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RESEARCH ARTICLE

# Impacts of soil qualities and *Prosopis juliflora* on density, canopy volume and community position of *Leptadenia pyrotechnica* in Arid regions of India

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## Abstract

In the present study, we explored how the combination of site soil qualities and invasion by *Prosopis juliflora* affects the species specific (*Leptadenia pyrotechnica*) morphological (canopy volume) and population traits (density and Relative Importance Value) in an arid region of the India. For this, we surveyed 9 sites, categorized under two scenarios sites (n = 5) invaded by *P. juliflora* (Scenario 1), and sites (n = 4) un-invaded with *P. juliflora* (Scenario 2). With respect to sites, density of both these species exhibited reverse trends to each other. Similar trends were also recorded for canopy volume and cover of *L. pyrotechnica* and *P. juliflora*, respectively. We found log-normal distribution types at all the studied sites. In our empirical study, fifteen Relative Importance Value (RIV) of *P. juliflora* was identified as threshold level beyond which it can drastically reduced the community diversity and niche space of various associates. Further, Relative Severity of Competition (RSC for density, canopy volume and cover) suggested that density (RSC 0.24) and canopy volume (RSC 0.20) of *L. pyrotechnica* suffered most due to invasion of *P. juliflora*. Partial Least Square (PLS), regression suggested that density of *L. pyrotechnica* and *P. juliflora* are orthogonal to each other indicated significant negative relationships between both of them ($r^2 = -0.95$). Soil potassium and organic carbon are located close to density of *L. pyrotechnica* that is both these two variables have positive impacts with density ($r^2 = 0.95$). Similar positive relationships also observed between canopy volume and clay content ($r^2 = 0.95$), while, sand content was orthogonal to this parameter ($r^2 = -0.95$). Present study suggested how the invasive *P. juliflora* along with certain soil factors controls the population, morphological and community position attributes of *L. pyrotechnica*.

**Keywords** Canopy volume · Density · Indian Arid region · Invasion ecology · *Leptadenia pyrotechnica* · Partial least square regression · *Prosopis juliflora* · Relative severity of competition

## Introduction

Alien invasive species have been shown to affect plant and animal communities (Schirmel et al. 2015; Rai and Singh 2020), ecosystem functioning (Pejchar and Mooney 2009; Linders et al. 2019), soil qualities and nutrient fluxes (Dassonville et al. 2008; Lee et al. 2016) in the sites they invade. Not surprisingly, the documented impacts of plant invasion on soil qualities are diverse. While most published studies reports increased soil nutrient stock and/or availability under invasive plant species compared to un-invaded ecosystems (Ye et al. 2019; Teixeira et al. 2020), other studies show the opposite pattern (Si et al. 2013; Baranova et al. 2017). *Prosopis juliflora* among the most invasive species in hot semi-arid and arid regions of the world including Saharan and southern Africa, the Middle East, Pakistan and India (Kumar and Mathur 2012; Castillo et al. 2021) where it appears to strongly suppress species native to those regions. *Prosopis juliflora* forms pure stands in its invaded range in India, and occurs in forests, wastelands and at the boundaries of crop fields (Kaur et al. 2012).

Pandey et al. (2019) reported the effects of four canopy sizes (i.e. small, medium, large and no-canopy/open plot), of *P. juliflora* shrub on native vegetation and soil fertility (0–20 cm depth) in the community grazing lands distributed in Jodhpur, Pali, and Sirohi districts in the Indian hot desert.

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Their study suggested that the soil organic carbon (SOC), total N, and available P and K concentrations were higher under all canopy sizes than in the open plots. However, these parameters were the highest under the large and lowest under small canopy size; and the parameters were positively correlated with the canopy size ($p < 0.5$ to $p < 0.01$). Unlike the SOC and total N content, C/N ratio was lower under all canopy sizes than in the open plot; and it was the lowest under the large and highest under small canopy size classes. Composition of native plant species changed and their richness and diversity declined under the canopy, but was higher under the larger canopy size. Only two annual grasses (i.e. *Brachiaria* spp. Griseb. and *Tetrapogon tenellus* (Roxb.Chiov) registered their presence under the large canopy shrub class. Almost all perennial and annual forbs were present under the small canopy shrub class.

*Leptadenia pyrotechnica* (Forssk.) Decne member of Asclepiadaceae an erect much branched leafless shrub, generally 0.6–2.5 m tall. Root system reported to penetrate to a depth of 11.5 m and has a lateral extension of 10 m, exploiting about 850 $m^3$ of soil (Sadeq et al. 2014) and reported to improve soil calcium and phosphorus concentration (Karim et al. 2009). As a xerophytes, *L. pyrotechnica* is well adapted to grow in extremely severe climatic conditions (− 0.4 to 49.5 °C) of tropical and sub-tropical arid regions of the world. The strong soil binding property of this species, due to its extensive and long root system, makes the species as a prime choice in sand dune fixation and desert afforestation programs (Sharma and Chouhan 2008; Mathur and Sundaramoorthy 2018). Beside its regulatory services, this species also serving many provisional (medicinal) and cultural services (Mathur and Sundaramoorthy 2013a). Apart from all these uses, it also serves as good quality fodder (Karakilcik and Kalyar 2014) provides protein, dietary fiber, calcium, phosphorus, iron and vitamin C (Goyal and Sharma 2009). In Indian desert it is browsed to some extent by all stock, but especially by camels (Ram 2016).

