Prosopis juliflora (Swartz) DC.: an invasive alien in community grazing lands and its control through utilization in the Indian Thar Desert

Article *in* Arid Land Research and Management · April 2019

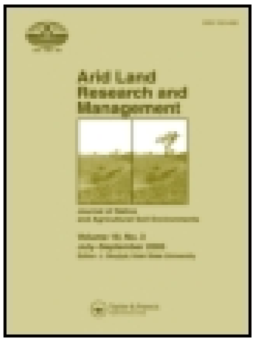
DOI: 10.1080/15324982.2018.1564402

Chandra BHUSHAN Pandey
Central Arid Zone Research Institute (CAZRI)

Dipankar Saha
Central Arid Zone Research Institute (CAZRI)

B.K. Mathur
Central Arid Zone Research Institute (CAZRI)

J. C. Tewari
Central Arid Zone Research Institute (CAZRI)



Taylor & Francis
Taylor & Francis Group

Arid Land Research and Management

ISSN: 1532-4982 (Print) 1532-4990 (Online) Journal homepage: https://www.tandfonline.com/loi/uasr20

Prosopis juliflora (Swartz) DC.: an invasive alien in community grazing lands and its control through utilization in the Indian Thar Desert

C. B. Pandey, A. K. Singh, D. Saha, B. K. Mathur, J. C. Tewari, M. Kumar, R. K. Goyal, M. Mathur & M. K. Gaur

ARID LAND RESEARCH AND MANAGEMENT
https://doi.org/10.1080/15324982.2018.1564402

Prosopis juliflora (Swartz) DC.: an invasive alien in community grazing lands and its control through utilization in the Indian Thar Desert

C. B. Pandey, A. K. Singh, D. Saha, B. K. Mathur, J. C. Tewari, M. Kumar, R. K. Goyal, M. Mathur, and M. K. Gaur

Central Arid Zone Research Institute, ICAR, Jodhpur, Rajasthan, India

ABSTRACT

Prosopis juliflora (Swartz) DC., an invasive alien plant species, is known as a threat to biodiversity and ecosystem services world over. It has heavily invaded community grazing lands (CGLs) in the Indian Thar Desert. The present study reports effects of four canopy sizes, (i.e. small, medium, large and no-canopy/open plot), of *P. julflora* shrub on native vegetation and soil fertility (0–20 cm depth) in the CGLs distributed in Jodhpur, Pali, and Sirohi districts in the Desert. In addition, economic profitability of *P. juliflora* based three enterprises, (i.e. charcoal making, pod-flour making, and sheep rearing in the grasslands if developed in the CGLs), was evaluated to find out invasion control measures of the shrub through utilization. Soil organic carbon (SOC), total N, available P and K, and mineral N (NO_3^-–N, NH_4^+–N) and soil-moisture contents were higher under the shrub canopy than in open plot; and they were the highest under the large and lowest under the small canopy sizes. But, light intensity (Lux) declined under the canopy. The decline, however, was the highest under the large and lowest under the small canopy sizes. Composition of native plant species changed and their richness and diversity declined under the canopy, but was higher under the larger canopy size. Economic analyses revealed that investment was the highest (5476US$ ha^{-1}) in the charcoal and lowest (486US$ ha^{-1}) in pod-flour enterprise, but gross profit and net present value (NPV) were the highest (10740US$ ha^{-1} and 5264US$ ha^{-1}, respectively) in the charcoal and lowest (895US$ ha^{-1} and 409US$ ha^{-1}, respectively) in pod-flour enterprise. Other economic parameters, like the annuity and internal rate of return (IRR), were also the highest in the charcoal and lowest in pod-flour enterprise suggesting that the charcoal enterprise is economically the most profitable enterprise; and it may control the invasion of the *P. juliflora* in the Desert.

ARTICLE HISTORY
Received 20 May 2018
Accepted 26 December 2018

KEYWORDS
Harsh climate; mesquite-based enterprises; net present value; plant diversity; soil fertility

Introduction

Invasive alien plant species, over the world, are the largest growing threats to biodiversity, and delivery of ecosystem services (Schei 1996; Van Wilgen, Le Maitre, and Cowling 1998; Wilcove et al. 1998; Levine et al. 2003; Sharma, Raghubanshi, and Singh

CONTACT C. B. Pandey cbpandey5@rediffmail.com ICAR- Central Arid Zone Research Institute, Jodhpur-342 003, Rajasthan, India.

Supplemental data can be accessed on the publisher's website.

2005; Mwangi and Swallow 2008). They are also a major cause of extinction of mammal, avian, and fish species; and they have threatened plant diversity in many regions (Schei 1996; Gaertner et al. 2009). However, unlike other alien invasives, *Prosopis juliflora* (Swartz) DC. is a controversial alien species having both harmful and beneficial attributes (Ilukor et al. 2016; Wakie et al. 2016). On the one hand, it improves soil fertility (Al-Homaid and Khan 1994; Singh and Shukla 2012) and serves as a cheap source of firewood, human food, animal feed, medicine, timber, honey, and energy products, charcoal and electric power in developing countries like Kenya, Ethiopia, Nigeria and India (Gupta 1985; Pasiecznik et al. 2001; Felker 2005; Sato 2013), on the other hand it casts a shade, which changes composition and reduces abundance, richness, and diversity of under-storey plant species (Collier, Vankat, and Hughes 2002; El-Keblawy and Al-Rawai 2007) and poses threats to ecosystem services (Blossey et al. 2001; El-Keblawy and Al-Rawai 2007). Efforts have been made in different parts of the world to eradicate the species by mechanical, chemical, and biological (seed feeding beetles) methods, but these methods have been found expensive and ineffective (McConnachie et al. 2012; Sato 2013). Therefore, utilization enterprises are advocated to be the best options to control the species from invasion as they provide employment to low-income groups of people in developing countries (Borokini and Babalola 2012; Tessema 2012; Wakie et al. 2016).

Prosopis juliflora, popularly known as mesquite, is an alien invasive weed in the Indian Thar desert (Harsh and Tewari 1998). The King of Jodhpur for the first time introduced it in 1913 in the Desert to moderate its high temperature. It got naturalized here very quickly and earned an accolade of being a Royal Plant in 1940 for its fast growth and lush green canopy (Harsh and Tewari 1998; Walker 2011). Later, the State Forest Department of Rajasthan planted it in degraded scrub forests (Harsh and Tewari 1998; Walker 2011). Thin vegetal cover of native flora owing to low rainfall and high temperature paved the way for its invasion in croplands, scrub forests, degraded lands, and common property resources (CPRs) that include *Oran* (secret lands around temples being used as grazing lands) and community grazing lands (CGLs) (Tewari et al. 2000). Canal networks and tube-wells came up in the desert during 1970s, which made some croplands waterlogged, particularly in canal command areas, and soils saline in tube-well irrigated areas, which further provided space for invasion, to the mesquite (CAD, IGNP 2009; Singh and Shukla 2012). According to Felker et al. (1981) the species has potential to tolerate electrical conductivity (EC) of soils nearly equal to that of sea water. Now, the *P. juliflora* has invaded either side of roads, scrub forests and community grazing lands (CGLs) heavily in the Desert (Harsh and Tewari 1998). Looking at the invasive nature of the species, Govt. of Rajasthan took a decision to get it uprooted from the forests, but its spreading following a partial uprooting was found more vigorous due to its coppicing ability (Abdulahi, Ute, and Regasa 2017). Presently the species serves 70% of the fuel needs of low-income group people (Harsh and Tewari 1998). *Panchayati Raj* institutions (PRIs), a village level democratically elected governing body, have now started to lease out the CGLs to turn *P. juliflora* biomass into charcoal. Some flour-mill owners make pod-flour from ripe pods of the species and mix it with other ingredients to make an animal feed (Tewari et al. 2000). Sheep rearing in the grasslands, if developed in the CGLs, may be another option to control invasion of the *P. juliflora*.

It is pertinent to mention that rural economy of the Thar Desert is based on small ruminants, like sheep and goat, but their rearing is done through free range grazing on well defined nomadic routes (Gaur et al. 2015). The different uses of *P. juliflora* in the CGLs have developed a conflict of interests among the stakeholders. Therefore, policy makers are unable to take a decision in lack of scientific information. Under such conditions, cost-benefit analysis gives a clear understanding about what could be the most economically profitable enterprise, which may control invasion of the *P. juliflora* in the Desert through utilization. Objectives of this study were to examine effects of *P. juliflora* on: (i) soil nutrient build up, and (ii) dominance (i.e. IVI, importance value index), richness and diversity of native plant species; and (iii) to understand economic profitability of *P. juliflora* based three enterprises, (i.e. charcoal making, pod-flour making, and sheep rearing in the grasslands if developed in the *P. juliflora* infested CGLs), to find out economically profitable enterprises for controlling the invasion of the species in the CGLs through utilization.

