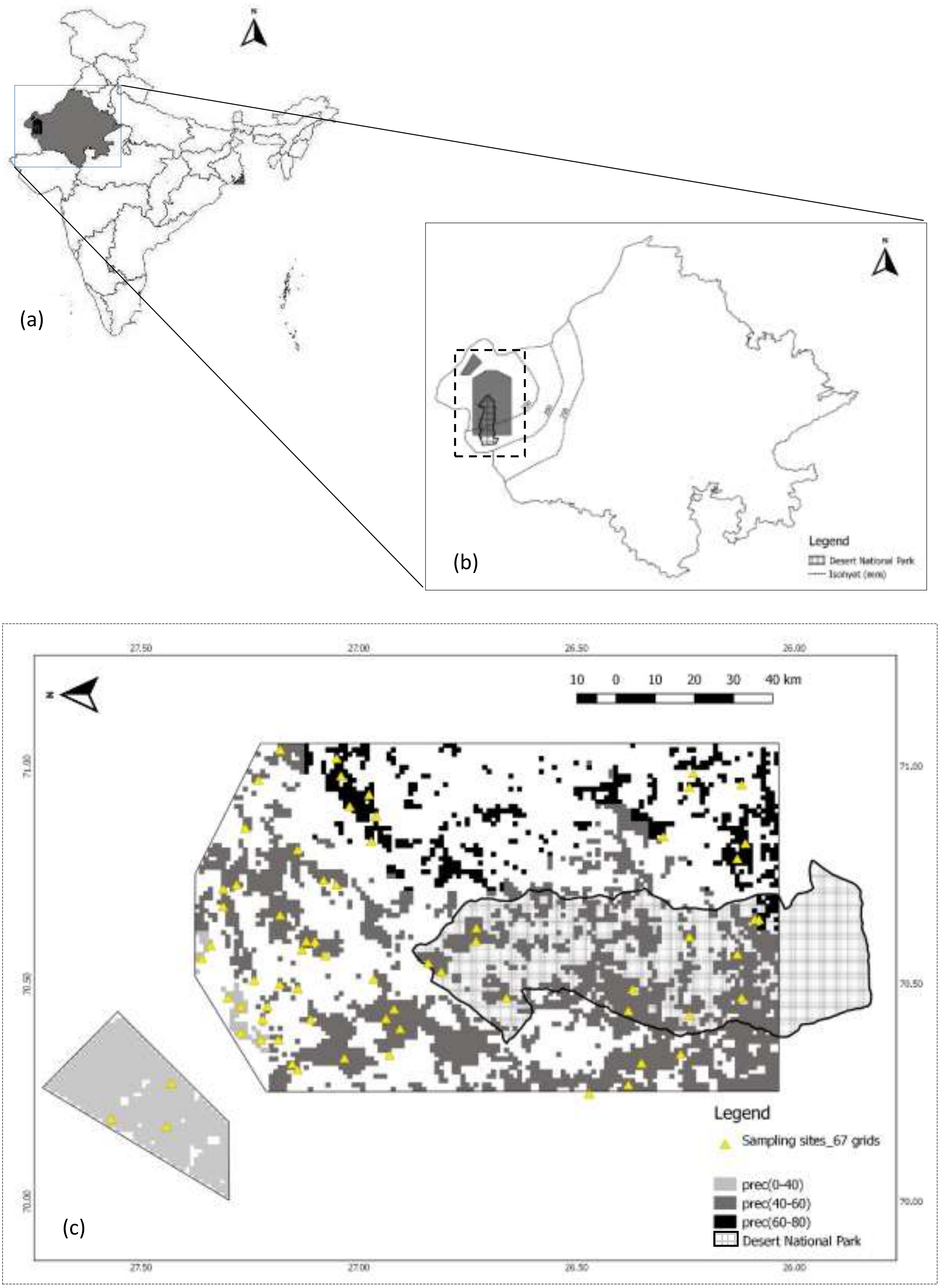


Fig. 3.1: Intensive study area (c) in State of Rajasthan (b), India (a)

The isohyet lines in (b) show 150 mm, 200 mm and 250 mm precipitation, empty space in (c) are grids that fell within 50m buffer of agricultural land/settlement that were excluded for sampling

3.2. Collection of covariates

3.2.a. Soil properties and precipitation

The 20 soil cores from each grid (5 samples x 4 ha) were composited into one by mixing soil cores equally either by weight or volume to represent the grid. The mixture was then sieved in 8 micron mesh. We analysed the sieved mixture for soil texture, total organic carbon, water holding capacity, loose and rodded bulk density. We used precipitation at a lower resolution, 1 km^2 resolution from WorldClim as one of the covariates.

3.2.b. Livestock grazing intensity

We assumed potential livestock density (number of livestock that might forage in the grid) to be a surrogate for livestock grazing intensity. To calculate potential livestock density, we performed a two-step process – i) determine the maximum daily ranging distance ii) determine the number of livestock that have potential access to our sampling grid.

To determine the maximum ranging distance, we tagged 28 livestock (7 cattle, 10 goats and 11 sheep) with Holux RCV 3000 GPS logger for 1-2 days each. The loggers were set to record and store GPS locations along with time, date, elevation and speed every two minutes. We mapped settlements *apriori* based on their type viz., village, dhani (hamlets) or isolated corrals to obtain a spatial spread as well as obtain variation in ranging pattern between livestock type and/or between settlement type. We tagged 1-3 livestock per day in the morning before the herding begins. The loggers were retrieved after the herd returns in the evening. The livestock type and time of deployment and retrieval were recorded. The ranging tracks were retrieved using Holux ezTour software and trimmed using QGIS.

To determine potential number of livestock, we initially assumed the maximum daily ranging distance from settlement to be 3 km. We created 3 km buffers around the selected sampling grids and mapped all the settlements that were visible on Google Earth satellite imagery. We visited all the mapped locations and surveyed 1-2 people to determine the number of each livestock type stocked in the settlement.

3.2.c. Livestock foraging strategy

To determine livestock foraging preference, we adopted a focal sampling on individuals (n=22) picked at random both in space and time. The sampling involved counting the number of bites of every plant species taken by the livestock in one minute. We assumed that area available for foraging for an individual in a given time is restricted by its average moving speed. For instance, if the average speed of cattle is 7 m/min, the area available for foraging is only 7 m on the three cardinal axis in that one minute, assuming there is no backward movement. Hence, we computed the average speed from the collared livestock and the forage availability was estimated in that area for every individual sampled.

3.3. Data Analysis

3.3.a. Vegetation Component

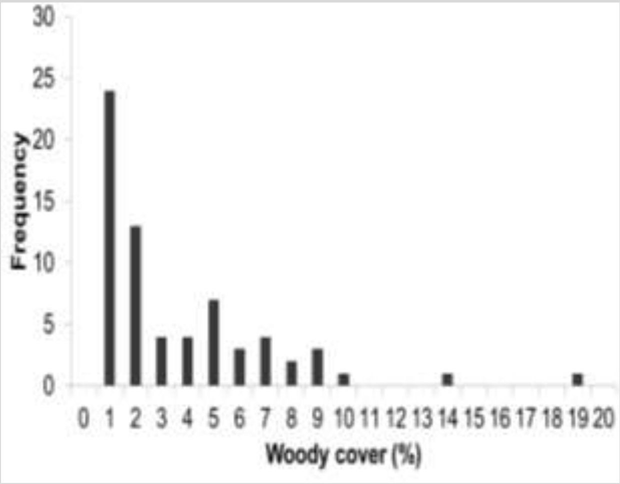
To determine vegetation composition, we calculated total tree basal area, tree and shrub abundances, and species wise tree, shrub and grass volume and cover in our sampled ha plots. We extrapolated shrub and grass data from their sub-plots to standard 1 ha. All the analyses that are at grid scale were carried out at 4 ha per grid without extrapolating it further to 1 km^2.

We transformed the data into community matrices of incidence, abundance and cover for compositional analysis.

We computed species richness using iNEXT package in RStudio.

To define vegetation structure, we computed frequency of woody cover (sum of tree cover and shrub cover) from the 67 sampled grids (Fig. 3.2). It shows that the distribution is bimodal and with transition between vegetation structures would occur between 2-4% in the arid landscape, grasslands have than 2% woody cover and savanna more than 4%. Using this information, we developed a key to classify the grids into distinct vegetation structure classes (Box. 3.1). The 67 grids were classified into mixed grassland (n=5), soft grassland (n=22), woody grassland (n=2), transition (n=6), shrub savanna (n=6), tree savanna (n=5) and tree shrub savanna (n=10).

Fig. 3.2: Defining vegetation structure type based on tree cover percent in the study area



Bimodal distribution in tree cover with two peaks indicating grasslands (0-2%), savanna (>4%) in the arid grassland-savanna of Thar. The intermediate bands (2-4%) are the tipping points where transitions between two vegetation structure type would occur. Note the definitions are different from those of the semi-arid savanna given by Hirota et al., (2011) (Fig. 1.1).

Box 3.1: Key used to classify vegetation community into distinct vegetation structural types

Criteria	**Resulting vegetation structure**
a) Woody cover less than 2%	Grassland
i) Rel. tussock grass cover more than 75%	*Tussock grassland*
ii) Rel. tussock grass cover between 25% and 75%	*Mixed grassland*
iii) Rel. tussock grass cover less than 25%	*Soft grassland*
b) Woody cover between 2% and 4%	Transition
c) Woody cover more than 4%	Savanna
i) Rel. tree cover more than 75%	*Tree savanna*
ii) Rel. tree cover between 25% and 75%	*Tree shrub savanna*
iii) Rel. tree cover less than 25%	*Shrub savanna*