Phyto-sociological studies to this species were conducted earlier from hyper arid biosphere reserve area in north Africa (Shaltout et al. 2010), Wadi Gimal, Red sea coast region of Egypt (Galal 2011), Algeria (Bouchneb and Benhouhou 2012), Indian hot arid region (Singh et al. 2012; Mathur and Sundarmoorthy 2013b; Mathur et al. 2020), Cholistan desert of Pakistan (Nisar et al. 2013) and Jazan region of Suadi Arabia (Salman 2015). El-Amier et al. (2015) studied its relationships with soil qualities like water holding capacity, electric conductivity and chlorides in the Egyptian desert. Ebad et al. (2011) had explored the metabolic adjustment strategies in this species during dry and wet conditions from the eastern desert of Egypt. Recently, Mathur and Sundaramoorthy (2019) provides its distribution and succession trends at various land forms and land uses of the arid and semi-arid regions of the Thar desert. On Sandy undulating buried pediments *Haloxylon salicornicum, Ziziphus nummularia, Lasiurus sindicus*, and *Panicum antidotale* are its major associates. While at sandy plain its mainly associate with *Crotalaria burhia*. While Mathur and Sundarmoorthy (2013b) described its temporal association types with various herbaceous components, and recently, Mathur et al. (2020) reported spatial distribution of this species from 12 arid sites and the patterns with soil and plant community composition.

Despite of its many phyto-sociological observations, there is very little information on interactive impacts of site soil qualities and invasion of *P. juliflora* on *L. pyrotechnica* in arid desert of the India. In the present study we explored how the combination of site soil qualities and invasion by *P. juliflora* affects the species specific (*Leptadenia pyrotechnica*) morphological and population traits in arid region of the India. The specific objectives of the present study were to assess the (a) site soil qualities (soil structure, soil electric conductivity, pH, organic carbon, phosphorus and potassium). Importance of these soil parameters as site quality factor was recommended by Mathur and Sundaramoorthy (2019). They suggested the use of these parameters to appraise the land degradation studies at various geographical regions, and (b) invasion of *P. juliflora* (with measurement of its density, canopy cover and RIV) on canopy volume, density/ha and community position of *L. pyrotechnica*. Based on the previous studies, we hypothesized specific population threshold of *P. juliflora* is required to alter the specific traits of *L. pyrotechnica.*

## Materials and methods

### Site and vegetation sampling

A survey was conducted (during 2017–2018) at different areas of Barmer, Jodhpur (arid western plain) and Pali (transitional Plain of the Luni River Basin) districts of Rajasthan, India. We surveyed 9 sites, (Fig. 1; Tables 1 and 2) categorized under two scenarios; Sites ($n = 5$) invaded by *P. juliflora* (Scenario 1 hereafter refer as S1 and more specifically we can assigned them as those sites that having both *Prosopis juliflora* and *Leptadenia pyrotechnica*), and sites ($n = 4$) un-invaded with *P. juliflora* (Scenario 2 hereafter refer as S2 i.e. having pure population of *L. pyrotechnica* i.e. absence of *P. juliflora*). Locations of studied sites were plotted with their respective latitudes and longitudes with the help of SAM software (Rangel et al. 2010). The authenticity of the *L. pyrotechnica* were cross checked with the flora of the India arid region (Bhandari 1978) as well as with the herbarium sheets available at Plant Ecology Section of ICAR-Central Arid Zone Research Institute, Jodhpur, India. To study the population dynamics of this species, 10

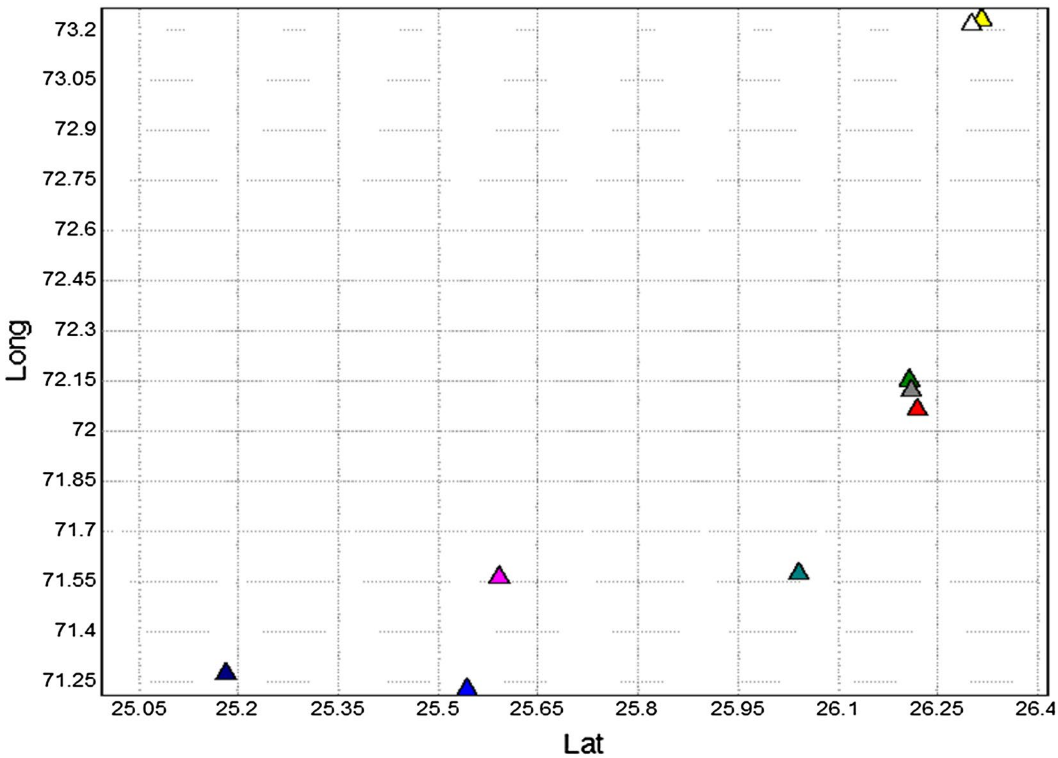


**Fig. 1** Locations of the studied sites plotted according to their Latitudes and Longitudes with the help of SAM software