Materials and methods

Study sites

Ten homogeneous sites, (i.e. 1 at Ketu Manawata, 5 at Rohat, 2 at Gajan Mata and 2 at Barloot in proportion to the vegetal cover of the *P. juliflora*), were selected randomly in the CGLs located in Jodhpur, Pali, and Sirohi districts of the Indian Thar Desert (24°19′34.72″ to 27°37′09″N lat. and 71°48′09″ to 74°24′25.28″ E long.) (Figure 1). Size of the CGLs ranges from 1000 to 3000 *beegha* (6 *beegha* = 1 ha); and their boundaries are decided by the Rajasthan state Govt. The CGLs are under administrative control of the *Panchayati Raj* institutions (PRIs). One or more than one adjoining villages form a PRI depending on population size. One PRI requires a population of 2000 adults (>18 yr). One *Sarpanch,* two *Up-sarpanch* and five members elected by the adults serve as office executives of a PRI. The *P. juliflora* shrub grows naturally in the CGLs without irrigation and fertilizers. Three sets of studies were conducted at the sites in 2017 and 2018. In the first and second set of the studies, impacts of the *P. juliflora* were evaluated on native plant species and soils. However, in the third set, economic profitability of the *P. juliflora* based three enterprises, (i.e. charcoal making, pod-flour making, and sheep rearing in grasslands under controlled grazing, if developed in the CGLs), were examined. At least one management option (charcoal making) was investigated at each site. Altitude of the sites ranges from 100 to 200 m above mean sea level. The soils in the study sites are Aridisols (Typic Haplocambids), sandy-loam in texture and alkaline in reaction and poor in nutrients (Patidar and Mathur 2017). The climate of the Desert is arid characterized by three seasons: rainy (June to September), winter (November to January) and summer (February to May); and October is a transition month between rainy and winter seasons. An average annual rainfall across the Desert ranges from 150 to 400 mm yr^{-1}, mostly (85%) occurring in the rainy season; it is the lowest in western and the highest in eastern parts. The rainfall distribution pattern, across the seasons, is shown in Figure 2. Open pan evaporation is higher than rainfall in almost all months, other than the rainy season, making the Desert water limiting. Mean maximum temperature varies from 24.9 to 41.6 °C and mean minimum from 10.3 to 28.9 °C. The

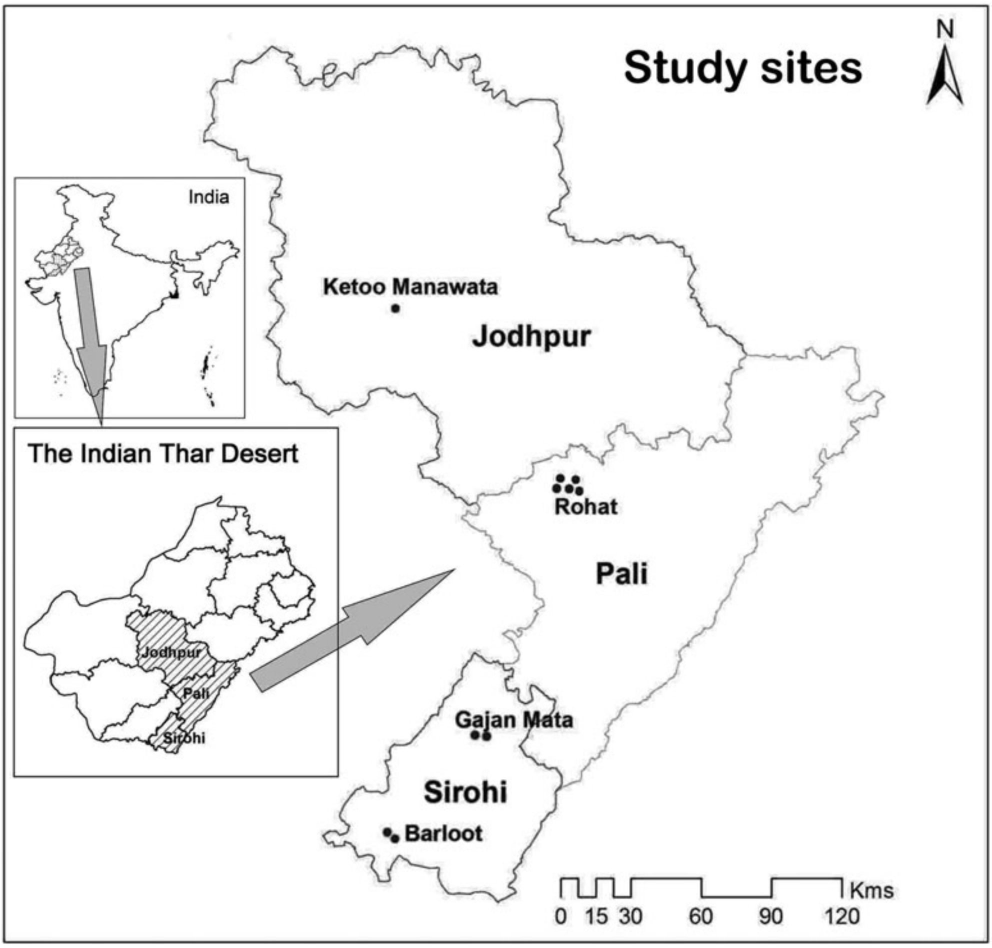


Figure 1. Location of the study sites in the community grazing lands (CGLs) in the Indian Thar Desert.

temperature rises up to 48 °C in the summer and drops to below zero occasionally in the winter season. Relative humidity ranges from 13% to 57% and wind velocity from 2.5 to 9.6 km hr^{-1}, across the seasons. However, the former is the lowest during the summer and highest during rainy season, but the latter is the highest during summer and the lowest during winter making the climatic conditions of the Desert inhospitable, particularly during the summer season (Rao 2009). Rain-fed agriculture has occured since generations; and crops are mostly pearl millet, moth bean, mung bean, and cluster bean, but now-a-days after development of irrigation facilities, like canals and tube-wells, crops like wheat, mustard, groundnut, castor, vegetables, and fruit-crops like pomegranate are also cultivated. Khejri (*Prosopis cineraria* (Linn.) Druce), recently declared as the State Tree of Rajasthan, is found in croplands as a way of traditional agroforestry. Rural economy of the Desert is based on livestock, particularly small ruminants. Each farmer, big or small, generally possesses cattle, goats, and sheep. But, the pastoralists, who belong to *Rabari* and *Raika* castes, keep sheep (Gaur et al. 2015). An average size of a herd is generally 250 to 500 sheep. The pastoralists generally graze

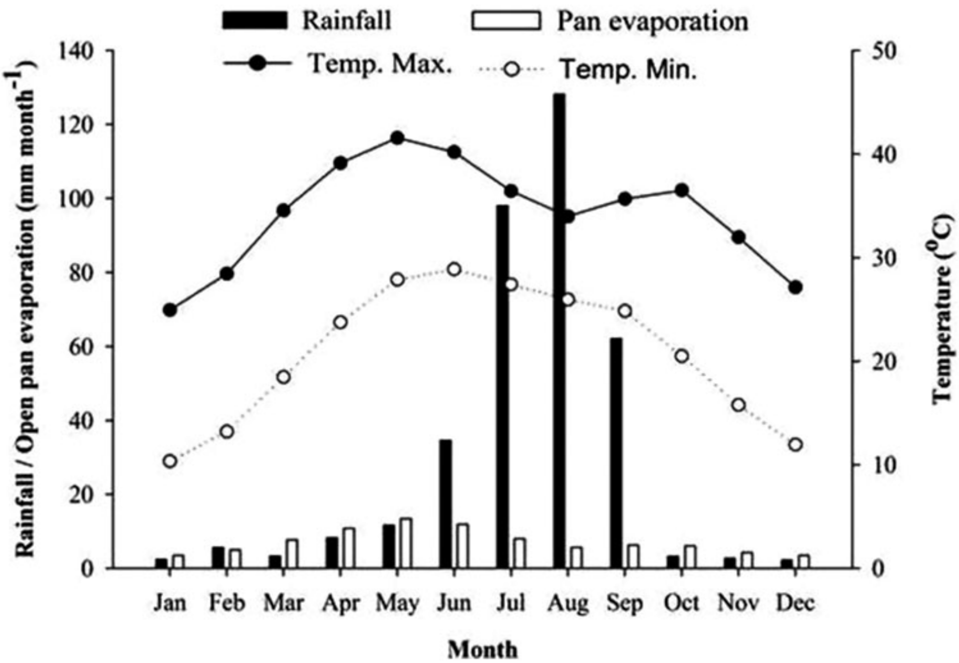


Figure 2. Seasonal variations in rainfall, maximum- and minimum-temperature, and pan evaporation in the Indian Thar Desert.

their sheep in local areas, but sometimes they move to different states on well defined nomadic migration routes (Gaur et al. 2015).