*****Types are underlined, while sub-types are italicized

3.3.b. Covariate component

i. Determining maximum grazing daily distance

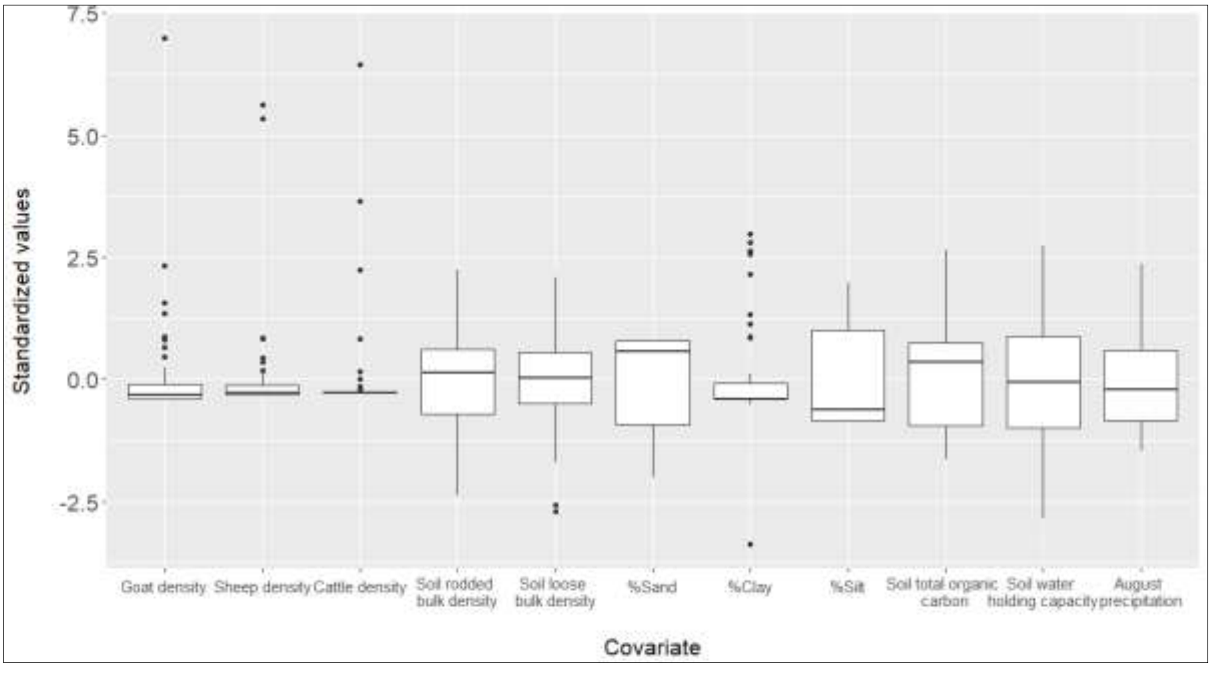
We computed maximum daily livestock distance for every tagged herd. We regressed the maximum distance against livestock type and settlement type using generalized linear model to check for variation. We found that the maximum distance vary only among livestock type. The maximum daily grazing distance for cow, goat and sheep predicted from the chosen model are 685 m, 1700 m and 1590 m, respectively. The results of all the models are presented in Annexure 1. For all the settlements that were mapped and surveyed for stocking numbers, we drew buffers using this maximum grazing distance on QGIS for every livestock type. Then for each buffer we calculated livestock density i.e. dividing the total livestock present by the area of the buffer. We then created 100 m^2 vector grids spanning our intensive study area and obtained the livestock density for every livestock by summing the densities of the underlying buffers in each of the grid. Then for all the sampled 1 km^2 grids, we averaged the livestock densities for the underlying 100 m^2 grids to obtain the maximum potential livestock grazing pressure for every grid.

ii. Treating collinearity in covariates

We had a total of 11 covariates, *viz.*, precipitation, soil water holding capacity, %sand, %silt and %clay in soil, rodded bulk density, loose bulk density, soil total organic carbon, cattle, goat and sheep densities. Apart from the livestock densities and %clay, the variation captured in the remaining seven covariates seem to be similar (Fig. 3.3). A spearman rank correlation test indicated significant collinearity among livestock densities, rodded and loose bulk density and among different soil texture (Annexure 2). To remove collinear variables, we eliminated %clay and %silt from the analysis. We summed goat and sheep densities into small livestock densties. And, from rodded and loose bulk density, we calculated the potential soil compaction by using the following formula. Following this process, we found no significant strong collinearity among the reduced seven covariates (Annexure 3). The variance inflation factor for the seven covariates calculated using ‘MuMIn’ package in RStudio were less than 1.29 and the correlation coefficient ranged between 0.011 and 0.33.

$$Potential\ soil\ compaction = \frac{Rodded\ Bulk\ density - Loose\ Bulk\ Density}{Loose\ Bulk\ Density} \times 100$$

Fig. 3.3 : Variation of covariates in the sampled grids



3.4. Analytical Methods

We used ordinary least square and generalized linear models to test relationships between our explanatory covariates, namely environmental variables and livestock densities, and (i) species richness, (ii) vegetation structure and (iii) percent cover of different life-forms. The models were built by forward selection and backward selection or by dredging models and performing a model averaging. Model selections were based on Akaike's Information Criteria (AIC). To test compositional similarity across the explanatory covariates, we used non-metric multidimensional scaling (NMDS) and tested the significance using *adonis* under 'vegan' package in RStudio. All statistical tests were tested at p 0.05 significance. We used Anderson-Darling test to check for normality. To remove collinear variables we used Spearman rank correlation test. We use chi-squared test to check for livestock forage preference.

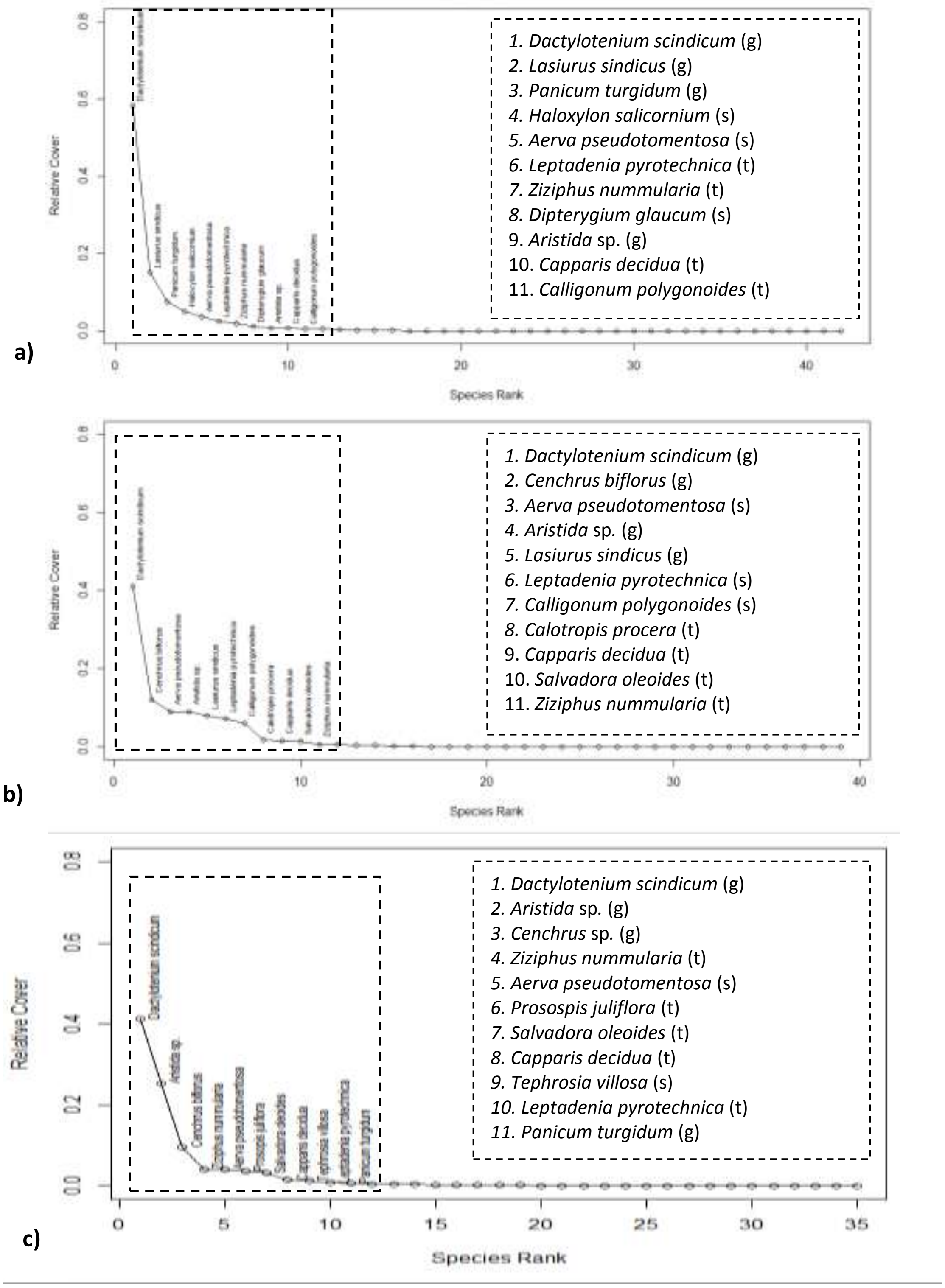
4. RESULTS

4.1. Overall pattern in the vegetation community

A total of 61 species were recorded during the sampling (Annexure 4). The rank-abundance curves (Fig. 4.1) show that the *Dactylotenium scindicum* is the dominant graminoid across precipitation classes. However, the sub-dominant grasses vary across the three precipitation classes. While *Lasiurus sindicus* - *Panicum turgidum* occur in the low precipitation class, *Cenchrus biflorus* - *L.sindicus* - *Aristida* sp. occur in the medium precipitation class and *Aristida* sp. - *Cenchrus* sp. occur in the high. With respect to shrubs, relative cover of *Haloxylon salicornium* declines as precipitation increases.

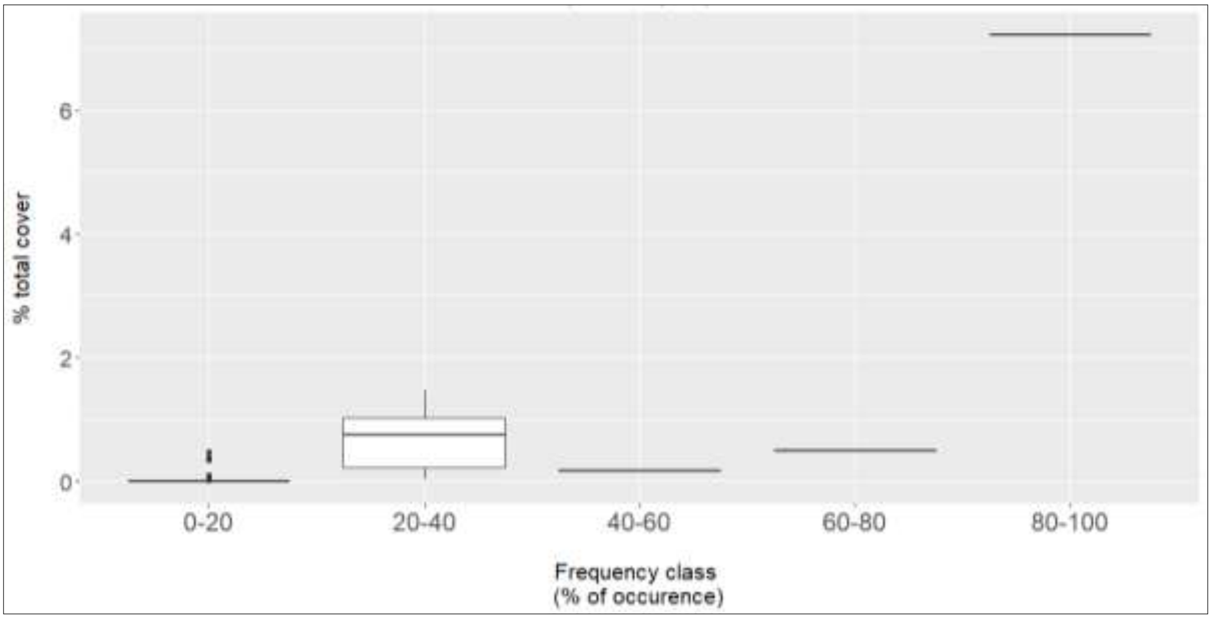
The dominance-frequency relationship shows that apart from one species that is both dominant (in % total cover) as well as frequently occurring, most other species despite being abundant occurred in less than 40% of the plots sampled indicating a high dominant species turnover (Fig. 4.2).