**Table 1** Site locations, soil, community and species parameters studied (sceneario-1 sites with invasion of *P. juliflora*), Rajasthan India

| Sites | Site 1 | Site 2 | Site 3 | Site 4 | Site 5 | |
|---|---|---|---|---|---|---|
| Geo reference of the study sites | 26° 22′ 1.9″<br>72° 07′ 57.8″ | 26°20′ 7.6″<br>72°16′ 40.9″ | 26° 31′ 54.5″<br>73° 24′ 31.6″ | 25° 54′ 27.8″<br>71° 23′ 35.2″ | 26°30′ 47.5″<br>73°22′ 31.2″ | Mean |
| Sand (%) | 92.8 | 90.7 | 90 | 92.2 | 86 | 90.3 |
| Silt (%) | 2.7 | 4.5 | 4.5 | 3.7 | 4 | 3.88 |
| Clay (%) | 4.5 | 4.8 | 5.5 | 4.1 | 10 | 5.78 |
| Soil pH | 8.68 | 8.65 | 8.63 | 8.86 | 8.72 | 8.70 |
| Soil EC ($dSm^{-1}$) | 0.06 | 0.13 | 0.06 | 0.40 | 0.08 | 0.14 |
| Soil Organic Carbon (%) | 0.05 | 0.08 | 0.01 | 0.12 | 0.10 | 0.07 |
| Soil Phosphorus (kg/ha) | 5.2 | 5.2 | 2.5 | 11.5 | 3.25 | 5.53 |
| Soil Potassium (kg/ha) | 140 | 182 | 80 | 260 | 212 | 174 |
| Species Richness (no) | 7 | 6 | 8 | 7 | 5 | 6.6 |
| Simpson index | 0.36 | 0.25 | 0.21 | 0.18 | 0.29 | 0.25 |
| Shannon—Wiener index | 1.39 | 1.5 | 1.76 | 1.76 | 1.37 | 1.55 |
| Evenness | 0.58 | 0.82 | 0.75 | 0.89 | 0.81 | 0.77 |
| Density of *L. pyrotechnica* (plant/ha) | 20 | 75 | 10 | 150 | 130 | 77 |
| Canopy volume of *L. pyrotechnica* (Sq m) | 0.51 | 0.38 | 1.66 | 0.41 | 3.06 | 1.20 |
| RIV of *L. pyrotechnica* | 6 | 8.2 | 7.41 | 23.05 | 26.28 | 14.1 |
| Density of *P. juliflora* (Plant/ha) | 80 | 65 | 90 | 50 | 40 | 65 |
| Cover of *P. juliflora* (Sq. m) | 5.32 | 9.86 | 7.74 | 4.21 | 9.2 | 7.26 |
| RIV of *P. juliflora* | 4.32 | 14.02 | 9.4 | 9.69 | 12.37 | 9.96 |

Site 1 = Chaba (Jodhpur); Site 2 = Shergargh (Jodhpur); Site 3 = Jhalamandia (Bhopalgarh); Site 4 = Kapoordi (Barmer) and Site 5 = Nandiya (Bhopalgarh); EC = Electrical Conductivity; RIV = Relative Importance Values index

**Table 2** Site locations, soil, community and species parameters studied (sceneario-2 sites without invasion of *P. juliflora*)

| Sites | Site 1 | Site 2 | Site 3 | Site 4 | |
|---|---|---|---|---|---|
| Geo reference of the study sites | 26° 21′ 3.7″<br>72° 13′ 4.5″ | 25° 59′ 44.7″<br>71° 57′ 12.2″ | 26° 04′ 24.9″<br>71° 58′ 26″ | 25° 18′ 19.5″<br>71° 28′ 37.1″ | Mean |
| Sand (%) | 90.5 | 91.5 | 91.7 | 92.8 | 91.62 |
| Silt (%) | 3.6 | 3.2 | 3.3 | 2.2 | 3.07 |
| Clay (%) | 5.9 | 5.3 | 5 | 5 | 5.3 |
| Soil pH | 8.60 | 8.82 | 8.80 | 9.12 | 8.83 |
| Soil EC ($dSm^{-1}$) | 0.07 | 0.10 | 0.10 | 0.22 | 0.12 |
| Soil organic carbon (%) | 0.06 | 0.06 | 0.04 | 0.05 | 0.05 |
| Soil phosphorus (kg/ha) | 5.70 | 3.70 | 3.80 | 17.50 | 7.67 |
| Soil potassium (kg/ha) | 135.00 | 161.00 | 132.00 | 153.00 | 145.2 |
| Species richness (no.) | 5.00 | 7.00 | 8.00 | 10.00 | 7.5 |
| Simpson index | 0.32 | 0.27 | 0.31 | 0.34 | 0.31 |
| Shannon–Wiener index | 1.28 | 1.41 | 1.34 | 1.87 | 1.47 |
| Evenness | 0.80 | 0.95 | 0.89 | 0.60 | 0.81 |
| Density of *L. pyrotechnica* (plant/ha) | 30.00 | 330.00 | 150.00 | 30.00 | 135 |
| Canopy volume of *L. pyrotechnica* (Sq m) | 0.34 | 2.99 | 1.75 | 2.56 | 1.91 |
| RIV of *L. pyrotechnica* | 9.2 | 20.38 | 21.09 | 4.58 | 13.81 |