Sampling design and laboratory analysis

Vegetation

After several reconnaissance and a preliminary study on dimensions of the *Prosopis juliflora* shrubs, 12 shrubs, similar in shape and size, of each small, medium and large canopy size, were selected randomly across the sites. Dimensions of the shrubs in terms of canopy sizes were as follows: (i) small (canopy cover = 6.92 ± 1.26 m^2, shrub height = 3.01 ± 0.21 m), (ii) medium (canopy cover = 33.19 ± 4.62 m^2, shrub height = 4.14 ± 0.24 m), and (iii) large (canopy cover = 59.54 ± 4.54 m^2, shrub height = 5.37 ± 0.22 m), with the variance of the mean as SE. In addition, 12 homogeneous random open plots (no-canopy) were selected as a control. Native vegetation was sampled for species composition and their phytosociological attributes like frequency and density using three quadrates (50 × 50 cm) under each selected shrub. Light intensity was measured under each selected shrub at three random places using a luxmeter. Diversity of the native species was calculated as $H' = -\sum P_i \log_2 P_i$ (Shannon and Weaver 1949), where P_i = the proportion of the density of species i. Species richness was calculated as (S-1)/ln N (Margalef 1958), where S is the total number of species in the community, and N the total density of all species. Equitability (E_c) was calculated as $S/(\ln n_m - \ln n_l)$ (Whittaker 1972), where S is the total number of species and n_m and n_l, the density values of the most and least important species, respectively.

To understand effects of the *P. juliflora* on the composition of native plant species, importance value index (IVI) of the species under the shrub canopy was calculated using relative frequency, relative density and relative abundance (Pandey, Rai, and Singh 2007).

Soils

To know the impact of the *P. juliflora* shrub on soil-fertility, five shrubs, of the twelve, of each canopy size class, and five open plots (no-canopy) were selected randomly across the sites. The soils (0–20 cm depth) were sampled from five random places under each selected shrub and an open plot and were composited for a shrub and an open plot. The composite soil samples were sieved through a 2 mm mesh screen and were divided into three parts. One part in the field-moist conditions was used for determination of pH, EC, mineral N (NO_3^-–N and NH_4^+–N) and available P and K content. The second part was air dried and used for determination of organic carbon (SOC) and total N content. Soil pH was measured by glass electrode and EC by conductivity meter (1:2, soil:water ratio). The SOC content was determined by Walkley and Black rapid titration method, and total N content was measured by microkjedhal digestion method. Available P content was determined by an ammonium molybdate-stannous chloride method (Sparling, Whale, and Ramsay 1985). Mineral N content like NO_3^-–N was measured by a phenol disulphonic acid method and NH_4^+–N by a phenate method (Wetzel and Likens 1979). Available K content was determined by the neutral normal ammonium extraction method using flame photometer. The third part of the sample (pre-weighed 100 g) was used for determination of soil-moisture content by drying at 105 °C. All soil data are presented on dry weight basis.

Data collection from *P. juliflora* based enterprises

The charcoal enterprise is comprised of a chain of components, like PRIs, contractors, charcoal making labourers, retailers, and consumers. The contractors take CGLs from the PRIs on lease and employ labourers to make charcoal from the *P. juliflora* in locally made kilns. They buy the charcoal made from the labourers and sell it to the retailers. The retailers sell the charcoal to consumers. We interviewed respondents like the charcoal making labourers (200), contractors (10) and retailers (10) to get information related to the charcoal making. However, for the pod-flour making, 10 pod collectors and 1 pod-flour mill owner were interviewed. Information was collected from the respondents in the way they perform their roles in the enterprises. The information related to weight of the charcoal produced in a kiln was verified by weighing it at three random sites. Cross verifications of the costs of the charcoal and pod-flour making enterprises were done at the labourers, contractors, retailers, and flour-mill owner's levels to make data authentic. Ten pastoralists were interviewed to understand economic profitability of sheep rearing in the grasslands under controlled grazing if developed in the *P. juliflora* infested CGLs. Information available in literature related to carrying capacity of the grasslands prevailing in the arid conditions was also collected (Patidar and Mathur 2017).

Economic analysis of P. juliflora based enterprises

The costs and benefits for the enterprises have been computed using the data generated through the interviews. For the enterprises, lifetime (n) of equipments and machineries is assumed to be 10 years and salvage value (value of the equipments and machines at the end of useful life) 10% of their initial costs. The annual depreciation of the machineries is estimated following the straight line method (Kepner, Bainer, and Barger 2005). Bank interest rate (i) was 12% for all calculations. The annual cost of machineries is calculated by adding an annual depreciation and an annual interest cost as follows:

$$\text{annual depreciation cost (D)} = (\text{initial cost} - \text{salvage value})/\text{n},$$

and

$$\text{interest cost (I)} = (\text{initial cost} + \text{salvage value}) \times \text{i}/2.$$

By computing the life cycle cost (LCC) or investment, and life cycle benefit (LCB) or gross profit, of the enterprises, five economic attributes, namely, benefit-cost ratio (BCR), net present value (NPV), annuity (A), internal rate of return (IRR), and pay back period (PBP) were determined for comparing economic profitability of the enterprises following Sodha et al. (1991) as follows:

$$\text{LCC} = \text{Land lease value} + C\frac{X(1-X^n)}{(1-X)} \tag{1}$$

$$\text{LCB} = R\frac{X(1-X^n)}{(1-X)} \tag{2}$$

Where,
C = annual operation and maintenance cost including labourers costs.
R = annual gross benefit.

$$X = \frac{1+e}{1+i}$$

e = annual escalation in cost in fraction (0.0). i = interest or discount rate in fraction (0.12). n = project life (10 years)

BCR, the ratio of discounted benefits to the discounted values of all costs given as:

$$\text{BCR} = \text{LCB}/\text{LCC} \tag{3}$$

NPV, a sum of all discounted net benefits throughout the project given as:

$$\text{NPV} = \text{LCB} - \text{LCC} \tag{4}$$

The annuity (A) of the project indicates the average net annual returns given as:

$$\text{A} = \frac{NPV}{\sum_{n=1\text{ to }10}\left[(1+e)(1+i)\right]^{n}} \tag{5}$$

IRR, the rate of interest which makes LCB and LCC equal (i.e. $LCB - LCC = 0$) is given as:

$$IRR = \text{lower discount rate} + (\text{Difference of discount rate} \times \text{NPV at lower discount rate}) / (\text{NPV at lower discount rate} - \text{NPV at higher discount rate}) \tag{6}$$

PBP is the length of time from beginning of the enterprises till the net benefit returns the cost of capital investments

$$\text{i.e. } LCB - LCC = 0 \tag{7}$$

Statistical analysis

The data of soil fertility, soil-moisture, light intensity and vegetation (IVI) were subjected to one way analysis of variance using SPSS statistical package. Treatments included four canopy sizes (i.e. small, medium, large, and no-canopy/open plot). Replicates for the IVI were twelve, but for the soil fertility, soil-moisture and light intensity related parameters, replicates were five. Means were compared using LSD ($p < 0.05$). The Pearson correlation coefficient technique was applied to know the relationship between two parameters.

Results

Light intensity and soil-moisture content

The soil-moisture content and light-intensity under the *P. juliflora* shrub varied significantly across the canopy sizes ($p < 0.001$). The soil-moisture content was higher under the shrub canopy than in open plot; and it was the highest under the large, but the lowest under the small canopy size (Table 1). On the contrary, the light-intensity declined under the shrub canopy compared to that in the open plot; the decline, however, was the lowest under the small and highest under large canopy size classes. The soil-moisture content was positively ($r = 0.996$, $p < 0.01$), whereas light intensity was inversely correlated ($r = -0.952$, $p < 0.05$) with the canopy size (Table 2).

Soils

The soil parameters, other than pH and EC, differed significantly among the canopy sizes ($p < 0.5$ to $p < 0.001$). Soil pH and EC did not vary significantly among the canopy sizes; the pH ranging from 7.96 to 8.10 indicated that the soils were slightly alkaline in reaction (Table 3). 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. The NH_4^+–N content was higher than NO_3^-–N content invariably under

Table 1. Dimensions (i.e. canopy size and height) of *P. juliflora* shrub, and light intensity, soil moisture and importance value index (IVI) of native plant species under the shrub in the community grazing lands (CGLs) in the Indian Thar Desert. Data are mean ± SD.