Fig. 4.1: Rank-abundance curve across precipitation classes



*****the habit for the species is indicated in parenthesis: g - grass, t – tree, s – shrub. Panel (a) corresponds to low precipitation gradient (0-40 mm), panel (b) with medium (40-60 mm) and panel (c) with high (60-80 mm)

Fig. 4. 2 : Dominance-frequency relationship of all species (in 255 ha plots)



4.2 Observed trends in species diversity

4.2.a. Species richness

Our regression results show that species richness has a significant relationship with precipitation among the seven covariates (Table 4.1). The relative importance of the variables further show that the precipitation to be the most important variable that explains species richness (Table 4.2) and that it is a linear increase with increase in precipitation (R^2=0.39, p= 1.029e^{-06}) (Fig. 4.3). However, the increase in richness is not uniform across all life forms. Species accumulation is shallow in grasses and shrubs, however, steeper in trees and herbs (Fig. 4.4). Species reaches near saturation in herbs at about 55 mm and only richness in trees increases beyond that. The increase in tree richness is not due to non-native species.

Table 4.1: Conditional average coefficients from models with <10 Δ AIC

	Estimate	**Std. Error**	**Adjusted SE**	**z value**	**Pr(>|z|)**
(Intercept)	-4.59277	14.61593	14.95635	0.307	0.759
Aug_prec	0.23657	0.04870	0.04980	4.750	2e-06 ***
Soil.compaction	0.09424	0.09140	0.09358	1.007	0.314
WHC	0.23409	0.22858	0.23404	1.000	0.317
Cow_dens	-0.44651	0.63514	0.65036	0.687	0.492
Small_livestock	-0.31584	0.66749	0.68255	0.463	0.644
TOC	-0.38094	1.77788	1.81966	0.209	0.834
x.sand	0.01385	0.30012	0.30729	0.045	0.964

*significant relationship is highlighted. Abbreviations used in the models: Aug_prec – precipitation, Soil.compaction – soil compaction, WHC – soil water holding capacity, Cattle_dens – cattle density, Small_livestock – small livestock density, TOC – soil total organic carbon, x.sand – %sand in soil.

Table 4.2: Relative importance of variables in explaining species richness

	Aug_prec	Soil compaction	WHC	Cow_dens	Small livestock	TOC	x.sand
Importance	1.00	0.34	0.34	0.31	0.29	0.23	0.23
N containing models	61	30	30	29	29	0.29	0.29

*total dredged models – 128, models with <10 Δ AIC – 61. Abbreviations used: Aug_prec – precipitation, Soil.compaction – soil compaction, WHC – soil water holding capacity, Cattle_dens – cattle density, Small_livestock – small livestock density, TOC – soil total organic carbon, x.sand – %sand in soil.

Fig. 4.3: Species richness along precipitation gradient

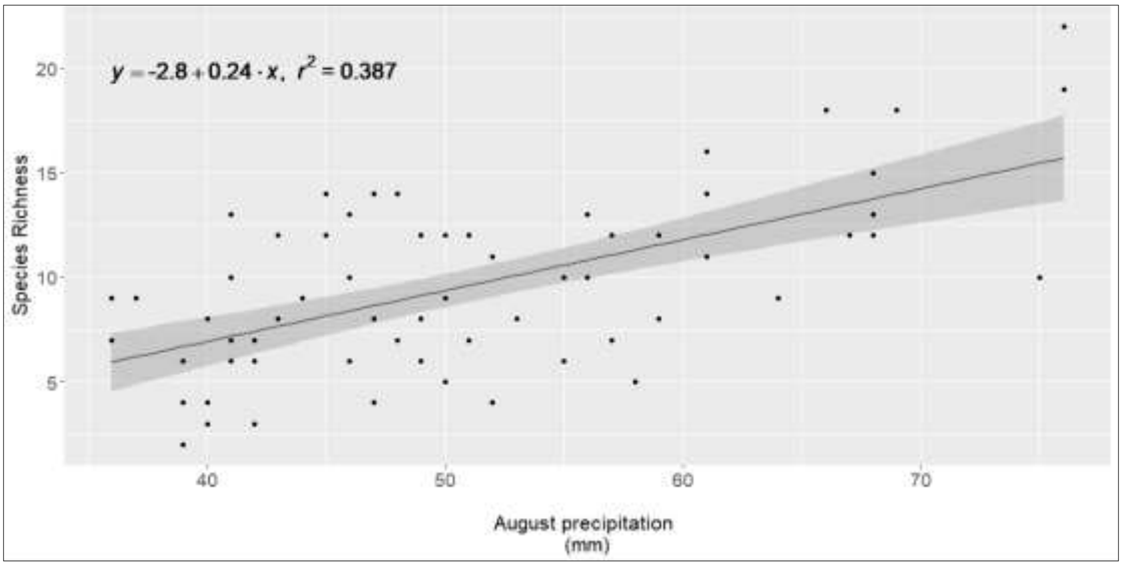
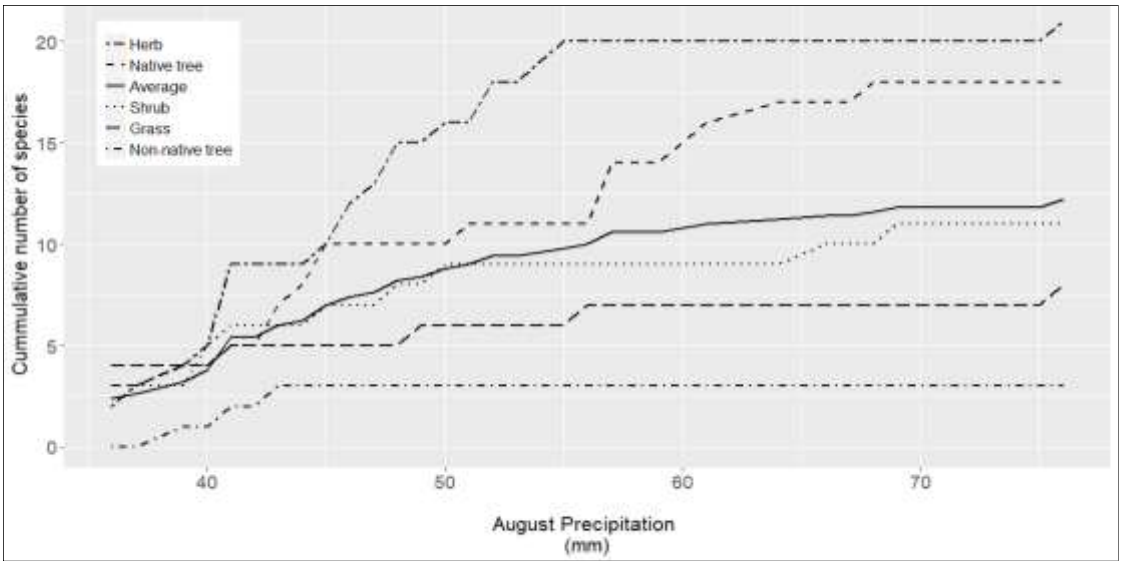


Fig. 4.4: Species accumulation curve of life forms along precipitation gradient



4.3 Overall trends in compositional similarity

Compositional similarity among the sampling grids were checked across the seven covariates. The results of the non-metric multidimensional scaling are given in Table 4.3. Precipitation and soil compaction were found to be the primary determinants for rendering vegetation communities dissimilar from each other (Fig. 4.5 – 4.6).

Table 4.3: Response of compositional similarity to the considered covariates

Covariate	Number of clusters	Bins of the clusters	p-value
Soil texture (%sand)	3	93.8 - 95.2, 95.2 - 96.6, 96.6 - 98	0.196
Total organic carbon (%)	3	0 - 0.364, 0.364 - 0.73, 0.73 - 1.09	0.628
Soil compaction	2	1.52-12.5 12.5 - 23.5	0.001*
Water holding capacity (%)	3	14 - 18, 18 - 22, 22 - 26	0.223
August precipitation (mm)	3	37 - 50, 50 - 63, 63 - 76	0.001***
Cattle density (per km^2)	2	>100, <100	0.831
Small livestock density (per km^2)	2	>75, <75	0.625

*significant relationships are highlighted.

Fig. 4.5: Vegetation compositional similarity across precipitation classes

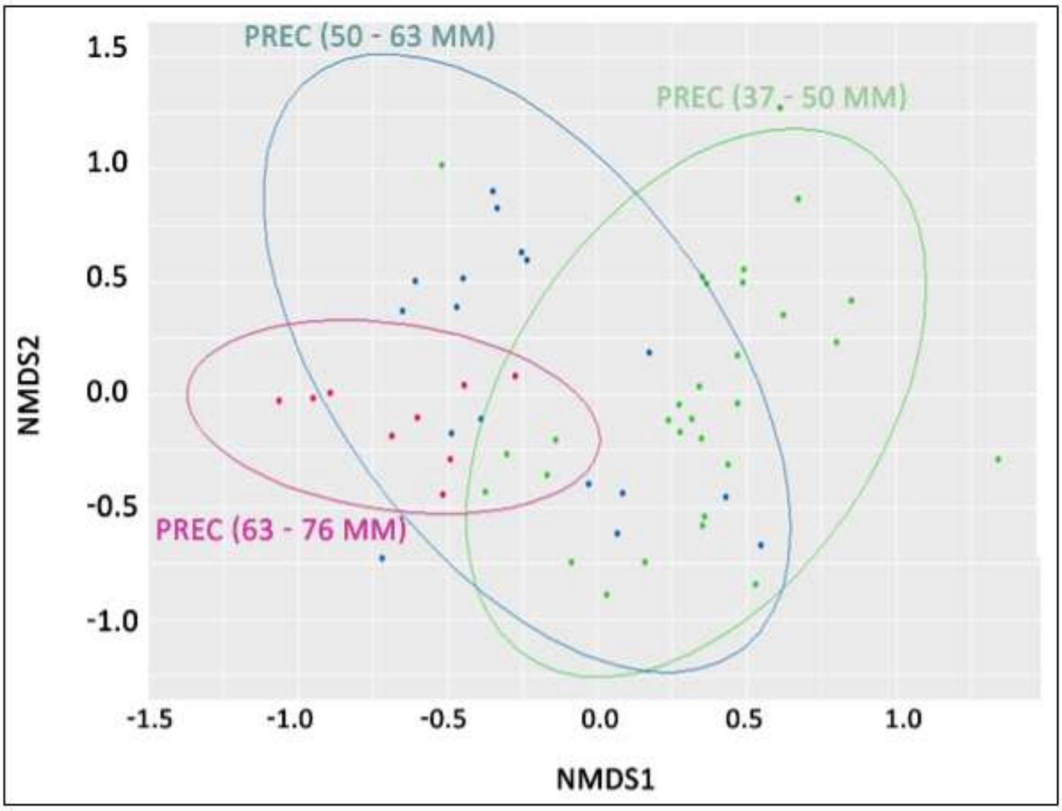
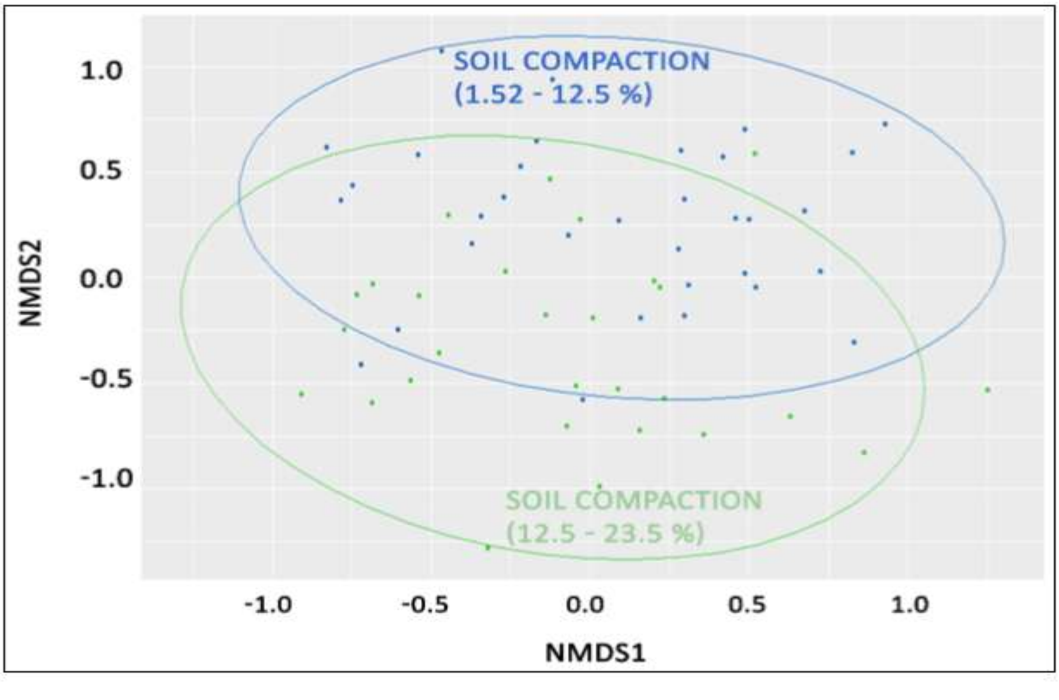