Site 1 = Guman Singh (Jodhpur); Site 2 = Jhund (Barmer); Site 3 = Chainpura (Barmer) Site 4 = Pooniyo ka bas (Barmer); EC = Electrical Conductivity; RIV = Relative Importance Values index

quadrats (10 × 10 m) were laid down at each site (Kent and Coker 1992). Ecological attributes like density, frequency, and abundance and Relative Importance Values index were quantified by using following formulas (Curtis and McIntosh 1950; Uddin et al 2020).

$$\textit{Density of a species} = \frac{\textit{Total number of a species in all the quadrats}}{\textit{Total number ofquadrats studied}}$$

$$\textit{Relative Importance Value of a species} = \frac{(\textit{Relative Density} + \textit{Relative Frequency} + \textit{Relative Abundance})}{3}$$

Quantification and interpretation of other community parameters (woody perennial richness, Shannon–Wiener index, Simpson index of dominance and evenness) were carried out by using standard methodology (Ludwig and Reynolds 1988). Canopy volume was quantified with using

$$\textit{Frequency of a species} = \frac{\textit{Total number the quadrats in which the species occured}}{\textit{Total number of quadrats studied}}$$

$$\textit{Abundance of a species} = \frac{\textit{Total number of individuals of a species in all the quadrats}}{\textit{Total number of quadrats in which the species occured}}$$

$$\textit{Relative Density of a species} = \frac{\textit{Density of a species}}{\textit{Densities of the all studied species}} \times 100$$

$$\textit{Relative Frequency of a species} = \frac{\textit{Frquency of a species}}{\textit{Frequencies of all the studied species}} \times 100$$

$$\textit{Relative Abundance of a species} = \frac{\textit{Abundance of a species}}{\textit{Total abundance of all the species}} \times 100$$

upper half spheroid geometric equations and expressed as 4/3 Π $r^2 \times h$ (Ludwig et al. 1974) where *r* and *h* denotes radius and height of the shrub, respectively. Dominance-diversity curves have been previously constructed for a range of ecosystems around the world to illustrate the dominance of particular species and show how their relative abundances compare between communities separated in time or space (Grant and Longeragan 2003). In this study, Dominance-diversity curves were constructed by ranking the log of the species RIV values from highest to lowest (Sinha et al. 1988) plotted with the help of Microsoft Excel. This was constructed for both types of studied sites (i.e. S1 and S2). With reference to *P. juliflora,* Relative Severity of Competition (RSC) for the attributes of *L. pyrotechnica* like density, canopy volume and RIV were quantified with using following formula (Snaydon 1991; Weigelt and Jolliffe 2003)

$$\text{RSC} = \text{Log}_{10}\left(\frac{\text{Attribute of } L.\,pyrotechnica_{\text{without } P.\,juliflora}}{\text{Attribute of L. pyrotechnica}_{\text{with } P.\,juliflora}}\right)$$

## Soil analysis

Soil samples from 0 to 30 cm depth were collected from all the studied sites. The collected soil samples were air-dried and sieved with a 2 mm screen, and subjected to physical and chemical analyses following standard analytical procedures. The pH and electrical conductivity (dS $m^{-1}$) was determined in supernatant solution of 1:2 soil: water suspensions using pH meter and conductivity meter (Jackson 1973). Organic carbon was determined by rapid titration method (Walkley and Black 1934). Available phosphorus was extracted with 0.5 M $NaHCO_3$ solution (8.5 pH) and phosphorus in the extract was estimated colorimetrically (Olsen et al. 1954). Available potassium was determined by extraction of soil with neutral normal ammonium acetate (pH 7.0 in 1:5, soil: solution ratio) and available potassium was estimated with the help of flame photometer (Pratt 1982). Soil textural analysis was carried out by international pipette method (Piper 1966) using sodium-hexameta-phosphate as a dispersing agent. The textural class was determined using the USDA textural triangle.

### Statistical analysis

According to Maitra and Yan (2008) as well as Scott and Crone (2021) principal component analysis looks for a few linear combinations of the variables that can be used to summarize the data without losing too much information in the process. However, one drawback associated with this technique in its original form is that it arrives at Standardized Linear Combination (SLC) that capture only the characteristics of the X-vector or predictive variables. No importance is given to how each predictive variable may be related to the dependent or the target variable. In a way it is an unsupervised dimension reduction technique (i.e. summarize variation in the data, without regard to the response). However, when our key area of application is multivariate regression, there may be considerable improvement if we build SLCs of predictive variables to capture as much information in the raw predictive variables as well as in the relation between the predictive and target variables. Partial least square (PLS) allows us to achieve this balance and provide an alternate approach to PCA technique. Further, Mathur and Mathur (2020) and Scott and Crone (2021), specifically for ecological data-set elaborated that "Partial least squares have been very popular where predictive variables often consist of many different measurements in an experiment and the relationships between these variables are ill-understood". Mathur et al. (2021) further explained that PLS regression is particularly suited when the matrix of predictors has more variables than observations, and when there is multi-collinearity among *X* values. In this study we had have fifteen predictors thus, based on these explanations, we preferred PLS over the PCA to identify cause and affect relationships between predictors and depended variables.

In this study, two steps partial least square (PLS) regression was carried out to develop the model equations. In the first step, the significant predictors were identified with the concept of variable importance for the projection (VIPs) and under this any predictive variable with a VIP value greater than 1 was considered as a highly significant predictor (Onderka et al. 2012). Then the second step PLS was conducted with significant variables (X) only, and the results were interpreted through model qualities, bi-plot relationships between exploratory (X) and dependent factors (Y) and finally model equations for different dependent variables (density, canopy volume and RIV of *L. pyrotechnica*) were developed.