IVI of native species under *P. juliflora* shrub	Canopy size			
	Small	Medium	Large	Open plot/No-canopy
Canopy cover (m^2)	^{a}6.92 ± 1.26	^{b}33.19 ± 4.62	^{c}59.54 ± 4.54	0.00
Light intensity (Lux)	^{a}30202.02 ± 1418.02	^{b}22098.01 ± 844.03	^{c}1160.03 ± 73.04	^{d}48700.11 ± 2850.01
Soil moisture (%)	^{a}6.18 ± 0.84	^{b}9.18 ± 0.89	^{c}14.20 ± 1.80	^{d}4.09 ± 0.65
Perennial grass				
Cenchrus biflorus Hook. f.	^{a}2.80 ± 0.74	^{b}1.50 ± 0.34	0.00	^{c}5.91 ± 2.11
Dichanthium annulatum (Forsk.) Stapf	^{a}2.01 ± 0.54	^{a}2.10 ± 0.46	0.00	^{b}5.80 ± 2.10
Annual grass				
Aristida funiculata Trin. et Rupr.	^{a}20.21 ± 1.80	0.00	0.00	^{b}5.11 ± 1.20
Digitaria spp. Heist. ex Fab.	0.00	0.00	0.00	3.50 ± 1.09
Eleusine compressa (Forsk.) Aschers. et Schweinf.	0.00	^{a}10.11 ± 0.84	0.00	^{b}5.30 ± 0.58
Eragrostis ciliaris (Linn.) R. Br.	0.00	0.00	0.00	3.31 ± 0.80
Brachiaria spp. Griseb.	0.00	^{a}21.20 ± 7.70	^{b}4.52 ± 0.46	^{c}7.60 ± 1.47
Melanocenchrus jacquemontii Jaub. et Spach.	0.00	18.52 ± 1.59	0.00	0.00
Oropetium thomaeum (Linn. f.) Trin.	0.00	^{a}17.80 ± 2.66	0.00	^{b}7.71 ± 1.08
Tetrapogon tenellus (Roxb.) Chiov.	0.00	0.00	^{a}9.01 ± 2.03	^{a}7.12 ± 2.22
Perennial forb				
Tephrosia purpurea (Linn.) Pers.	9.01 ± 1.02	0.00	0.00	0.00
Annual non forb				
Boerhavia diffusa Linn.	0.00	0.00	0.00	2.90 ± 0.24
Corchorus tridens Linn.	0.00	0.00	0.00	3.81 ± 1.09
Cyperus spp. Linn.	0.00	0.00	^{a}40.91 ± 4.30	^{b}16.90 ± 4.12
Euphorbia hirta Linn.	0.00	0.00	0.00	4.71 ± 1.47
Gisekia pharnacioides Linn.	30.91 ± 3.15	0.00	0.00	0.00
Indigofera cardifolia Heyne ex Roth	0.00	0.00	0.00	3.71 ± 1.06
Peristrophe bicalyculata (Retz.) Nees	^{a}23.61 ± 4.70	^{b}29.60 ± 2.90	^{c}45.81 ± 8.65	^{c}11.02 ± 2.10
Sonchus asper Fig.	7.81 ± 0.50	0.00	0.00	0.00
Tragus biflorus (Roxb.) Schult.	^{a}3.81 ± 0.08	0.00	0.00	^{a}4.01 ± 0.5
Tribulus terrestris Linn.	0.00	0.00	0.00	2.11 ± 1.20
Diversity parameters				
Richness (Margalef number)	8	7	4	17
Diversity (Shannon and Weaver number)	1.74	1.67	1.07	2.69
Equitability (Whittaker number)	0.87	0.92	0.84	0.96

Data with same superscript letter in a row are not significant at $p < 0.05$.

all canopy sizes suggesting that NH_4^+–N dominated in the soils. The NH_4^+–N and NO_3^-–N content were positively correlated with the canopy size and the SOC content ($p < 0.05$). The NH_4^+–N content was inversely correlated with C/N ratio ($p < 0.05$) (Table 2).

Vegetation

Composition of native plant species changed under the shrub canopy compared to that in the open plot (Table 1). Importance Value Index (IVI), showing dominance of the native plant species, varied significantly among the canopy sizes ($p < 0.05$). The IVI of

Table 2. Pearson correlation coefficients and their level of significance between independent (canopy size, light intensity, soil moisture) and dependent parameters (pH, EC, SOC, total N, C/N ratio, NO_3^-–N, NH_4^+–N, available P and K content) under different canopy sizes of *Prosopis juliflora* shrub in the community grazing lands (CGLs) in the Indian Thar Desert.

Parameters	Light intensity (Lux)	Soil moisture (%)	pH (1:2)	EC (dSm^{-1})	SOC (%)	Total N (%)	C/N ratio	NO_3^--N ($\mu g\ g^{-1}$)	NH_4^+-N ($\mu g\ g^{-1}$)	Available P ($\mu g\ g^{-1}$)	Available K ($\mu g\ g^{-1}$)
Canopy size	−0.952*	0.996**	−0.969*	−0.974*	0.993**	0.964*	-0.706^{NS}	0.993*	0.979*	0.976*	0.948*
Light intensity (Lux)	–	−0.976*	0.954*	0.910^{NS}	−0.976*	−0.984*	0.842^{NS}	−0.965*	−0.946*	−0.985*	−0.999**
Soil moisture (%)	–	–	−0.974*	−0.965*	0.998**	0.979*	-0.753^{NS}	0.995**	0.978*	0.985*	0.973*
SOC (%)	–	–	–	–	–	0.968*	-0.728^{NS}	0.999**	0.963*	0.975*	0.969*
Total N (%)	–	–	–	–	–	–	-0.870^{NS}	0.995*	0.984*	0.999**	0.990**
C/N ratio	–	–	–	–	–	–	–	-0.692^{NS}	−0.889*	-0.856^{NS}	-0.867^{NS}

*$p < 0.05$; **$p < 0.01$; NS: not significant at $p < 0.05$.

Table 3. Soil organic carbon (SOC), total nitrogen and available N (NO_3^-–N and NH_4^+–N), P and K concentrations under different canopy size classes of *Prosopis juliflora* shrub in the community grazing lands (CGLs) in the Indian Thar Desert. Data are mean ± SD.

	Canopy size class			
Parameters	Small	Medium	Large	Open plot/No-canopy
pH	^{a}8.05 ± 0.22	^{a}7.96 ± 0.54	^{a}7.96 ± 0.32	^{a}8.10 ± 0.13
EC (dSm^{-1})	^{a}0.13 ± 0.05	^{a}0.12 ± 0.04	^{a}0.12 ± 0.03	^{a}0.13 ± 0.02
SOC (%)	^{a}0.26 ± 0.04	^{b}0.32 ± 0.03	^{c}0.42 ± 0.02	^{d}0.22 ± 0.02
Total N (%)	^{a}0.03 ± 0.002	^{b}0.05 ± 0.003	^{c}0.06 ± 0.005	^{d}0.02 ± 0.002
C/N ratio	^{a}8.40 ± 1.20	^{b}7.16 ± 0.99	^{b}7.40 ± 0.53	^{c}13.79 ± 0.89
NO_3^-–N (μg g^{-1})	^{a}0.28 ± 0.01	^{b}0.37 ± 0.02	^{c}0.52 ± 0.02	^{d}0.24 ± 0.01
NH_4^+–N (μg g^{-1})	^{a}0.88 ± 0.02	^{b}1.28 ± 0.02	^{c}1.46 ± 0.04	^{d}0.72 ± 0.02
Available P (μg g^{-1})	^{a}19.42 ± 0.62	^{b}22.26 ± 0.45	^{c}24.84 ± 1.58	^{d}16.58 ± 0.43
Available K (μg g^{-1})	^{a}187.20 ± 3.85	^{b}197.46 ± 6.07	^{c}257.80 ± 10.26	^{d}165.70 ± 2.92

Data following the same superscript letter in a row are not significantly different at $p < 0.05$.

perennial grasses declined under the shrub canopy. The decline, however, increased up to the medium canopy size class. Under the large canopy size class, the perennial grasses were not present. The IVI of almost all annual grasses was higher under the shrub's canopy than in the open plots. But, IVI of most of the annual grasses was the highest under the medium canopy shrub class. 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. But, only two non-forb annuals, (i.e. *Cyperus* spp. Linn. and *Peristrophe bicalyculata* (Retz.) Nees), were found under the large canopy shrub class.