Fig. 4.6: Vegetation compositional similarity across soil compaction classes



4.4. Observed trends in vegetation structure

4.4.a. Densities of life form

Results from univariate regression against all explanatory variables show that the abundances of woody species and tree cover increase linearly with precipitation (*p* = 0.02e-02 and *p* = 0.002, respectively) (Table 4.4 gives the p-values for all the univariate regression carried out testing relationship between the vegetation variable in the rows and explanatory variable in the columns; Table 4.5 gives the coefficients for the significant relationships). Shrub cover is found to have a negative relationship with both soil compaction (*p* = 2.86e-07) and small livestock grazing intensities (*p* = 0.00815). Grass cover was found to be not determined by livestock grazing intensity or environmental factors. However, grass cover shows a negative relationship with shrub cover (*p*=2.86e-05 ***) with no significant relationship with tree cover (*p* = 0.251).

Table 4.4: Response of the vegetation to environmental factors and grazing

	Prec	WHC	%sand	TOC	Cattle density	SL density	Soil comp
Tree-shrub abundances	0.000207 ***	0.583	0.653	0.169	0.366	0.209	0.641
Tree cover	0.00209 **	0.365	0.922	0.294	0.136	0.229	0.519
Shrub cover	0.3	0.083	0.805	0.522	0.605	0.00815 **	2.86e-07 ***
Grass cover	0.682	0.511	0.787	0.934	0.351	0.491	0.616

*the significant relationships are highlighted. Abbreviations used: Prec – precipitation, WHC – soil water holding capacity, %sand – %sand in soil, TOC – soil total organic carbon, SL density – small livestock density, Soil comp – soil compaction

Table 4.5: Relationship between life forms and their significant explanatory variables

	Intercept	Variable	Estimate	Std. Error	z value	Pr(>|z|)	Pseudo R^2
Tree shrub abundance	3.1158	Prec	0.0458	0.0123	3.710	0.0002 ***	0.169
Tree cover	3.8330	Prec	0.0523	0.0170	3.077	0.0020 **	0.089
Shrub cover	6.5748	SL density	-0.0014	0.0005	-2.646	0.00815 **	0.026
Shrub cover	9.1882	Soil comp	-0.2332	0.0454	-5.132	2.86e-07 ***	0.172
Grass cover	8.6727	Shrub cover	-0.0005	0.0001	-4.185	2.86e-05 ***	0.157

*Abbreviations used: Prec – precipitation, SL density – small livestock density, Soil comp – soil compaction. Psuedo R^2 calculated by 1-(residual deviance/null deviance)

4.4.b. Determinants of vegetation structure

Based on the key, the 67 grids belonged to 7 vegetation types. A multinomial regression showed that the vegetation structure can be modelled best with precipitation and soil compaction (Table 4.6). The nature of the relationships with the determinants indicates that two or three vegetation structure types respond similarly to change in the determining variables. From the table (Table 4.7), it is evident that possibility of tree savanna or a tree shrub savanna increases with an increase in precipitation and soil compaction (Fig. 4.7).

Table 4.6: Top 8 models with the lowest AIC tested for determinants of vegetation structure

Model	df	AIC	Δ AIC	Pseudo R^2
Model 5: Vegetation.Structure ~ Aug_prec	12	190.4852	0	0.127
Model 10: Vegetation.Structure ~ Aug_prec + comp	18	191.0714	0.5862	0.187
Model 12 : Vegetation.Structure ~ Cattle_dens	12	196.0751	5.5899	0.098
Model 14: Vegetation.Structure ~Aug_prec + WHC + x.sand + comp	30	196.8653	6.3801	0.282
Model 22: Vegetation.Structure ~ small_livestock_dens * comp	24	197.1835	6.6983	0.218
Model 16 : Vegetation.Structure ~Aug_prec * comp	24	198.8948	8.4096	0.209
Model 32: Vegetation.Structure ~ small_livestock_dens	12	200.1134	9.6282	0.077
Model 4: Vegetation.Structure ~ Cow.Dens + small_livestock_dens	18	200.9256	10.4404	0.135

*chosen model is highlighted. Abbreviations used in the models: Vegetation.Structure – type of vegetation structure, Aug_prec – precipitation, comp – soil compaction, WHC – soil water holding capacity, Cattle_dens – cattle density, small_livestock_dens – small livestock density, TOC – soil total organic carbon, x.sand – %sand in soil.

Table 4.7: Relationship between type of vegetation structure and the environmental determinants

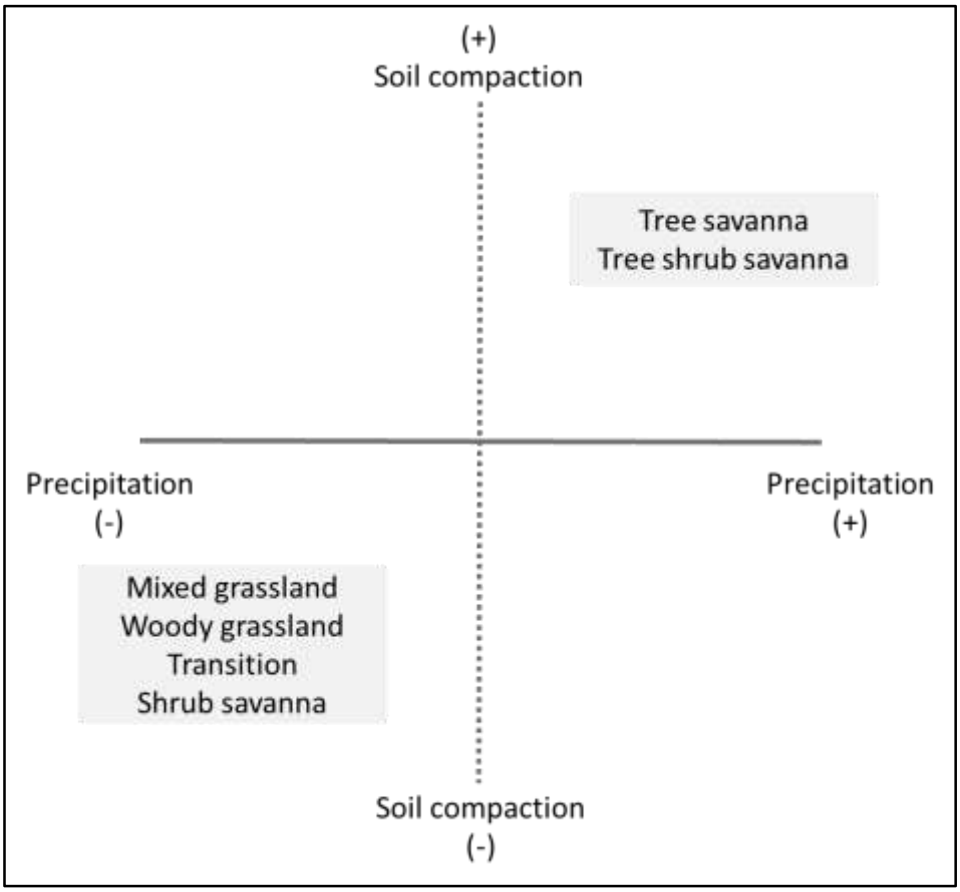
Chosen model: Vegetation.Structure ~ Aug_prec^2 + comp,

	Intercept	**Std.Error**	**Aug_prec**	**Std.Error**	**comp**	**Std.Error**
Shrub savanna (n=6)	0.3973	5.9304	0.0604	0.1353	-0.2468	0.1612
Soft grassland (n=22)	-8.9955	5.1126	0.2133	0.1146	0.0335	0.1275
Transition (n=6)	-6.8238	5.5187	0.1878	0.1230	-0.1246	0.1515
Tree savanna (n=5)	-17.2979	6.2237	0.3381	0.1301	0.0136	0.1667
Tree shrub savanna (n=10)	-11.8887	5.4996	0.3063	0.1216	-0.1842	0.1473
Woody grassland (n=2)	1.2681	8.4827	0.0139	0.1951	-0.2416	0.2181

*****the intercepts are of the binomial link function and are untransformed. The number in parenthesis indicates the samples sized from which the model was built along with mixed grassland (n=5).

Pseudo *R*-squared computed from deviance: 0.187. The prediction using the chosen model was 42% accurate.

Fig. 4.7: A visual representation of the factors that determine vegetation structure shifts



*The grey boxes indicate the resulting vegetation structure due to the determining factors that lie on the axes *viz.,* precipitation and soil compaction. (+) indicates increase in the determining factor and (-) indicates a decrease.

Predicting vegetation structure for the study area:

From the chosen model, it is evident that vegetation structure could be predicted with 42% accuracy using two determinants, namely, precipitation of August month and soil compaction. Data on precipitation is available at WorldClim data. To estimate soil compaction we used regression analysis to check its relationship with the remote sensed soil texture data available at NRSC website (Annexure 5). Our regression analysis showed that the soil compaction could be predicted using the index of the soil loam content ($R^2 = 0.1092$, $p = 0.01027$). We extracted precipitation and index for loam content for all the grid centroids in the study area. We predicted soil compaction using loam content. Then by using precipitation and soil compaction, we predicted the vegetation structure in the study area.

The predicted reveal the presence of four vegetation structures in the landscape, namely, mixed grassland, soft grassland, tree savanna and tree shrub savanna with the Desert National Park covering one of the vegetation types (Fig.4.8). Superimposing the human-dominated land-use types, namely agriculture and settlement, the map shows a 62% loss in the vegetation types to agriculture and settlements (empty cells in Fig. 4.9).