## Results

The present study was conducted during 2017–2018 at three arid regions. During that period the onset of monsoon rains was late (14th July; CAZRI, 2018). Districts like Jalore, Pali and Barmer received heavy rains. Weather remained dry since 18th September and monsoon withdrew from arid parts during 27–30 September. Highest maximum temperature ranged from 45 °C (Pali) to 47 °C (Chandan, Jaisalmer), while lowest recorded minimum temperature varied from 4.5 °C (Jodhpur) to − 3.5 °C (Jaisalmer). The locations of the studied sites are graphically depicted in Fig. 1. Attributes quantified in this study are depicted in Tables 1 and 2. Woody perennial species richness at invaded sites (S1: Table 1) ranged from 5 (at site five) to 8 (site three). While, at un-invaded sites (S2) richness was ranged from 5 to 10 (Table 2). Shannon–Wiener index that measure the species diversity of a community and its higher value represent higher diversity which normally approached 3 or more and rarely exceeded to 4.5 and lower value indicates the lower diversity. At S1, it was recorded 1.37 (site five) to 1.76 (at sites three and four). At S2 this diversity parameter was ranged from 1.28 to 1.87. Contrasting to species richness, evenness which pertains to relative abundance and distribution of the species, and in this study it was ranged from 0.58 to 0.89 and 0.60 to 0.95 at S1 and S2, respectively. Similarly, Simpson index of dominance was ranged from 0.18 to 0.36 (S1) and 0.27 and 0.34 (S2). Inter-scenario mean difference for these community parameters suggested that sites with invasion of *P. juliflora* are more diversified (Shannon–Wiener index 1.55) while evenness suggested the un-invaded sites have little bit more even communities (evenness 0.84) compared to invaded sites (0.77).

Different traits of *L. pyrotechnica* like density (plants/ha.), Canopy volume (Sq m), and Relative Importance Value (RIV) recorded with both type of scenarios are depicted in Tables 1 and 2. With respect to sites, density of *L. pyrotechnica* and *P. juliflora* showed reverse trends (S 1). Density (plants/ha.) of former one was recorded maximum (150 plants/ha) at site four and minimum (10) at site three. While, density of *P. juliflora* was recorded maximum (90) at site three and minimum (40) at site five. Similar trends were also recorded for canopy volume and cover of *L. pyrotechnica* and *P. juliflora,* respectively. Canopy volume was recorded highest (3.06 sq. m.) at site five and lowest (0.3 sq. m.) at site two, while the cover of *P. juliflora* was recorded highest (9.86 sq. m.) at site two and lowest (4.21 sq. m.) at site four. Relative Importance Value (RIV) of targeted species was recorded maximum (26.28) at site five and minimum (6) at site one, and for invaded species this was ranged from 4.32 (site one) to 14.02 (site two). At S2, both density and canopy volume of L. *pyrotechnica* were recorded higher (330 and 2.99, respectively) at site 2, while the RIV was recorded higher at site 3. Species specific impact of *P. juliflora* clearly visualized in term of density of and canopy volume of *L. pyrotechnica*. The mean values of both these parameters were recorded higher (135 plants/ha and 1.91 sq m) at un-invaded sites (S2) compared to invaded sites (77 plants/ha and 1.20 sq m). However, mean values of RIV of *L. pyrotechnica* at un-invaded sites showed little bit lesser (13.81) compared to invaded sites (14.1). DD curves of both types of studied site (with and without invasion of *P. juliflora*) are presented in Figs. 1 and 2, respectively. With respect to DD curves, we found log-normal distribution types at all the studied sites (Figs. 2, 3). In such type of model, occupation of niche space is basically governed by various interacting factors that influence the result of inter-specific competition, abundances governed by many independent factors and in such situation resource utilization characterized as multidimensional.

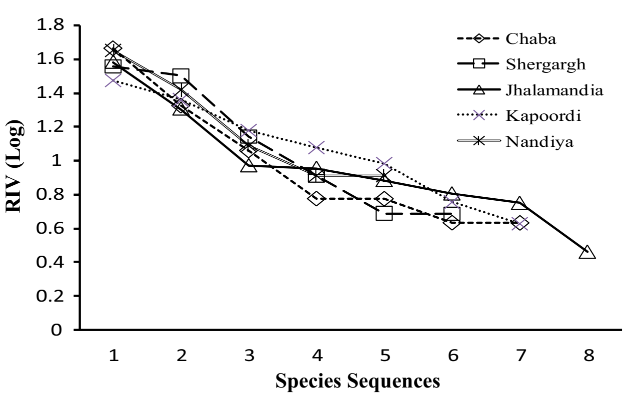


**Fig. 2** Dominance Diversity Curves (RIV Based) at studied sites invaded with *P. juliflora* (S1)

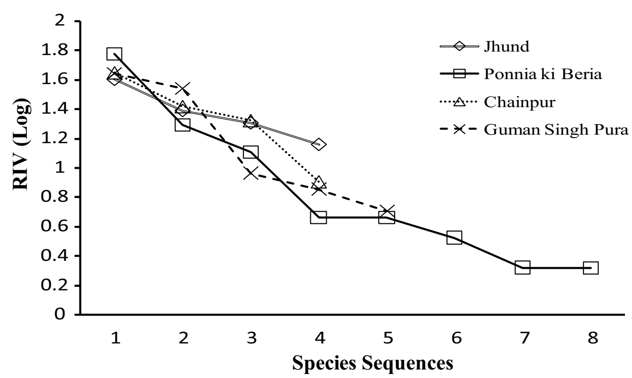


**Fig. 3** Dominance Diversity Curves (RIV Based) at studied sites without invasion of *P. juliflora* (S2)

**Table 3** Mean values of density (plant/ha), canopy volume (Sq m), RIV and relative severity competition index of these parameters of *L. pyrotechnica* naturally grown with and without *P. juliflora*

| Mean values | Density | Canopy volume | RIV |
|---|---|---|---|
| With *P. juliflora* (S1) | 77 ± 59 | 1.20 ± 1.09 | 14.18 ± 9.11 |
| Without *P. juliflora* (S2) | 135 ± 123.35 | 1.91 ± 1.07 | 13.85 ± 7.50 |
| Index of Relative severity of Competition | 0.24 | 0.2 | − 0.01 |