Charcoal enterprise

The PRIs provide the CGLs on lease to those contractors who pay the highest bidding. A contractor generally takes 2–3 CGLs on the lease and engages 40 to 50 labourer's families in a CGL for the charcoal making. Working members in a labourer family are a man and his wife. Children and old aged members generally do not participate in the charcoal making works. The contractors provide implements to the labourers for the charcoal making works, but recover their costs from income of the labourers in several installments. The contractors do not provide daily wages to the labourers for the charcoal making works, but buy the charcoal made by them at 8US$ kg^{-1}. The labourer's families put makeshift huts in a CGL and stay there until they convert all biomass of *P. juliflora* into charcoal using local kilns and after that they move to another CGL. Each family works for 20 to 40 days to make a local kiln. The charcoal making works in the local kilns include cutting of *P. juliflora* close to the ground, debranching of stems, making pieces of the stems (30–50 cm long and 1.71–4.96 cm diameter), air-drying of the stem pieces, piling the stem pieces on ground, covering the stem pieces with air dried thin stem branches, leaves and pods of the felled *P. juliflora* and soil-dusts, carbonation, cooling of charcoal, and filling of bags. The contractors provide bags to the labourers. One kiln requires *P. juliflora* biomass from 1.5 *beegha* CGL; and from one hectare CGL, 4 kilns are prepared. Each bag contains 30 kg charcoal. The contractors transport the charcoal filled bags to retailers, who sell the charcoal to consumers in local market; this is described as case I of charcoal enterprise in the text. Though their

Table 4. Investment (or life cycle cost, LCC), gross profit (life cycle benefit, LCB), net present value (NPV), internal rate of return (IRR), annuity, payback period (PBP) and benefit/cost ratio (BCR) of *Prosopis juliflora* based different enterprises in the community grazing lands (CGLs) in the Indian Thar Desert.

Enterprise	Investment (US$ ha^{-1})	Gross profit (US$ ha^{-1})	NPV (US$ ha^{-1})	Annuity (US$ ha^{-1} yr^{-1})	IRR (%)	PBP (yr)	BCR
Charcoal							
Case I	5476	8479	3003	832	88	1.42	1.61
Case II	5476	10740	5246	1458	134	0.90	2.00
Pod-flour	486	895	409	113	88	1.40	1.91
Sheep rearing	1549	2187	638	113	27	4.83	1.42

1US$ = INR72.

numbers are very few, some landowners, who own *P. juliflora* infested lands, get charcoal made by the labourers, but do not sell it to the retailers. They sell the charcoal directly from their own outlets. This direct selling is described as case II of the charcoal enterprise in the text.

Totally, 7200 kg charcoal (30 kg × 240 bags) is produced from one hectare CGL in a 5-year rotation period. Economics of the charcoal enterprise, considering 7200 kg ha^{-1} charcoal production, and 10-year as a lifetime of the enterprise, is given in Table 4, Tables S1 and S4. Investment in the enterprise is 5476US$ ha^{-1}, whereas gross income is 8479US$ ha^{-1} and 10,740US$ ha^{-1} with NPV 3003US$ ha^{-1} and 5264US$ ha^{-1} and annuity 832US$ $ha^{-1}yr^{-1}$, and 1458US$ $ha^{-1}yr^{-1}$ for the Case I and Case II, respectively (Eq. [1], [2], [4], and [5]). The positive NPV indicates that the enterprise is economically profitable with BCR of 1.6 and 2.0, respectively (Eq. [3]). But, all economic parameters are higher in the case II than in the case I, suggesting that the second model of the enterprise is economically more profitable. Internal rate of return (IIR) is at 88% and 134% and payback period is 1.4-year and 0.9-year, respectively, indicating that the enterprise earns more than lending rate (12%); thus the enterprise has potential to repay the loan if taken from a bank within a short period (Eq. [6] and [7]). A sensitivity analysis, however, indicates that the enterprise is sensitive to labourers and escalations in labourers' costs more than 14% in the case I and 16% in the case II will affect the enterprise adversely (Table 5).

P. juliflora *based pod-flour enterprise*

Villagers of low-income group who live close to the CGLs collect ripe pods from *P. juliflora* thickets. Generally they enter into the thickets where pods are ripe and shake their branches violently with a stick having a sickle shape bend on its top. Ripe pods are white, hence visible from distant places. They sweep the fallen pods on the ground by a broom and carry the swiped pods to their houses in sacks. Pod-flour mill owners buy the pods from the villagers, transport them to their flour-mills and make flour from them. The flour and other feed ingredients are mixed in 20:80 ratios to make an animal-feed.

Economic analyses of the pod-flour enterprise are given in Table 4, Tables S2 and S4. The pods ripe two times a year; the first ripening season is during December to mid February and the second ripening season is during May to June. Production of the pods

Table 5. Effect of escalation in labour cost on net present value (NPV) for *Prosopis juliflora* based different enterprises in the community grazing lands (CGLs) in the Indian Thar Desert.

	Charcoal NPV (US$ ha^{-1})			
Escalation in labour cost (%)	Case I	Case II	Pod- flour NPV (US$ ha^{-1})	Sheep rearing NPV (US$ ha^{-1})
0	3004	5265	409	–
2	2556	4817	371	–
4	2057	4318	329	NA
6	1501	3762	283	–
8	884	3145	231	–
10	197	2458	174	–
14	−1420	841	38	–
16	−2368	−107	−42	–

NA = not applicable as the sheep rearing is managed by family members.
1US$= INR72.

is 600 kg ha^{-1} with maximum (75%) occurring during the rainy season. The villagers collect the pods as a part time job when they are free from agricultural and other household works. Therefore, the pod collection works are converted into man-days for the economic analyses. A man-day is equal to 8 h works by a labourer. An average 8 man-days are required to collect the pods from one hectare CGL. The transport of the pods to flour-mills, sacks, labourers for milling the pods, and electricity bills are other expenses for making the pod-flour. The flour-mill owners buy the pods at 0.07US$ kg^{-1}. Investment in the pod-flour making is 486US$ ha^{-1}, whereas gross income is 895US$ ha^{-1} with NPV 409US$ ha^{-1}, annuity 113US$ ha^{-1}yr^{-1} and BCR 1. 9. IRR of the enterprise is at 88%, which is 7.33 times higher than lending rate (12%) of a bank and payback period is 1.4-year; these suggest that the enterprise is economically profitable, and loan from a bank, if taken, can be repaid quickly within one-and-a-half year (Eq. [1–4], Eq. [6], and [7]). However, this business is sensitive to labourers and escalations in labourers' costs more than 16% will affect it adversely (Table 5).

Sheep rearing enterprise in the CGLs

The economics of the sheep rearing enterprise under controlled grazing in the CGLs has been computed using information generated by the Central Arid Zone Research Institute (CAZRI) located about 40–50 km away from the study sites to understand whether or not conversion of the CGLs into grasslands and their uses in sheep rearing under controlled grazing would be economically profitable (Patidar and Mathur 2017). *Cenchrus ciliaris* Linn. is a suitable grass for the study area and carrying capacity of *C. ciliaris* grasslands under controlled grazing is 0.8 ACU (adult cattle unit) at the CAZRI, which experiences similar rainfall and soil conditions as the study sites do (Patidar and Mathur 2017). However, soils of the CGLs are relatively more fertile. Therefore, we have considered carrying capacity of the grasslands under controlled grazing in the CGLs as 1 ACU for the economic analyses. One ACU is equal to 6 sheep (based on metabolic weight); this suggests that a pastoralist can run the sheep rearing enterprise with 6 sheep in 1 ha grassland and he can maintain the number of sheep by selling excess ones from time to time. Conversion of the *P. juliflora* infested CGLs into grasslands requires uprooting and removal of the species by an excavating machine on payment basis. The cleared lands are levelled, ploughed, and farmyard manures (FYM) are applied on them. After thorough mixing of the manure with soils, the grass seeds are spread and mixed with the soils in such a way that they may not go deeper than 0.4 cm. When the grass is germinated, watering is done and fertilizers are applied once during the first year. For controlled grazing, the grasslands are protected by erecting fences.

Once established, a grassland is found to survive for more than 20-years in the CAZRI, but in this study we have considered life-span of the grassland to last for 10-years for this economic analysis. An adult sheep gives birth to 1 or 2 lambs every year, and 10% of them die. Ultimately 4 to 5 lambs join the herd (i.e. 6 adult sheep equivalent to 1 ACU) every year. Nomads sell 2 to 6 adult sheep every year to maintain size of the herd as 6 adult sheep, so that grazing pressure is maintained within the range of the carrying capacity of the grasslands. Over a period of 10-year, nomads may sell 40 sheep. Investment in the enterprise is 1549US\$ ha^{-1}, whereas gross income is 2187US\$ ha^{-1} with NPV 638US\$ ha^{-1}, annuity is 113US\$ $ha^{-1}yr^{-1}$, and BCR 1.4. IRR of the enterprise is at 27%, and payback period is 4.8-year (Table 4, Tables S3 and S4; Eq. [1–7]).