Fig. 4.8: Predicted vegetation structure in the study area highlighted with the regions protected by the Desert National Park

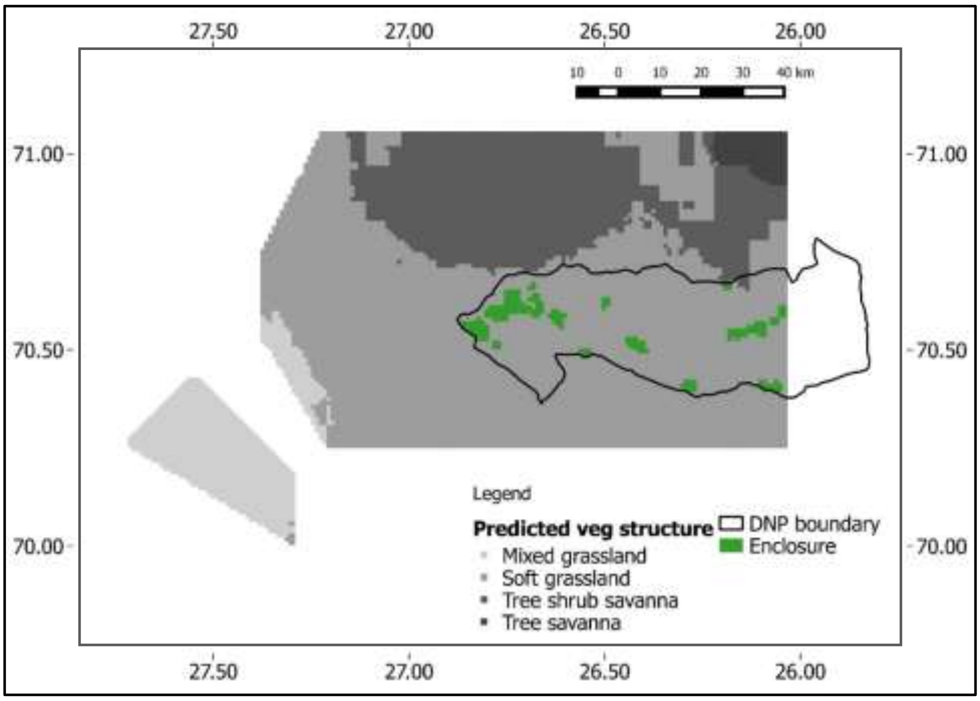
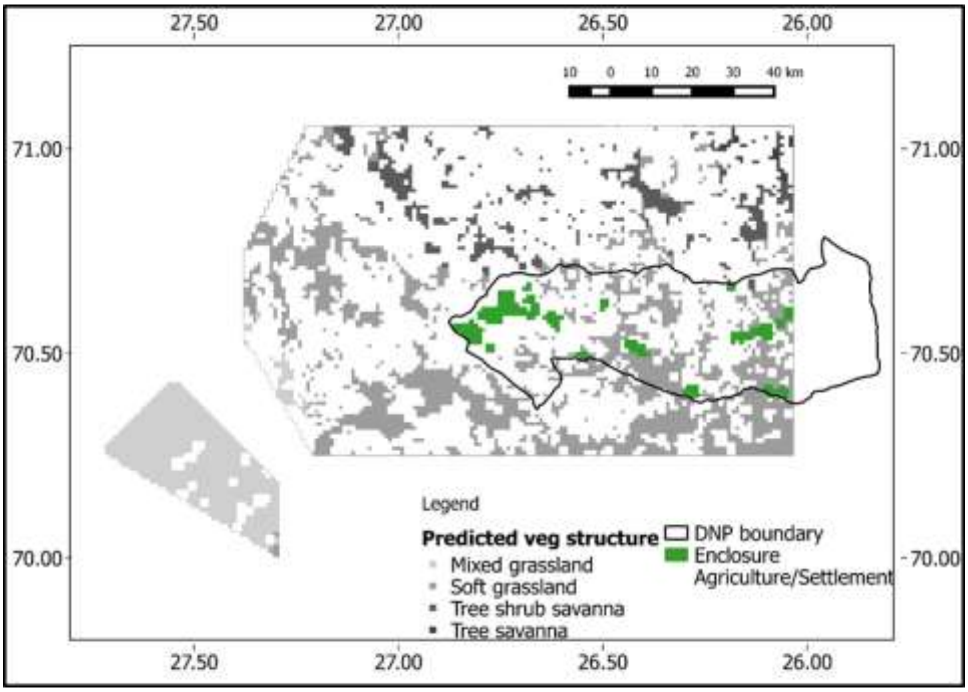


Fig. 4.9: Land-use types masking the vegetation structure types in the study area



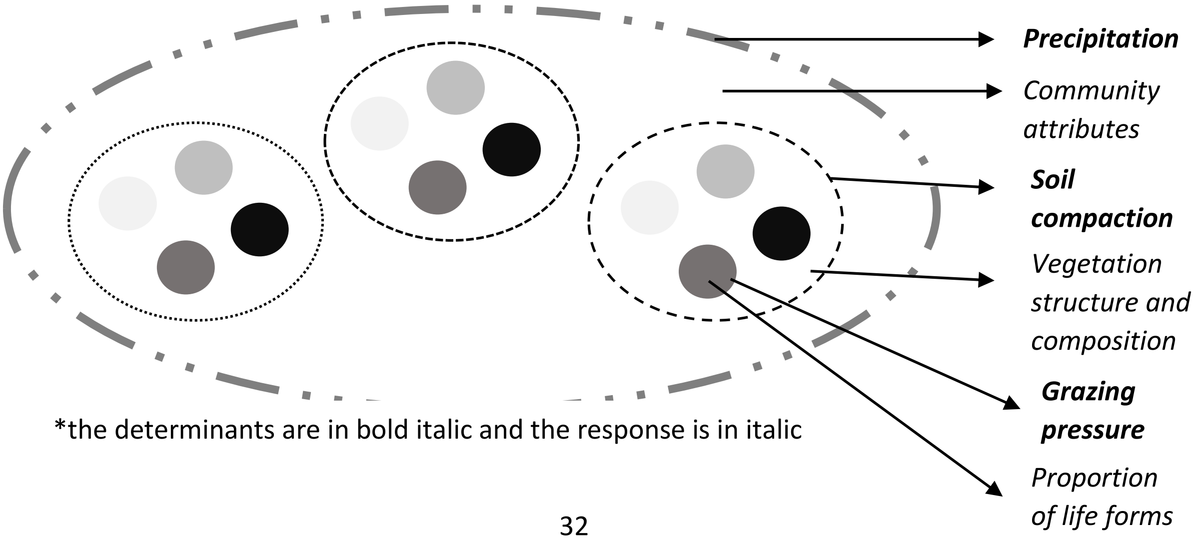
4.5. Livestock foraging preference

The conducted bite count studies on livestock show no preference for any plant species within any of the livestock types (cow: X-squared = 16.272, df = 15, *p* = 0.3642, Goat: X-squared = 9.4513, df = 15, *p* = 0.8528, Sheep: X-squared = 8.2269, df = 11, *p* = 0.6928, all livestock: X-squared = 25.976, df = 18, *p* = 0.1003). The analysis show no preference for any life forms within any of the livestock types (cow: X-squared = 4.3526, df = 2, *p* = 0.1135, Goat: X-squared = 1.4216, df = 2, *p* = 0.4912, Sheep: X-squared = 2.3215, df = 2, *p* = 0.3133, all livestock: X-squared = 5.1939, df = 2, *p* = 0.0745). An Ivlev selectivity index calculated for all the plant species foraged by each of the livestock types are given in Annexure 6 and 7.

5. DISCUSSION

We find that precipitation plays a dominant role in determining many of the community attributes as it was found to significantly explain species richness (global pattern by Beier et al., 2012), compositional similarity between regions as well defining vegetation structure shifts. Soil compaction determined vegetation composition (Cuevas et al., 2012) and structure (From Fig. 4.5, 4.6 and 4.7). We also found that the proportion of life forms depend on livestock grazing pressure (from table 4.4). But as Mills (2006) noted, the determinants of these attributes are scale-dependent and never single factor determined. From the significant covariates we found, namely, precipitation, soil compaction and grazing pressure, precipitation operates at the largest scale as differences in precipitation are more observable as distance increases. Whereas, changes in soil compaction changes occurs within a precipitation belt eg. within the 0-40 precipitation belt, the soil compaction ranged from 3 - 21% in the sampled grids. The grazing operates at much finer scales i.e, within a soil compaction belt, the grazing pressure can vary considerably. Hence, we put forth the scale dependent and nested relationship between the covariates and the vegetation composition and structure in the arid zones (an indicative visual representation of how the determining factors of vegetation varies with scale is given in Fig. 5.1).

Fig. 5.1: A visual representation of how the determining factors varies with scale -the **precipitation** defines **community attributes**, **soil compaction** under the precipitation umbrella defines **vegetation structure** and **composition**, the **grazing pressure** especially the smaller livestock defines the proportion of the **life forms** within each vegetation structure



*the determinants are in bold italic and the response is in italic

5.1 Inferences from the large scale patterns in species composition

The vegetation composition is defined by the species richness, the proportion of their respective life-forms and their relative abundances (or in this study, percent cover). While species richness was defined by the precipitation, an interplay of precipitation and edaphic factors determine the evenness of the life forms and species. It is seen that there is a linear increase in species richness along precipitation which is consistent pattern globally (Field et al., 2009) and for deserts (Xia et al., 2010 in Chihuahuan desert) and it is contributed by increase in tree species. However, though it is not evident whether the species turnover in trees is gradual or abrupt, an apparent pattern seem to exist with the grasses. This is indicated by the rank abundance curves plotted against differing precipitation which show a rather gradual replacement of sub-dominant grass species instead of an abrupt replacement of species.

5.2 Inferences from the smaller scale patterns in vegetation structure

Two primary determinants of vegetation structure were found to be soil precipitation and soil compaction. Our results show that the resulting vegetation structure depends on the directionality of the determinants. However, two or more structures are found to occur under similar conditions indicating that they exist as alternate stable states (Bond et al., 2005). Hence, simulating and predicting vegetation structure shifts using the determinants will be a 50% or in some cases 33% accurate considering that there are 2 or 3 possible results.

This leads us to emphasize that vegetation structure transition, if occurs, will be a result of environmental factors and not due to the recent livestock grazing. Hence, the vegetation structure shifts will be gradual. However, there are very few regions of natural vegetation left unconverted from the growing human-dominated land-use types. Predicted vegetation structure using estimated soil compaction (with 42% accuracy) for the study area show that it is composed of four vegetation structure types, namely, mixed grassland, soft grassland, tree savanna and tree shrub savanna. However, 62% of the grids were found to have changed to human-dominated land-use types namely agriculture and settlement. The enclosures of the Desert National Park protects less than 1% of the cover and only covers three of the vegetation types. Hence, the threat posed by land conversions would wipe out the distinct vegetation structures, in comparison to the gradual transition that may occur due to changing environmental factors.