**Table 4** Variable importance in the projection (VIP) assessed with PLS 1

| Variable | F1 | F2 | F3 |
|---|---|---|---|
| Clay (%) | 0.92 | 1.29 | 1.31 |
| Density of *P. juliflora* (plant/ha) | 1.63 | 1.40 | 1.30 |
| Sand (%) | 0.88 | 1.25 | 1.21 |
| Soil potassium (kg/ha) | 1.45 | 1.28 | 1.19 |
| Soil organic carbon (%) | 1.46 | 1.27 | 1.19 |
| Soil pH (soil water suspension) | 1.27 | 1.13 | 1.16 |
| Species richness (number) | 1.06 | 0.97 | 0.99 |
| Evenness | 1.22 | 1.05 | 0.98 |
| Soil electric conductivity ($dSm^{-1}$) | 0.92 | 1.03 | 0.95 |
| Soil phosphorus (kg/ha) | 0.71 | 1.02 | 0.94 |
| RIV of *P. juliflora* | 0.78 | 0.69 | 1.01 |
| Cover of *P. juliflora* (Sq. m) | 0.03 | 0.52 | 1.01 |
| Shannon–Wiener index* | 0.05 | 0.32 | 0.50 |
| Silt (%)* | 0.18 | 0.29 | 0.47 |
| Simpson* | 0.50 | 0.47 | 0.45 |

*Parameters with less than one VIPs and these were removed in 2nd PLS

Mean values (along with their standard errors) of density, canopy volume and RIV of *L. pyrotechnica* naturally grows at different types of sites (S1 and S2) are provided in Table 3. Results revealed distinct impact of invasion on its density which was 135 without *P. juliflora* that decreased up-to 77 (plants/ha) with invasion. Canopy volume also showed this trend which were reduced from 1.91 to 1.20 (Sq. m) with invasion. However, RIV values not exhibit any significant difference which further confirmed the output of DD curves. Results of relative severity of competition (Table 3) for the above three attribute also suggested that density (RSC 0.24) and canopy volume (RSC 0.20) of *L. pyrotechnica* suffered most due to invasion of *P. juliflora*.

Soil analysis revealed the higher proportion of sand at the sites pertains to both types of scenarios. Comparison of the mean values of different studied soil parameters between Scenario 1 and 2 showed almost similar trends (Tables 1 and 2), except large difference was recorded for potassium and its mean value was 174 at S1 compared to 145.2 at S2.

Variable importance for the projection (VIPs) for each exploratory variable with PLS 1 are presented in Table 4. This method allowed us to identify which exploratory variable that contributed most to the model. Any independent variable with a VIP value greater than 1 was considered as a highly important predictor (Onderka et al. 2012). Among the studied parameters Shannon–Wiener index, Simpson index

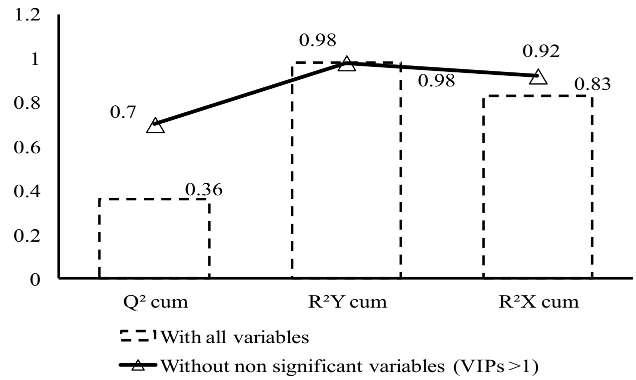


**Fig. 4** Model quality parameters of Partial Least Square (PLS) analysis suggesting removal of non-significant variables (attributes having VIP value < 1.0) improves the overall model quality

of dominance and soil silt content were identifies as non-significant variables (VIPs < 1.0). The quality of PLS analysis can be judge on the basis of three index, $Q^2$ cumulated index that measures the global goodness of fit (ideally it should be close to 1) and the values of cumulated $R^2Y$ (dependent score) and $R^2X$ (independent score). Our results suggested that the two steps PLS improves our model quality ($Q^2$) which was 0.36 (with all the variables) which is increased up-to 0.70 (Fig. 4) after elimination all non-significant variables (VIPs < 1.0). The similar patterns were also recorded for $R^2X$. Overall the cumulated $R^2Y$ and $R^2X$ corresponds to the correlation between the exploratory (X) and dependent (Y) variables with the component close to one with 3rd component generated by PLS ($2^{nd}$) summarized well both by $X_S$ (0.92) and the $Y_S$ (0.98) for the studied parameters (Fig. 4). PLS bi-plot revealed that cumulatively four axes together accounted 100% variability with their individual contribution accounts 49.98, 34.94, 9.5 and 5.5% variance, respectively. Their eigenvalue scores for axes one to four as follows: 7.49, 5.24, 1.42 and 0.83, respectively. The PLS bi-plot (Fig. 5) revealed that density of *L. pyrotechnica* and *P. juliflora* are orthogonal to each other that suggested the significant negative relationships between both of them ($r^2 = -0.95$). Soil potassium and organic carbon are located close to density of *L. pyrotechnica* that is both these two variables have positive impacts with this density ($r^2 = 0.95$). Similar positive relationships also observed between canopy volume and clay content ($r^2 = 0.95$), while, sand content was orthogonal to this parameter ($r^2 = -0.95$). Similarly, density of *P. juliflora* and RIV of *L. pyrotechnica* were also orthogonal to each other but their relationships were statistically non-significant. After eliminating non-significant predictors the model equations for individual parameter of *L. pyrotechnica* were as follows:

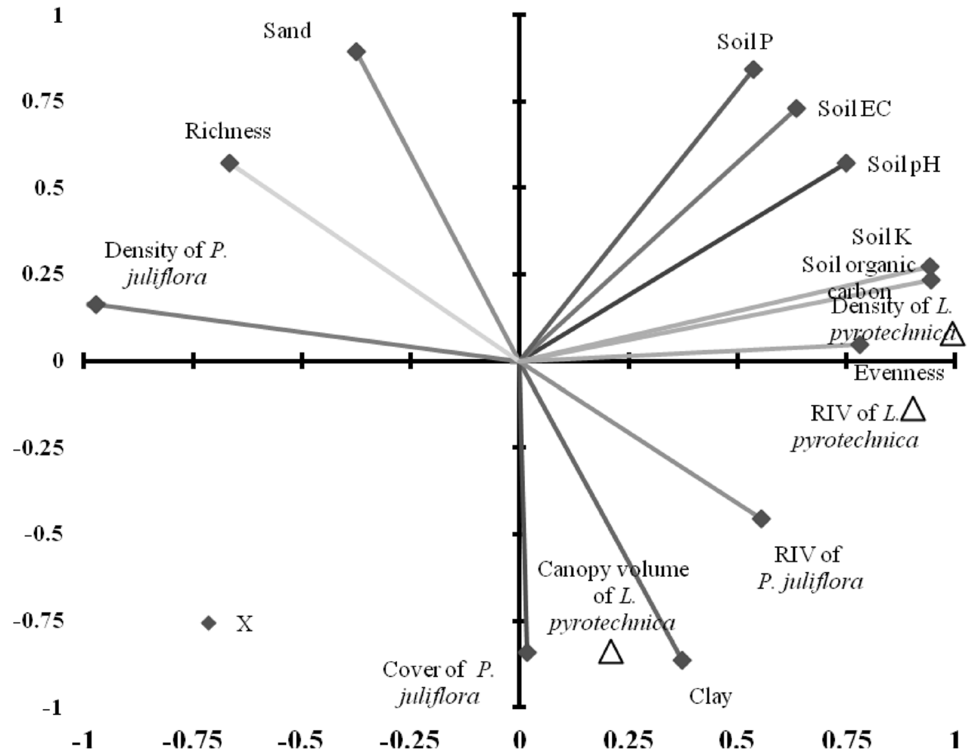


**Fig. 5** Partial Least Square Bi-plots after removing all independent variables having < 1 VIPs. Cumulatively four axes together accounted 100% variability with their individual contribution accounts 49.98, 34.94, 9.5 and 5.5% variance, respectively

$$\begin{aligned}\text{Density of } \textit{L.pyrotechnica} = {} & -770.11 - 2.35 \times \text{Sand (\%)} + 2.87 \times \text{Clay (\%)} \\ & + 114.45\ \text{Soil pH} + 50.29 \times \text{Soil EC (dSm} - 1) \\ & + 225.26 \times \text{Soil Organic Carbon (\%)} \\ & + 1.56 \times \text{P (kg/ha)} + 0.14 \times \text{K (kg/ha)} - 0.55 \times \text{Density of } \textit{P. juliflora} \\ & - 1.04 \times \text{Cover of } \textit{P. juliflora} + 0.95 \times \text{RIV of } \textit{P. juliflora} \\ & - 5.17 \times \text{Richness} + 72.57 \times \text{Evenness} \left(r^2 = 0.99\right).\end{aligned}$$

$$\begin{aligned}\text{Canopy volume of } \textit{L.pyrotechnica} = {} & 2.42 - 0.18 \times \text{Sand (\%)} + 0.23 \times \text{Clay (\%)} \\ & + 1.90 \times \text{Soil pH} - 0.83 \times \text{Soil EC} \left(\text{dSm}^{-1}\right) \\ & - 1.40 \times \text{Soil Organic Carbon (\%)} - 0.06 \times \text{P (kg/ha)} - 0.001 \times \text{K (kg/ha)} \\ & - 0.007 \times \text{Density of } \textit{P. juliflora} - 0.05791 \times \text{Cover of } \textit{P. juliflora} \\ & - 0.05 \times \text{RIV of } \textit{P. juliflora} + 0.02 \times \text{Richness} - 0.008 \times \text{Eveness} \left(r^2 = 0.95\right).\end{aligned}$$

$$\begin{aligned}\text{RIV of } \textit{L.pyrotechnica} = {} & -141.57 - 1.052 \times \text{Sand (\%)} + 1.37 \times \text{Clay (\%)} + 28.30 \times \text{Soil pH} \\ & + 4.98 \times \text{Soil EC (dSm} - 1) + 21.73 \times \text{Soil Organic Carbon (\%)} \\ & + 0.009 \times \text{P (kg/ha)} + 0.013 \times \text{K (kg/ha)} - 0.09 \times \text{Density of } \textit{P. juliflora} \\ & - 0.70 \times \text{Cover of } \textit{P. juliflora} - 0.27 \times \text{RIV of } \textit{P. juliflora} \\ & - 0.08 \times \text{Richness} + 8.36 \times \text{Evenness} \left(r^2 = 0.98\right).\end{aligned}$$