Discussion

The higher SOC, total N, and available P and K content under the *P. juliflora* shrub than in the open plot seem to have occurred due to accumulation of organic matters through leaf litters above-the-ground and dead roots below-the-ground for a long period of more than three decades as the shrub is managed by rotational felling at 5-year intervals. *P. juliflora* is reported to increase SOC, total N, and available P and K content in the sandy soils of UAE (El-Keblawy and Al-Rawai 2007) and western Rajasthan, India (Singh and Shukla 2012). The soil parameters are also reported to have increased under the shrub in the sodic soils of north India (Mishra, Sharma, and Gupta 2003) and silvopasture soils in the semi-arid conditions of Brazil (Menezes, Salcedo, and Elliott 2002). The higher pool of nutrients under the bigger canopy size in the present study may be attributed to the accumulation of higher amount of leaf and root litters (Pandey, Singh, and Sharma 2000). Atmospheric nitrogen fixation may be another pathway of the nitrogen input under the shrub as it is a nitrogen fixing shrub (Aronson, Ovalle, and Avendano 1992). The larger available N (particularly NH_4^+–N) content under the bigger canopy size in this study may be attributed to the lower C/N ratio and greater soil-moisture content, which interactively together are found to have increased soil N mineralization under agroforestry trees (Pandey, Singh, and Sharma 2000; Pandey, Rai, and Singh 2007). It seems low availability of carbon due to low C/N ratio does not support microbial population and as a result mineral N becomes available in soils (Pandey et al. 2011). But, unlike the humid tropical soils (Pandey, Srivastava, and Singh 2009), dominance of NH_4^-–N in the present study was probably due to leaching of NO_3^-–N into deeper depths of the sandy soils (Singh and Shukla 2012).

The change in species-composition and decline in richness and diversity of the native plant species under the shrub canopy could be due to the reduction in light intensity, because soil-moisture and nutrient contents were higher under the shrub canopy than in the open plot. Elimination of indigenous species and reduction in species richness and diversity under *P. juliflora* are well documented (Prieur-Richard et al. 2002; Badano and Pugnaire 2004; Hoffmann et al. 2004). In the present study, elimination of the perennial grasses under the large canopy size class may be attributed to the least availability of light for a long time (>3-decades) with intermittent illuminations due to the rotational felling (Pandey and Singh 1991, 1992). The elimination of the perennial grasses in the present study is in stark contrast with the observations made in UAE, where annuals rather than perennial grasses have been found to be eliminated under the shrub (El-Keblawy and Al-Rawai 2007). The greater IVI of some forb- and non-forb species under the shrub, than in open plot in this study suggests that they are more tolerant to the shade than the perennial grasses. The greater soil-moisture content under the shrub in this study could be due to reduction in evaporation losses under its canopy (Pandey et al. 1999). The theory of allelopathy eliminating native species under the shrub as advocated by Noor, Salam, and Khan (1995), Warrag (1995), and Nakano et al. (2001) did not hold good in the present study, because forb- and non-forb species were present abundantly under the shrub as was also observed by Singh and Shukla (2012). It seems that water soluble allelochemicals, if present in leaf leachate, are leached down quickly in the sandy soils and thereby cause no effects on seed germination of the native species.

All over the world, chemical and biological methods are being developed to control invasion of *P. juliflora* (McConnachie et al. 2012; Sato 2013). But, the methods are not only expensive, but also ineffective (Wise, van Wilgen, and Le Maitre 2012; Sato 2013; Wakie et al. 2016). Therefore, several developing countries like India, Ethiopia, Nigeria, and Kenya (Gupta 1985; Tessema 2012; Sato 2013; Onekon and Kipchirchir 2016) prefer to control *P. juliflora* through different uses, because they create new income avenues to low-income groups of people. In the present study, the charcoal making using indigenous knowledge is the most profitable, hence suitable enterprise for controlling invasion of *P. juliflora* in the Desert. The charcoal making in the present study is broadly similar to that found in African countries like Ethiopia (Wakie et al. 2016). In the present study, contractors never pay salary to the labourers, but buy the charcoal made by them. This model of charcoal making is a win–win situation to both contractors and labourers. The contractors need not put extra manpower to supervise the charcoal making works by the labourers and the labourers are free to do the works on their own will and those who put in more time can earn more money. The charcoal has a huge demand in India as low income group of people and local restaurants (*Dhabas*) located along national and local highways (roads) use it for cooking meals. In addition, caterers use it for baking an indigenous bread called *tandoori roti* for marriage parties. But, quality of the charcoal is a big concern to the consumers as low quality charcoal generates a huge amount of smoke during cooking. Densification alters micro-chemical bonds, reduces moisture content and increases calorific value of the charcoal at par to export grade black coal (Wakie et al. 2016; Parsa et al. 2017), but so far no low cost technologies are available. Another disadvantage of the enterprise is that, it is an unorganized sector, therefore, the labourers do not get Employee Provident Fund (EPF) facility, which is otherwise available to the labourers of organized sectors in India. Though data are lacking, people's perception is that the rotational felling for the charcoal making has reduced spreading of *P. juliflora* substantially in the Desert. The people are also of the view that the *P. juliflora* shrub has contributed significantly to moderate environmental conditions in the Desert, as evident from reduction in wind velocity and frequency of dust storms (Santra et al. 2017).

The pod-flour enterprise is another option to control invasion of the *P. juliflora* through use, because it ensures removal of the mesquite's seeds after being crushed to the flour together with dried-pods. But, the flour making enterprise in the Desert suffers due to low availability of the pods though the flour-mills are limited in numbers (2–4). It is simply because of poor demand of the feed in villages where 90% of the total livestock are found. Villagers still follow the age old practice of free range grazing to feed their livestock. They generally feed *Bata* (boiled discarded grains from human consumption) to only milking cows when they come back home in the evening after the grazing. Only in cities, those who run a dairy business buy the animal feed. The flour-mill owners mix 20% of the pod-flour with 80% other ingredients to make the feed, because *P. juliflora* seeds contain tannins and polyphenols (Jama and Zeila 2005; Tegegn 2008; Girma, Urge, and Animut 2011), which bind nitrogen and hinder protein availability to livestock. The 20% pod-flour mixing is found safe for livestock feeding (Roy et al. 2014). However, to make the pod-flour enterprise remunerative the animal feed needs to be supplemented with antiemetic medicines and its marketing needs to be done as an animal feed that controls worms and increases livestock productivity (Syomiti et al. 2015).

The conversion of the *P. juliflora* infested CGLs to grasslands and their uses for sheep rearing under controlled grazing is yet another enterprise to control invasion of the shrub by use in the Desert. The Desert experiences a very low amount of rainfall (100–400 mm yr^{-1}), which makes crop productivity very low (Rao 2009). But, grasses which are well acclimatized for the harsh conditions of the Desert grow well and produce reasonably good amount of forage (Patidar and Mathur 2017). Therefore, rural economy of the Desert depends on livestock, particularly small ruminants like sheep and goats. Generally, nomads prefer sheep rearing, probably, owing to their multiple uses like milk, meat, and wool. During the nomadism there are conflicts between farmers and nomads on the nomadic routes as the sheep destroy crops in the crop-fields on either side of roads. The conversion of the CGLs to grasslands under controlled grazing is expected to offer four benefits: first, it eliminates the conflicts; the second, it settles lives of nomads; the third, it helps improve conditions of CGLs; and fourth, it fetches income to PRIs that can be utilized for social welfare. If, the sheep are kept in enclosures, land degradation owing to hoofing will be reduced substantially on the nomadic routes and in addition they will enrich the CGLs with nutrient rich urine and faeces (Santra et al. 2017).

The high BCR, seven times more IRR than the bank's lending rate and small pay back period (PBP) together with the highest values of NPV and annuity make the charcoal enterprise the most efficient among the enterprises. The high demand and well established marketing systems are the drivers, which cause the enterprise to earn the highest NPV and annuity. Wakie et al. (2016) also found *P. juliflora* charcoal enterprise the most efficient among 19 enterprises in north-eastern Ethiopia. A major advantage of the charcoal enterprise is that *P. juliflora* is an obnoxious, fire resistant plant, and survives in low rainfall and high temperature regimes of the Desert without extra management. In addition, being a coppicer, it grows more profusely if cut. This enterprise is running in several states of India since last several decades, but regulatory policies are not yet in place (Saxena 1997). During the survey, traders expressed their concerns that the charcoal enterprise is a non-organized sector, therefore, different players in the charcoal making chain are not fully committed to their jobs. This leads sometimes to non-availability of adequate amount of charcoal in markets. Countries like Australia (1941), Brazil (FAO 2007) and Kenya (2009) have developed policies related to charcoal making that protect labourer's rights and damage to environment. Therefore, Indian Govt. should develop policy guidelines for the charcoal making as Australia (1941), Brazil (FAO 2007), and Kenya (Kenya's Forest [Charcoal] Rules 2009) did. The guidelines are expected to help develop the charcoal enterprise as a strong business module like other organized energy sectors (Sato 2013). It has potential to generate about 391,000 employment to labourers in the Desert in addition to reduction in GHG emissions (Faaij and Domac 2006). Though, the BCR, PBP, and IRR of the pod-flour enterprise were closely equal to that of the charcoal enterprise, NPV and annuity was 7.3 and 7.4 times, respectively lower than that of the charcoal enterprise, which made the enterprise relatively inefficient. The poor demand of the animal feed from villages likely made NPV and annuity the low. The sheep rearing is the least efficient among the enterprises, because of the high investment. However, efficiency of the enterprise can be increased by reducing the cost of uprooting and removal of *P. juliflora* by burning the stump of the shrub after spraying a mixture of kerosene and motor oils in 50:50 ratios following felling of the shrub for the charcoal making. The burning of the stump of the shrub with the oil mixture kills epicormic buds below the surface, which are sensitive to fire (Al-shurai and Labrada 2006). But, the enterprise suffers badly during the droughts, which occur very often at 2–3 year intervals in the Desert (Rao 2009). The droughts, not only cause grasslands to grasslands/pastures crash, but also kill livestock due to starvation (Gaur 1993). Once the enterprise is damaged heavily, its revival becomes uneconomical.