5.3 Inferences from the smallest scale patterns in life form

The trees are found to respond positively to precipitation both as abundance and cover and shrub cover is found to reduce with soil compaction and grazing pressure. Grass cover shows no response to any of the covariates considered in the study however it is found to be dependent on shrub cover. Woody cover is also found to be dependent on precipitation and edaphic properties, namely, soil total organic carbon and soil compaction. There are three noteworthy findings here i) Shrub cover reduces with increase in soil compaction and grazing pressure specific to the smaller livestock namely, goat and sheep. ii) Though shrub cover shows a negative response with both soil compaction and grazing pressure, we found no correlation between livestock grazing intensities and soil compaction. This is yet another contrasting result that stands out of the popular notion that grazing pressure increases soil compaction (Castellano and Valone, 2007), iii) grass cover, though not dependent on the environmental factors, shows a decrease with the increase in shrub cover. This reveals that the grazing pressure rather increases the grass cover by a two-step process, first by reducing the shrub cover and thereby increasing grass cover. One possible explanation to this finding is that the grazing pressure especially of the smaller livestock is more on shrubs than grasses. This may be due to the non-availability of grasses in summer and since the livestock are predominantly dependent on natural fodder, they might have adopted an ‘adaptive foraging strategy’ foraging on the abundant life-forms irrespective of their species. This is seen by the low preference exhibited by all the livestock types towards foraging on particular species or life forms. This leads us to state that we did not find a reduction in grasses due to livestock grazing in this study area (Krishna et al., 2014; Mertia et al., 2006; Roy and Roy, 1996, but see (Cipriotti and Aguiar, 2005)).

6. CONCLUSION

1. Arid grasslands are found to be characterised by less tree cover compared to that of semi-arid grasslands. While semi-arid grasslands are known to have less than 5% tree cover, we found that arid grasslands have less than 2% tree cover. Also the transition zone between grasslands and savanna is smaller, 5% in the case of semi-arid grasslands to shift to a savanna and 2% in the case of arid grasslands to shift to a savanna.

2. The determinants of vegetation community composition are scale dependent. Precipitation plays the dominant role in determining community attributes. The species richness increases with precipitation, and is associated with a gradual species turnover. The composition similarity decreases with precipitation and increases with soil compaction.

3. Vegetation structure transitions can be determined with precipitation and soil compaction. But, there are two or more stable states that are possible to result under similar environmental conditions. Vegetation structures being determined by environmental variables would, hence, be gradual. However, the land use change to agriculture and settlements has wiped out 62% of the study area and the Desert National Park is protecting less than 1% of the grasslands as enclosures. The loss of vegetation structure poses a larger threat to these grasslands than the expected vegetation structure transitions.

4. Grazing pressure from smaller livestock (goat and sheep) decreases shrub densities, and grass cover increases with decrease in shrub densities This, we hypothesise could be due to an ‘adaptive foraging strategy’ by smaller livestock that feed on the most abundant species leading to no apparent selection pressure on specific life-forms.

7. CONSIDERATIONS AND METHODOLOGICAL LIMITATIONS

The grazing pressure is an estimated measure and hence, the difference between the maximum grazing pressure and the on-ground grazing pressure might be highly variable. Also the variation in livestock grazing was not large among the sampled grids, especially with cattle that were absent in 75% of the grids. Further, the vegetation structure predicted only 4 out of the 8 possible vegetation structures though it had an overall 42% accuracy. An equal effort in all the vegetation structures may improve the model.

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Annexure 1: Results of regression models to determine maximum daily grazing distance

Table: Models tested for maximum daily grazing distance

Model	df	AIC	Δ AIC
maxdist~ani_type	4	541.60	0
maxdist~ ham_type	4	545.45	3.85
maxdist~1	2	551.26	9.66
maxdist~ ani_type + ham_type	6	555.02	13.42

*chosen model is highlighted. Abbreviations used in the models: maxdist – maximum daily grazing distance, ani_type – livestock type (cattle/goat/sheep), ham_type – settlement type (settlement/hamlet/isolated corral)

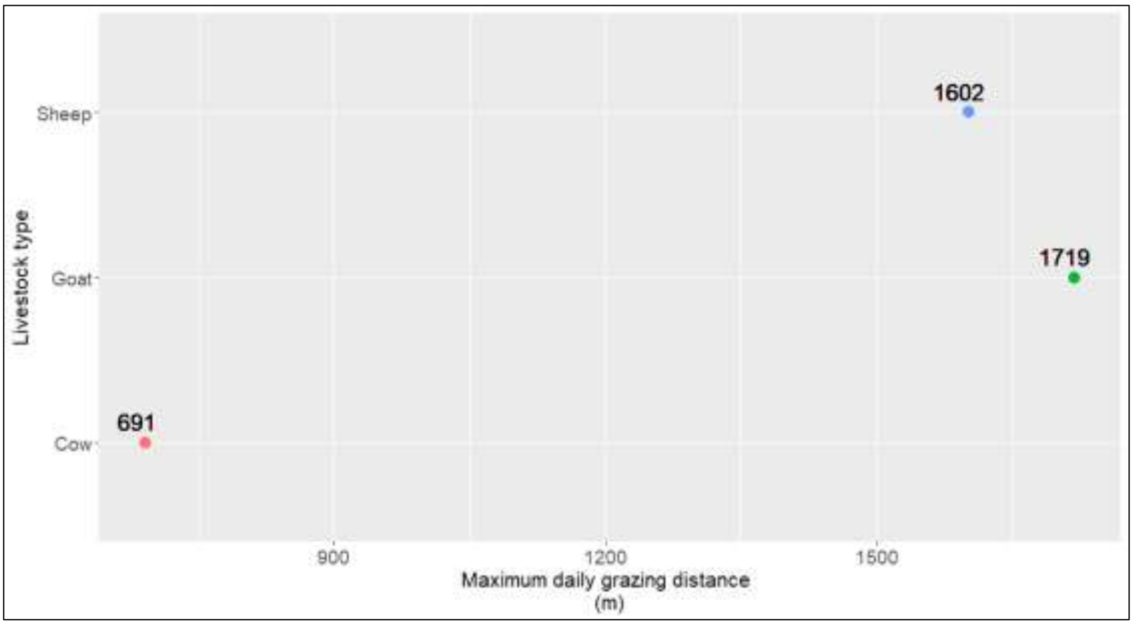
Table: Relationship between maximum daily grazing distance and livestock type

Chosen model: maxdist~ani_type

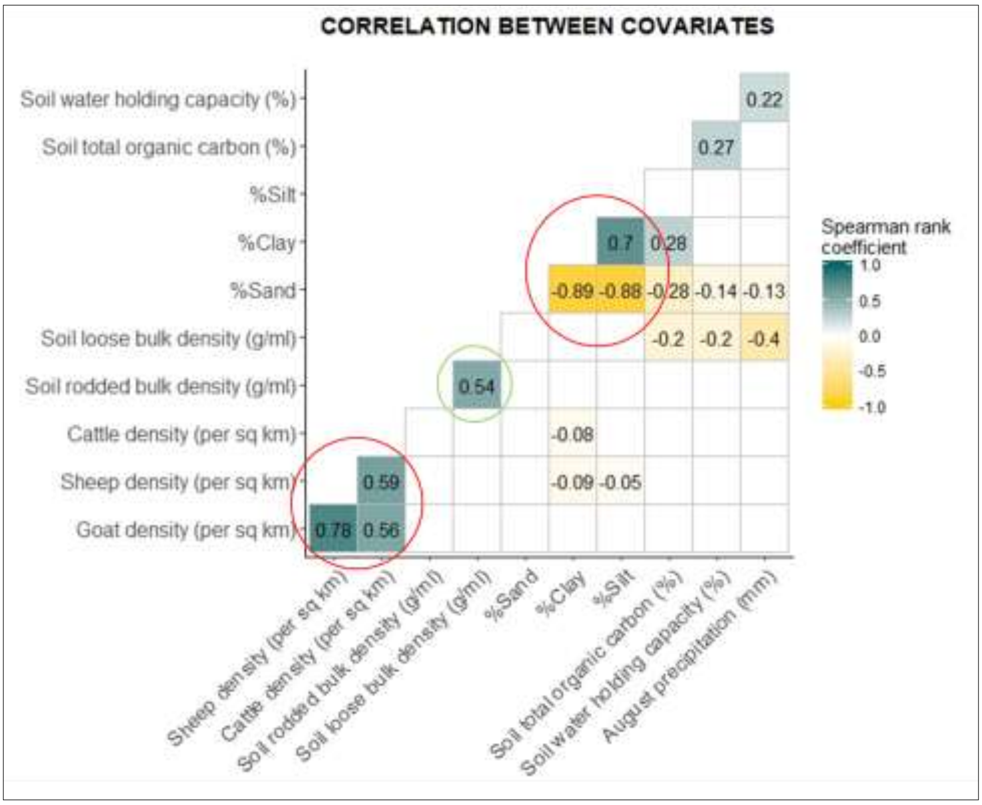
	Estimate	Std.Error	z value	Pr(>|z|)
(Intercept)	6.5388	0.1724	37.927	< 2e-16 ***
maxdist$ani_typeGoat	0.9105	0.2241	4.063	4.85e-05 ***
maxdist$ani_typeSheep	0.8400	0.2279	3.685	2.28e-04 ***

*****the intercepts are of the negative binomial link function (log) and are untransformed.

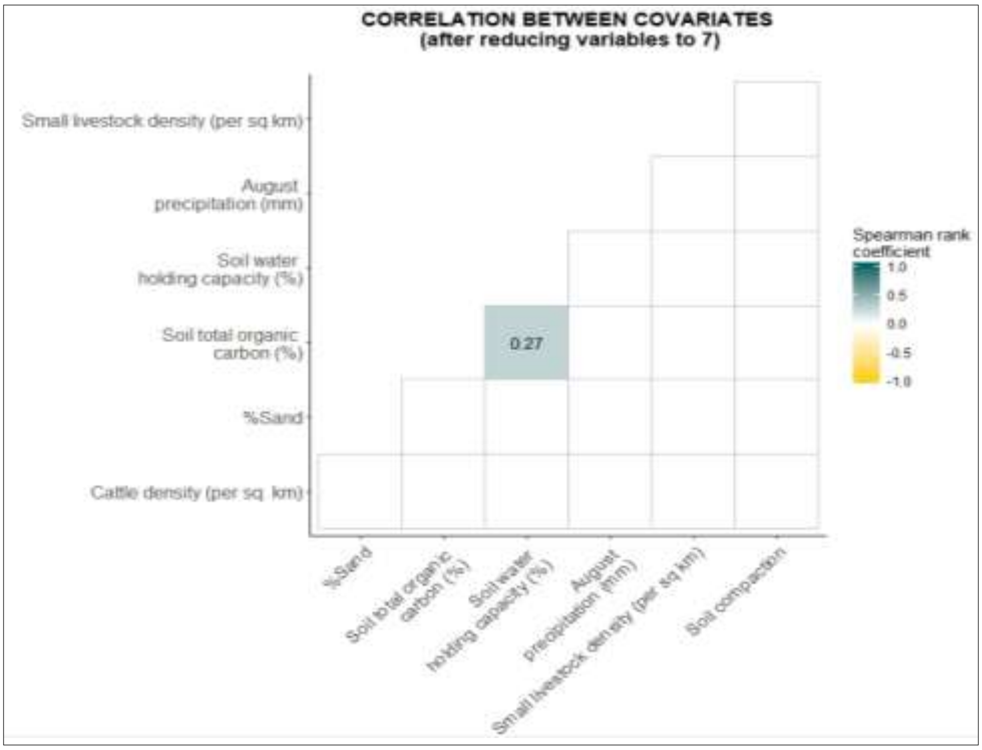
Fig : Predicted maximum daily grazing distance from chosen model