## Discussion

The Indian desert spreads across the state of Rajasthan and parts of Gujarat in western India covers about 200,000 $km^2$ and about 61% of the Indian desert is in Rajasthan covering 12 districts. In this region, the number of tree species are very limited and the dominated shrubs are *L. pyrotechnica*, *Calligonum polygonoides*, *Calotropis procera*, *Acacia jacquemontii*, *Ziziphus nummularia*, etc. (Nawal et al. 2006; Khalik et al. 2013). Many of these species are suffering from over-exploitation for their varying uses resulting in shrinkage of their habitats and loss of land phytomass. Singh et al. (2012) were assessed productivity and carbon storage capacity of *L. pyrotechnica* in three agro-climatic zones in the Indian Desert. According to them *L. pyrotechnica* showed compartmentalization in carbon and nitrogen accumulation probably an adaptation mechanism of this species. Conclusively, in this region, *L. pyrotechnica* having significant impacts on plant population dynamics, basal area, biomass production and carbon accumulation, as well as help in stabilizing wind prone soil. Removal of this species under over-exploitation not only leads to land degradation, but also affect the ecology and carbon stock of the arid soil (Mathur and Sundaramoorthy 2018).

Dominance Diversity (DD) curves may be log normal, geometric, logarithmic, and MacArthur's broken-stick types and these can be utilize as a way to express resource partitioning where the numerical value of a species is equivalent to the percentage of space it occupies (Magurran 2004), and the status of environmental stability (Kumar and Mathur 2012). Geometric distribution type prevails at relative species poor community where a single environmental resource (like moisture) is extremely important to species survival and is utilized in a strongly hierarchical fashion. Under such condition a single dominant species preempts a large fraction of the resource; the next most successful species preempts a smaller fraction of the remaining resources and so forth. Broken-stick model assumes that the species in a community partition or utilize some critical resources with no overlapping between the species while large species assembly with sub-equal abundance is the characteristic feature of log normal model (Suhs 2019). Lognormal expect that the significance of species is governed by the connections between a substantial numbers of factors deciding success in the niche hyperspace (Mathur et al. 2019). Log-normal could arise simply as the result of the multiplicative interaction of many normal random processes affecting the growth of population or could arise by combining unrelated samples (Mathur 2015).

With our experimental set up, we can say that invasion of *P. juliflora* (RIV below 15) in the community cannot change spaces occupied by the other species. Thus, threshold community position of this species may be a good indicator to predict the invasion of *P. juliflora,* beyond which it affects the other associates and modifies the habitats and spread at the entire habitat. This finding supports our hypothesis in which we stated that "specific population threshold of *P. juliflora* is required to alter the specific traits of *L. pyrotechnica"*. Such predictions are helpful to reveal the potential risk of land degradation associated with this species. Our finding is supported with recently conducted biome level research by Dakhil et al. (2021). They utilized climate, soil and human factors with MaxEnt model and their study suggested that potential risk of this species can be more accurately predicted with adding the soil variables, particularly soil pH and clay fraction, particularly from arid and semi-arid lands. In our case, although this study is regional one, even then, findings sufficiently indicates that community position of this species itself is also a good indicator to visualize the invasion behaviour of this species. In present study, higher soil potassium content at S1 compared to S2 are corroborated with the findings of study of Pandey et al. (2019) who reported higher potassium under shrub canopy than in open plots. Contrary to expectations, inter-scenario mean difference for community parameters suggested that sites with invasion of *P. juliflora* are more diversified (Shannon–Wiener index 1.55). Possible factors responsible include the facilitation effects of *P. juliflora* (e.g. *P. juliflora* leaf litter enriching the soil, its canopy providing shade or trapping wind born plant propagules). Increased alpha diversity in *P. juliflora* invaded communities found in our study is due to preponderance of lower order successional species or ruderals. A similar trend was reported by Gordon (1998) who showed that increased representation of ruderals occurred as a process of homogenization exerted by highly invasive nonindigenous species. Similar findings were reported by Lonsdale (1999) and Kumar and Mathur (2014)

The orthogonal relationships between *L. pyrotechinca* and *P. juliflora* can be explained with differences of spatial patterns of both these species (Mathur et al. 2020). The former one is naturally dispersed through air as well as non-palatable that lead its clumped type distribution. On the other hand, *P. juliflora* pods are generally dispersed through livestock that facilitate their random pattern. With PLS equations, we showed how the density, canopy volume and RIV of *L. pyrotechnica* behave with combined actions of soil texture (sand and clay), soil chemical parameters (pH, EC, soil organic carbon, phosphorus and potassium) and community parameters (species richness and evenness) along-with traits of *P. juliflora* (density, cover and RIV). Therefore, we can say that invading impacts of *P. juliflora* on dynamics of *L. pyrotechnica* will be further imposed with the help of other parameters associated with soil and community attributes. Similar findings were also reported by Srinivasu and Toky

(1996), Theoharides and Dukes (2007) and Dakhil et al. (2021).

## Conclusion

Empirical evidences of the present study further confirmed the invasion potentials of *P. juliflora* on other species. From the Indian arid environment, first time we visualized that density, canopy volume and community position of *L. pyrotechnica* does not solely affect with simple introduction of *P. juliflora* in their native sites. These morphological, population and community traits of *L. pyrotechnica* are governed through combined actions of soil qualities (sand, clay, soil pH and EC, soil organic carbon, soil phosphorus and potassium), *P. juliflora* traits (density, cover and RIV) and plant community attributes like richness and evenness. Scientific information of the present work could be utilized for sand-dune stabilization with *L. pyrotechnica* as well as for restoration and reclamation of degraded sites.

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