In the arid conditions, plant growth is very slow due to low availability of water, but the *P. juliflora* grows very fast (Tewari et al. 2000). Keeping this in view, grafting of *P. alba* Griseb. on the root stocks of *P. juliflora* may be one more option to control invasion of the *P. juliflora* through utilization in the Desert (Felker, Ewens, and Ochoa 2000). The *P. alba* is found to perform well in the experimental fields of the CAZRI, Rajasthan, India (Tewari et al. 2000). Felker, Ewens, and Ochoa (2000) have successfully grafted *P. alba* on the rootstocks of *P. ruscifolia* and thus have converted undesirable stands of *P. ruscifolia* Griseb. into desirable stands of *P. alba*. The *P. alba* contains high sugar content in pods which serves as a human and animal food (Burkart 1976; Oduol et al. 1986) and also provides a good quality lumber, having low radial and tangential shrinkage, that produces a fine quality furniture (Turc and Cutter 1984; Felker, Ewens, and Ochoa 2000).

Conclusions

The study concludes that the *P. juliflora* in the CGLs conserves soil moisture, builds nutrient pool, and increases their availability, but reduces light intensity under its canopy. The reduction in the light intensity changes composition and reduces richness and diversity of native plant species and eliminates some species, particularly perennial grasses. The economic analyses of three *P. juliflora* based enterprises, (i.e. charcoal making, pod-flour making, and sheep rearing), however, suggest that the charcoal making is the most profitable and the pod-flour making the least profitable enterprise. The sheep rearing seems a reasonably good and profitable enterprise, but frequent droughts, which often occur in the Thar Desert, are expected to make it finally uneconomical. The charcoal enterprise has, however, potential to control invasion of the *P. juliflora* efficiently, because the shrub is felled at a 5-year interval and seeds of the shrub are burnt in the kiln during the carbonation. Moreover, it is the most preferred enterprise in the Desert, because it provides employment to low-income groups of people. But, the enterprise suffers sometimes due to an inadequate supply of charcoal from the contractors to retailers, because different players involved in the business are apprehensive about the future of the enterprise, they are not committed to their jobs. Therefore, policy guidelines need to be formulated by the Indian Govt. to protect labourer's rights and damage to the environment of the Desert.

Acknowledgments

The authors are grateful to the respondents for sparing their valuable time to provide information, the three anonymous reviewers and editor for their critical comments on the manuscript; Dr. H. M. Meena for helping in soil sampling, Dr. G. Singh for analyses of the soil samples and Professor S. N. Pandey for editing the English language are thankfully acknowledged.

Funding

The study was funded, under Institute Research Program, by Indian Council of Agricultural Research, New Delhi, India.

ORCID

C. B. Pandey http://orcid.org/0000-0002-1597-4305

References

Al-Homaid, N., and M. H. Khan. 1994. Performance of *Prosopis juliflorra* in different geomorphic units within a sandy desert ecosystem. *Arid Land Research and Management* 8 (2):155–60.

Al-shurai, A., and R. Labrada. 2006. Problems posed by *Prosopis* in Yemen. In *Problems posed by the introduction of Prosopis spp. in selected countries*, edited by R. Labrada, 21–27. Rome: FAO.

Abdulahi, M. M., J. U. Ute, and T. Regasa. 2017. *Prosopis juliflora L*: Distribution, impacts and available control methods in Ethiopia. *Tropical Subtropical Agroecosystems* 20:75–89.

Aronson, J., C. Ovalle, and J. Avendano. 1992. Early growth rate and nitrogen fixation potential in forty-four legume species grown in an acid and a neutral soil from central Chile. *Forest Ecology and Management* 47:1–4.

Australia. 1941. Charcoal (producer gas) act. 1941. legislation.nsw.gov.au/acts/1941-60.pdf.

Badano, E. I., and F. I. Pugnaire. 2004. Invasion of Agave species (Agavaceae) in south-east Spain: Invader demographic parameters and impacts on native species. *Divers Distribution* 10: 493–500. doi:10.1111/j.1366-9516.2004.00086.x

Blossey, B., V. Nuzzo, H. Hinz, and E. Gerber. 2001. Developing biological control of *Alliaria petiolata* (M. Bieb.) Cavara and Grande (garlic mustard). *Natural Areas Journal* 21:357–67.

Borokini, T., and F. Babalola. 2012. Management of invasive plant species in Nigeria through economic exploitation: Lessons from our countries. *Management of Biological Invasions* 3 (1): 45–55. doi:10.3391/mbi.2012.3.1.05

Burkart, A. 1976. A monograph of the genus *Prosopis* (leguminosae subfam. Mimosoidae). *Journal of Arnold Arboretum* 57:219–49.

CAD, IGNP. 2009. Command area development. Indira Gandhi, Nahar Pariyojana, Report, Bikaner, India.

Collier, M. H., J. L. Vankat, and M. R. Hughes. 2002. Diminished plant richness and abundance below *Lonicera maackii*, an invasive shrub. *American Midland Naturalist* 147:60–71. doi: 10.1674/0003-0031(2002)147[0060:DPRAAB]2.0.CO;2

El-Keblawy, A., and A. Al-Rawai. 2007. Impacts of the invasive exotic *Prosopis juliflora* (Sw.) D.C. on the native flora and soils of the UAE. *Plant Ecology* 190:23–35. doi:10.1007/s11258-006-9188-2

Faaij, A. P. C., and J. Domac. 2006. Emerging international bioenergy markets and opportunities for socio-economic development. *Energy Sustainable Development* 10 (1):7–19. doi:10.1016/S0973-0826(08)60503-7

FAO. 2007. Sustainable wood fuel production in Brazil. In *Food and Agriculture Organization Report*, eds. L. A. H. Nogueira, S. T. Coelho, and A. Uhlig. Rome: Food and Agriculture Organization of UN.

Felker, P. 2005. Mesquite flour: New life for an ancient staple. *Gastron Journal of Food Culture* 5 (2):85–9. doi:10.1525/gfc.2005.5.2.85

Felker, P., P. R. Clark, A. E. Laag, and P. F. Pratt. 1981. Salinity tolerance of the tree legumes: Mesquite (*Prosopis glandulosa* var. torreyana, *P. velutina* and *P. articulata*), algarrobo (*P. chilensis*), kiawe (*P. pallid*) and tamarugo (*P. tamarugo*) grown in sand culture on nitrogen-free media. *Plant Soil* 61:311–7. doi:10.1007/BF02182012

Felker, P., M. Ewens, and H. Ochoa. 2000. Environmental influences on grafting success of *Prosopis ruscifolia* (vinal) onto *Prosopis alba* (algarrobo blanco). *Journal of Arid Environments* 46:433–9. doi:10.1006/jare.2000.0686.

Gaertner, M., A. Den Breeyen, C. Hui, and D. M. Richardson. 2009. Impacts of alien plant invasions on species richness in Mediterranean-type ecosystems: A meta-analysis. *Progressive Physical Geography* 33:319–38.

Gaur, M. K. 1993. Shadows of 1987 drought: A catastrophe of Thar Desert. In *Environmental degradation and global awakening*, edited by S. P. Agnihotri, 439–52. Allahabad, India: Chug Publisher.

Gaur, M. K., K. Chand, A. K. Misra, M. M. Roy, M. Louhaichi, and D. E. Johnson. 2015. Monitoring of sheep migration in arid region of Rajasthan, India using EO data. *Journal of Ecological Ecography* 6 (2):1–6. doi:10.4172/2157-7625.1000190.

Girma, M., M. Urge, and G. Animut. 2011. Ground *Prosopis juliflora* pods as feed ingredient in poultry diet: Effects on growth and carcass characteristics of broilers. *International Journal Poultry Science* 10 (12):970–6. doi:10.3923/ijps.2011.970.976

Gupta, T. 1985. Economics of silvi-pastoral systems in India. *FAO Conservation guide* 10:159–67.