Annexure 2: Correlation of initial covariates before treatment



Annexure 3: Correlation of covariates after treating the autocorrelation and reducing to 7

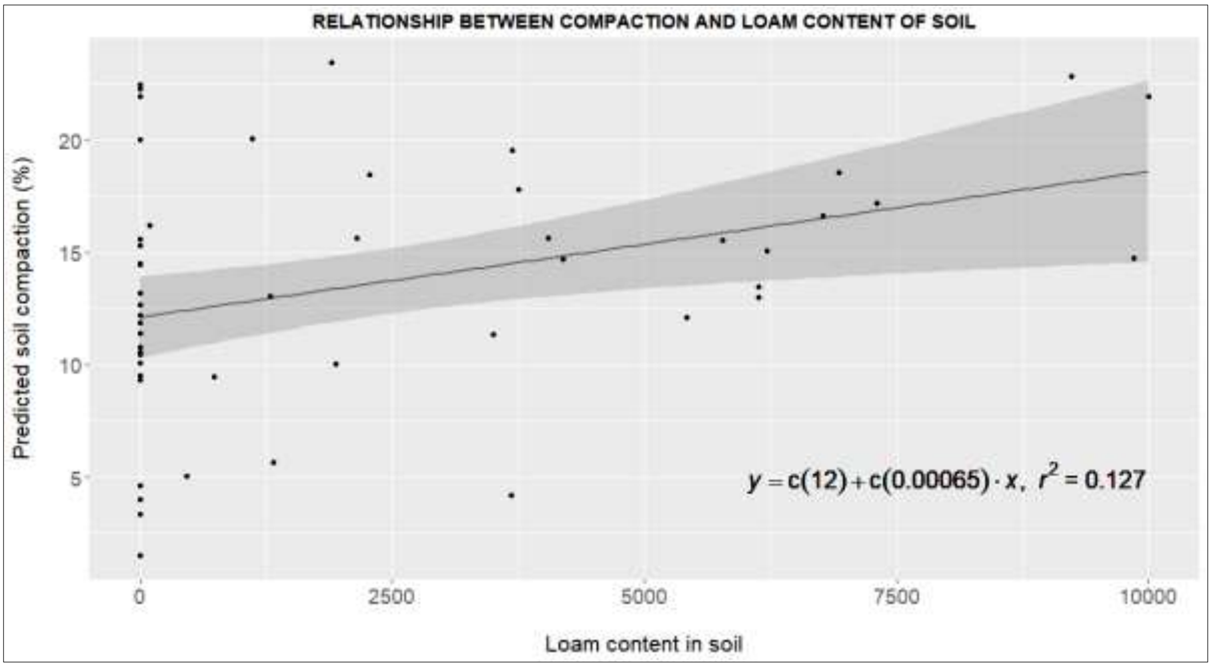


Annexure 4: Plant species recorded during the study

Scientific Name	**Family**	**Habit**
Calotropis procera (Aiton)	Apocynaceae (Asclepiadaceae)	Tree
Leptadenia pyrotechnica (Forssk.) Decne.	Apocynaceae (Asclepiadaceae)	Tree
Tecomella undulate (Sm.) Seem.	Bignoniaceae	Tree
Commiphora wightii (Arn.) Bhandari	Burseraceae	Tree
Capparis decidua (Forssk.) Edgew.	Capparidaceae	Tree
Seddera latifolia Hochst. & Steud.	Convulvulaceae	Tree
Euphorbia caducifolia Haines	Euphorbiaceae	Tree
Acacia Grey Stem	Fabaceae: Mimosoideae	Tree
UNID (Acacia red)	Fabaceae: Mimosoideae	Tree
Mimosa hamate Willd.	Fabaceae: Mimosoideae	Tree
Prosopis cineraria (L.) Druce	Fabaceae: Mimosoideae	Tree
Prosopis juliflora (Sw.) DC.	Fabaceae: Mimosoideae	Tree
Senegalia senegal (L.) Britton	Fabaceae: Mimosoideae	Tree
Vachellia eburnea (L.f.) P. Hurter & Mabb.	Fabaceae: Mimosoideae	Tree
Vachellia tortilis (Forssk.) Galasso & Banfi	Fabaceae: Mimosoideae	Tree
Calligonum polygonoides L.	Polygonaceae	Tree
Ziziphus nummularia (Burm. f.) Wight & Arn.	Rhamnaceae	Tree
Salvadora oleoides Decne.	Salvadoraceae	Tree
Maytenus sp. Molina	Solanaceae	Tree
Tamarix sp. L.	Tamaricaceae	Tree
Grewia tenax L.	Tiliaceae	Tree
Barleria sp. L.	Acanthaceae	Shrub
Aerva pseudotomentosa Blatt. & Hallb.	Amaranthaceae	Shrub
Haloxylon salicornium moq. Bunge ex Boiss (Rimth)	Amaranthaceae	Shrub
Heliotropium sp. L. (star flowered)	Boraginaceae	Shrub
Heliotropium sp. L. (yellow flowered)	Boraginaceae	Shrub
Dipterygium glaucum Decne.	Capparidaceae	Shrub
Crotalaria burhia Benth.	Fabaceae: Faboideae	Shrub
Indigofera cordifolia Roth	Fabaceae: Faboideae	Shrub
Tephrosia villosa (L.) Pers.	Fabaceae: Faboideae	Shrub
Fagonia cretica L.	Zygophyllaceae	Shrub
UID (Helio type)		Shrub
UID (Hygrophila)	Acanthaceae	Herb
UID (Star F)	Brassiacaceae	Herb
Citrullus colocynthis (L.) Schrad.	Cucurbitaceae	Herb
Chrozophora sp. A. Juss.	Euphorbiaceae	Herb
Euphorbia clarkiana Hook	Euphorbiaceae	Herb

Scientific Name	Family	Habit
Indigofera sp. L.	Fabaceae: Faboideae	Herb
UID (Purple stalk grass)	Poaceae	Herb
Tribulus sp. L. (red)	Xygophyllaceae	Herb
Tribulus terrestris L.	Zygophyllaceae	Herb
UID (2 leaved)		Herb
UID (3 leaved)		Herb
UID (Bagri)		Herb
UID (Champri)		Herb
UID (Dhakle)		Herb
UID (Purple underneath)		Herb
UID (Silver stem)		Herb
UID (Wrinkled)		Herb
UID (Unidentified shrub)		Herb
UID (phone)		Herb
UID (white flower)		Herb
UID (small pink flowers)		Herb
Aristida sp. L.	Poaceae	Grass
Broom Grass (Eleucine type)	Poaceae	Grass
Cenchrus biflorus Roxb.	Poaceae	Grass
Cenchrus sp. L.	Poaceae	Grass
Dactylotenium scindicum Boiss.	Poaceae	Grass
Eleucine type	Poaceae	Grass
Lasiurus sindicus Henr.	Poaceae	Grass
Panicum turgidum Forssk.	Poaceae	Grass

Annexure 5: Predicting soil compaction from sand and loam content of soil texture map available from NRSC



Correlation between actual compaction and predicted using loam content: 0.36

Model selection for relationship between soil compaction using soil texture and precipitation available from remote sensed data

Table: Top 8 models with the lowest AIC tested for soil compaction

Model	df	AIC	Δ AIC	Loglik
Comp ~ Loam_content	3	316.1489	0	-155.0744
Comp ~ Loam_content+Aug_prec	5	318.4705	1.81	-154.8005
Comp ~ Sand_content	3	318.5613	1.90	-156.0253
Comp ~ Sand_content+Loam_content	4	318.7499	2.09	-154.9402
Comp ~ Sand_content +Aug_prec	4	319.6496	2.99	-155.3900
Comp ~ Sand_content + Loam_content +Aug_prec	5	320.6063	3.95	-154.6365
Comp ~ 1	2	321.3240	4.66	-158.5370
Comp ~ Aug_prec	3	321.4335	4.77	-157.4614

*chosen model is highlighted. Abbreviations used in the models: Comp – soil compaction, Aug_prec – precipitation, Sand_content – Sand content in soil from remote sensed soil texture data (NRSC), Loam_content – Loam content in soil from remote sensed soil texture data (NRSC),

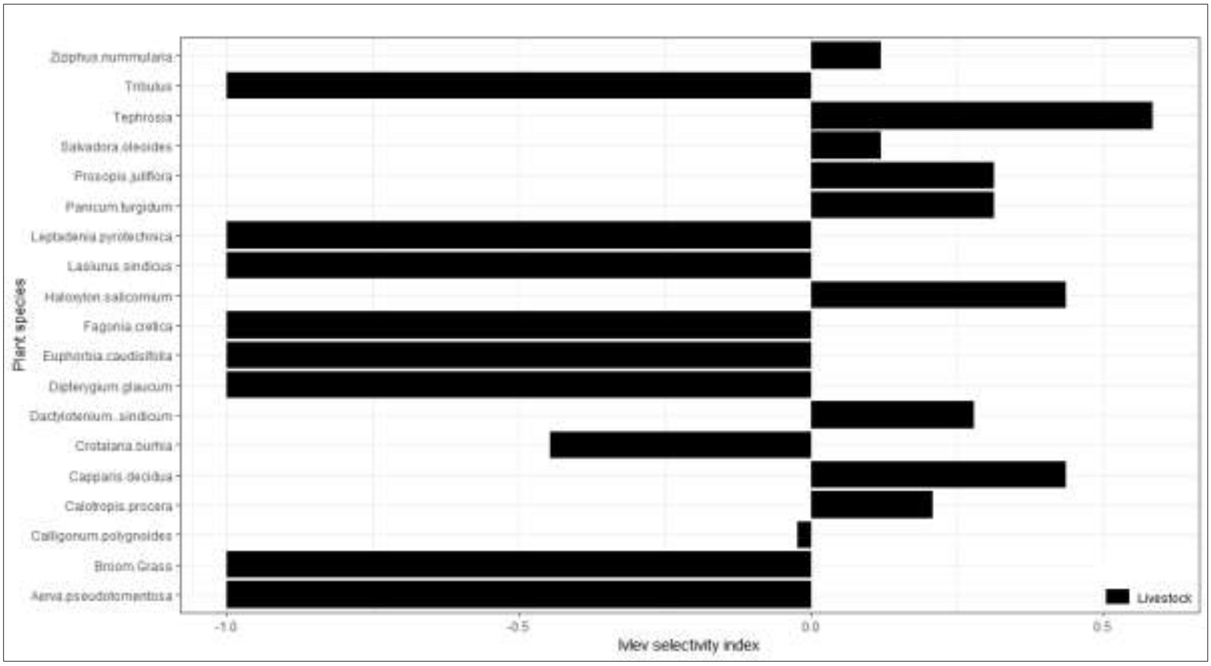
Table: Relationship between soil compaction and loam content in soil

Chosen model:

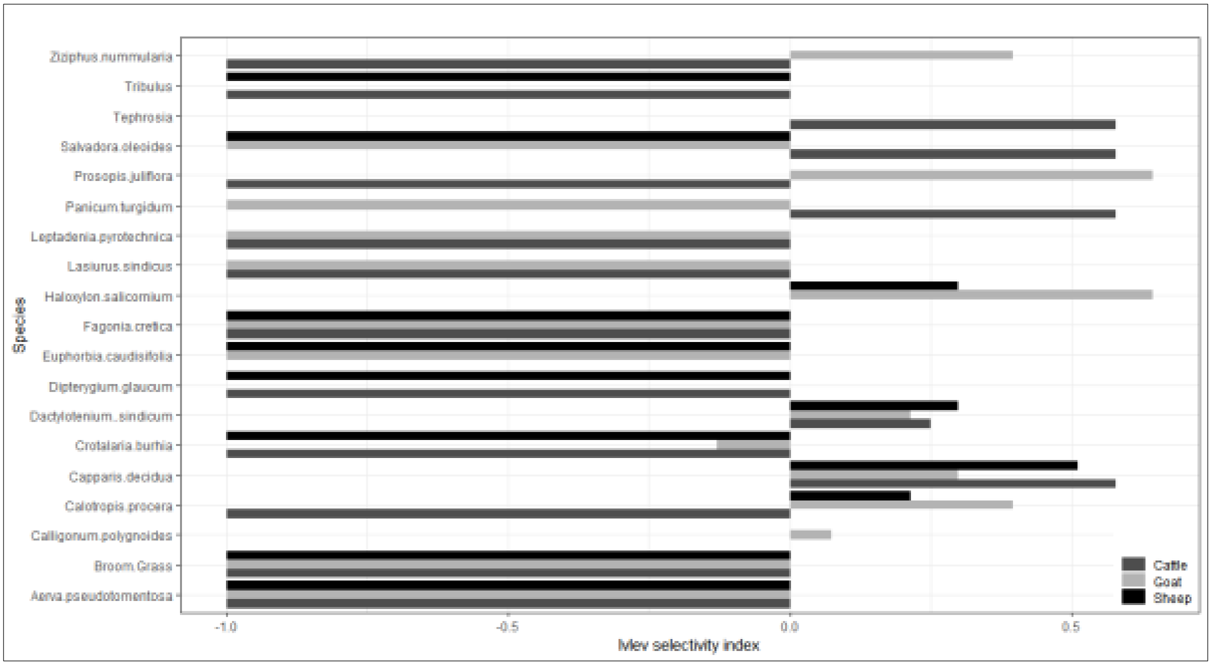
	Estimate	**Std.Error**	**t value**	**Pr(>|t|)**
Intercept	1.214e+01	9.095e-01	13.34	<2e-16 ***
Loam_content	6.481e-04	2.428e-04	2.67	0.0103 *

Adjusted *R*-squared: 0.1092; p-value: 0.01027

Annexure 6: Ivlev selectivity index for all livestock



Annexure 7: Ivlev selectivity index for every livestock type



Supplementary S1: Two factorial clustering of grid centroids by soil texture-precipitation

i) Extracting soil texture values for grids:

Three soil maps, one of sand, loam and clay were available at Rajasthan NRSC website. The raster maps had different ranges (sand ranging 0 to 4090, loam 0 to 9840 and clay 0 to 9750). We extracted values for each of the grid centroids from the three maps using QGIS. We then standardized the three values to range between 0 and 10000 each. The intensive study area had no gradient in clay and hence was excluded from this procedure. Since sand and loam are theoretically mutually exclusive, the total for standardized sand and loam should amount to 10000. However, there were some grids that didn't add up to 10000, possibly due to presence of other unmapped texture such as gravel or rocks. This led to a third soil texture component named 'unknown'. Then, we split the three values into classes of 1000 each leading to 10 classes for sand, loam and unknown each. The 3186 grids were then clustered based on the combination of classes the centroid yielded eg. One of the clusters is Class1 Class8 Class1 (i.e. sand index ranging from 0 to 1000, loam ranging from 7000 to 8000 and unknown ranging from 0 to 1000 for a particular centroid). This resulted in 36 unique soil texture clusters in the intensive study area among the 1000 possible permutations (Table s1).

Table s1: Frequencies of the unique soil texture clusters in the intensive study area

	Soil texture clusters	**Frequency**
1	Class1 Class1 Class10	48
2	Class1 Class10 Class1	2240
3	Class1 Class2 Class9	9
4	Class1 Class4 Class7	5
5	Class1 Class5 Class6	14
6	Class1 Class6 Class5	4
7	Class1 Class7 Class3	4
8	Class1 Class7 Class4	1
9	Class1 Class8 Class3	5
10	Class1 Class9 Class1	3
11	Class1 Class9 Class2	24
12	Class10 Class1 Class1	206
13	Class2 Class1 Class9	7
14	Class2 Class8 Class1	12
15	Class2 Class9 Class1	24
16	Class3 Class1 Class7	3
17	Class3 Class1 Class8	36

18	Class3 Class3 Class6	14
19	Class3 Class8 Class1	62
20	Class4 Class1 Class7	26
21	Class4 Class6 Class1	23
22	Class4 Class7 Class1	50
23	Class5 Class1 Class6	35
24	Class5 Class6 Class1	25
25	Class6 Class3 Class2	3
26	Class6 Class5 Class1	45
27	Class7 Class1 Class4	9
28	Class7 Class3 Class1	6
29	Class7 Class3 Class2	12
30	Class7 Class4 Class1	46
31	Class8 Class1 Class3	73
32	Class8 Class2 Class1	3
33	Class8 Class3 Class1	41
34	Class9 Class1 Class1	9
35	Class9 Class1 Class2	26
36	Class9 Class2 Class1	33
	Total	**3186**

*Classes are in the order of sand, loam and clay.

ii) Extracting precipitation values for grids:

Month wise precipitation data was available at WorldClim at 2.5 sq km resolution. We extracted August month precipitation data (being maximum) for the grid centroids. The grids were then classed into three classes of 20 mm intervals, namely 0-40, 40-60, 60-80 (Fig. s1).

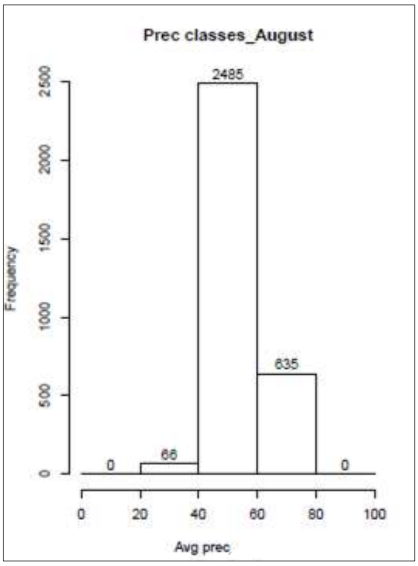


Fig. s1: Histogram of the precipitation classes in the intensive study area

iii) Obtaining soil texture-precipitation clusters:

We performed a two factorial clustering of the grids using the soil texture and precipitation clusters. For this, we classified the grids belonging to the 36 unique clusters obtained in (i), further by the precipitation clusters obtained in (ii). This resulted in 53 unique soil texture-precipitation clusters in the intensive study area. eg. Class1 Class10 Class1 prec(0-40), Class1 Class10 Class1 prec(40-60). The frequencies of the 3186 cells belonging to the different soil texture-precipitation clusters in the intensive study area are given in (Table s2). We then selected a proportionate sample of the grids as sampling units keeping required sampling units as 75 and minimum per class as one. Apart from this, three more grids were selected from a new sub-block to get enough sample size for the 0-40 precipitation gradient (smaller sub-block in Fig. 1(c)).

Table s2: Frequencies of the unique soil texture-precipitation clusters in the intensive study area and the number of sampling units selected per cluster

	Soil texture-precipitation clusters	**Frequency**	**Selected no. of samples**
1	Class1 Class1 Class10 prec(40-60)	48	2
2	Class1 Class10 Class1 prec(0-40)	11	1
3	Class1 Class10 Class1 prec(40-60)	1808	16
4	Class1 Class10 Class1 prec(60-80)	421	4
5	Class1 Class2 Class9 prec(0-40)	9	1
6	Class1 Class4 Class7 prec(40-60)	5	1
7	Class1 Class5 Class6 prec(40-60)	14	1
8	Class1 Class6 Class5 prec(40-60)	4	1
9	Class1 Class7 Class3 prec(40-60)	4	1
10	Class1 Class7 Class4 prec(60-80)	1	1
11	Class1 Class8 Class3 prec(40-60)	5	1
12	Class1 Class9 Class1 prec(40-60)	3	1
13	Class1 Class9 Class2 prec(0-40)	10	1
14	Class1 Class9 Class2 prec(40-60)	2	1
15	Class1 Class9 Class2 prec(60-80)	12	1
16	Class10 Class1 Class1 prec(0-40)	14	1
17	Class10 Class1 Class1 prec(40-60)	106	2
18	Class10 Class1 Class1 prec(60-80)	86	2
19	Class2 Class1 Class9 prec(40-60)	7	1
20	Class2 Class8 Class1 prec(40-60)	1	1
21	Class2 Class8 Class1 prec(60-80)	11	1
22	Class2 Class9 Class1 prec(0-40)	2	1
23	Class2 Class9 Class1 prec(40-60)	12	1
24	Class2 Class9 Class1 prec(60-80)	10	1
25	Class3 Class1 Class7 prec(40-60)	3	1
26	Class3 Class1 Class8 prec(40-60)	36	1

27	Class3 Class3 Class6 prec(0-40)	14	1
28	Class3 Class8 Class1 prec(0-40)	3	1
29	Class3 Class8 Class1 prec(40-60)	45	1
30	Class3 Class8 Class1 prec(60-80)	14	1
31	Class4 Class1 Class7 prec(40-60)	26	1
32	Class4 Class6 Class1 prec(40-60)	18	1
33	Class4 Class6 Class1 prec(60-80)	5	1
34	Class4 Class7 Class1 prec(40-60)	36	1
35	Class4 Class7 Class1 prec(60-80)	14	1
36	Class5 Class1 Class6 prec(40-60)	35	1
37	Class5 Class6 Class1 prec(40-60)	25	1
38	Class6 Class3 Class2 prec(40-60)	3	1
39	Class6 Class5 Class1 prec(40-60)	27	1
40	Class6 Class5 Class1 prec(60-80)	18	1
41	Class7 Class1 Class4 prec(40-60)	9	1
42	Class7 Class3 Class1 prec(40-60)	6	1
43	Class7 Class3 Class2 prec(40-60)	12	1
44	Class7 Class4 Class1 prec(40-60)	37	1
45	Class7 Class4 Class1 prec(60-80)	9	1
46	Class8 Class1 Class3 prec(40-60)	73	2
47	Class8 Class2 Class1 prec(0-40)	3	1
48	Class8 Class3 Class1 prec(40-60)	40	1
49	Class8 Class3 Class1 prec(60-80)	1	1
50	Class9 Class1 Class1 prec(60-80)	9	1
51	Class9 Class1 Class2 prec(40-60)	26	1
52	Class9 Class2 Class1 prec(40-60)	9	1
53	Class9 Class2 Class1 prec(60-80)	24	1

*Classes are in the order of sand, loam and clay.

Supplementary S2: Sampling design adopted for vegetation sampling