Harsh, L. N., and J. C. Tewari. 1998. *Prosopis* in the arid regions of India: Some important aspects of research and development. In *Prosopis species in the arid and semi-arid zones in India*, eds. J. C. Tewari, N. M. Pasiecznik, L. N. Harsh, and P. J. C. Harris, 5–10. Coventry, UK: Prosopis Society of India and the Henry Doubleday Research Association.

Hoffmann, W. A., V. M. P. C. Lucatelli, F. J. Silva, I. N. G. Azeuedo, M. S. Marinho, A. M. S. Albuquerque, A. O. Lopes, and S. P. Moreira. 2004. Impact of the invasive alien grass *Melinis minutiflora* at the savanna-forest ecotone in the Brazilian Cerrado. *Divers Distribution* 10: 99–103. doi:10.1111/j.1366-9516.2004.00063.x

Ilukor, J., S. Rettberg, A. Treydte, and R. Birmer. 2016. To eradicate or not to eradicate? Recommendations on *Prosopis juliflora* management in Afar, Ethiopia, from an interdisciplinary perspective. *Pastoralism: Research, Policy and Practice* 6:14–21. doi:10.1186/s13570-016-0061-1

Jama, B., and A. Zeila. 2005. Agroforestry in the drylands of eastern Africa: A call to action. *ICRAF Working Paper – No. 1*. Nairobi, World Agroforestry Centre.

Kenya's Forest (Charcoal) rules. 2009. faolex.fao.org/docs/pdf/ken101362.pdf. [Rev. 2012] F11-97 Forest (Charcoal) rules, 2009.

Kepner, R. A., R. Bainer, and E. L. Barger. 2005. *Principles of farm machinery*. New Delhi, India: CBS Publishers and Distributors.

Levine, J. M., M. Vila, C. M. D'Antonio, J. S. Dukes, K. Grigulis, and S. Lavorel. 2003. Mechanisms underlying the impacts of exotic plant invasions. *Proceedings Royal Society London B* 270:775–81. doi:10.1098/rspb.2003.2327

Margalef, R. 1958. Information theory in ecology. *General Systematics* 3:36–71.

McConnachie, M., R. Cowling, B. van Wilgen, and D. McConnachie. 2012. Evaluating the cost-effectiveness of invasive alien plant clearing: A case study from South Africa. *Biological Conservation* 155:128–35. doi:10.1016/j.biocon.2012.06.006

Menezes, R. S. C., I. H. Salcedo, and E. T. Elliott. 2002. Microclimate and nutrient dynamics in a silvopastoral system of semi-arid northeastern Brazil. *Agroforestry Systems* 56:27–38. doi:10.1023/A:1021172530939

Mishra, A., S. D. Sharma, and M. K. Gupta. 2003. Soil rehabilitation through afforestation: Evaluation of the performance of *Prosopis juliflora, Dalbergia sissoo* and *Eucalyptus tereticornis* plantations in a sodic environment. *Arid Land Research and Management* 17 (3):257–69. doi:10.1080/15324980301597

Mwangi, E., and B. Swallow. 2008. *Prosopis juliflora* invasion and rural livelihood in the lake Baringo area of Kenya. *Conservation and Society* 6:130–40.

Nakano, H., Y. Fujii, T. Suzuki, K. Yamada, S. Kosemura, S. Yamamura, and K. Hasegawa. 2001. A growth-inhibitory substance exuded from freeze-dried mesquite (*Prosopis juliflora* (Sw.) DC.) leaves. *Plant Growth Regulator* 33:165–8. doi:10.1023/A:1017505702039

Noor, M., U. Salam, and M. A. Khan.1995. Allelopathic effects of *Prosopis juliflora* Swartz. *Journal of Arid Environment* 31:83–90. doi:10.1006/jare.1995.0051

Oduol, P. A., P. Felker, C. R. McKinley, and C. E. Meier. 1986. Variation among selected *Prosopis* families for pod sugar and protein contents. *Forest Ecology and Management* 16: 423–31. doi:10.1016/0378-1127(86)90038-1

Onekon, W. A., and K. O. Kipchirchir. 2016. Assessing the effect of charcoal production and use on the tradition to a green economy in Kenya. *Tropical and Subtropical Agroecosystems* 19: 327–35.

Pandey, C. B., A. K. Singh, and D. K. Sharma. 2000. Soil properties under *Acacia nilotica* trees in a traditional agroforestry systems in Central India. *Agroforestry Systems* 49:53–61. doi:10.1023/A:1006314411454

Pandey, C. B., K. S. Pandya, D. Pandey, and R. B. Sharma. 1999. Growth and productivity of rice (*Oryza sativa*) as affected by *Acacia nilotica* in a traditional agroforestry system in central India. *Tropical Ecology* 40 (1):109–17.

Pandey, C. B., and J. S. Singh. 1991. Influence of grazing and soil conditions on secondary savanna vegetation in India. *Journal of Vegetation Science* 2:95–102. doi:10.2307/3235901

Pandey, C. B., and J. S. Singh. 1992. Influence of rainfall and grazing on herbage dynamics in a seasonally dry tropical savanna. *Plant Ecology* 102:107–24. doi:10.1007/BF00044728

Pandey, C. B., R. B. Rai, and L. Singh. 2007. Seasonal dynamics of mineral N pool and N mineralization in soils under homegarden trees in South Andaman, India. *Agroforestry Systems* 71: 57–66. doi:10.1007/s10457-007-9073-6

Pandey, C. B., R. B. Rai, L. Singh, and A. K. Singh. 2007. Homegardens of Andaman and Nicobar, India. *Agricultural Systems* 92:1–22. doi:10.1016/j.agsy.2006.01.009

Pandey, C. B., R. C. Srivastava, and R. K. Singh. 2009. Soil nitrogen mineralization and microbial biomass relation, and nitrogen conservation in humid tropics. *Soil Science Society of America Journal* 73:1142–49. doi:10.2136/sssaj2008.0182

Pandey, C. B., S. K. Verma, J. C. Dagar, and R. C. Srivastava. 2011. Forage production and nitrogen nutrition in three grasses under coconut tree shades in the humid tropics. *Agroforestry Systems* 83:1–12. doi:10.1007/s10457-011-9407-2

Parsa, M. R., Y. Tsukasaki, E. L. Perkins, and A. L. Chaffee. 2017. The effect of densification on brown coal physical properties and its spontaneous combustion propensity. *Fuel* 193:54–64.

Pasiecznik, N. M., P. Felker, P. Harris, L. Harris, G. Cruz, J. C. Tewari, K. Cadoret, and L. Maldonado. 2001. *The Prosopis juliflora – Prosopis pullida complex: A monograph*. Coventry, UK: HDRA.

Patidar, M., and B. K. Mathur. 2017. Enhancing forage production through a silvi-pastoral system in an arid environment. *Agroforestry Systems* 91:713–27. doi:10.1007/s10457-016-0033-x

Prieur-Richard, A. H., S. Lavorel, Y. B. Linhart, and A. Dos Santos. 2002. Plant diversity, herbivory and resistance of a plant community to invasion in Mediterranean annual communities. *Oecologia* 130:96–104. doi:10.1007/s004420100774

Rao, A. S. 2009. Climate variability and crop production in arid western Rajasthan. In *Trends in Arid Research in India*, edited by. A. Kar, B. K. Garg, M. P. Singh, and S. Kathju, 48–61. Jodhpur, India: Central Arid Zone Research Institute.

Roy, M. M., J. C. Tewari, B. K. Mathur, R. K. Kalia, A. V. S. Sirohi, and P. Rathakrishnan. 2014. *Value chain of value added products derived from Prosopis juliflora. Final Report. Component II, NAIP-ICAR*. Jodhpur, India: Central Arid Zone Research Institute.

Santra, P., P. C. Moharana, M. Kumar, M. L. Soni, C. B. Pandey, S. K. Chaudhari, and A. K. Sikka. 2017. Crop production and economics loss due to wind erosion in hot arid ecosystem of India. *Aeolian Research* 28:71–82. doi:10.1016/j.aeolia.2017.07.009

Sato, T. 2013. Beyond water-intensive agriculture: Expansion of *Prosopis juliflora* and its growing economic use in Tamil Nadu, India. *Land Use Policy* 35:283–92. doi:10.1016/j.landusepol.2013.06.001

Saxena, N. C. 1997. *The woodfuel scenario and policy issues in India*, 75. Bangkok, Thailand: FAO.

Schei, P. J. 1996. Conclusions and recommendations from the UN/Norway conference on alien species. *Science International* 63:32–6.

Shannon, C. E., and W. Weaver. 1949. *The mathematical theory of communication*. Urbana: University of Illinois Press.

Sharma, G. P., A. S. Raghubanshi, and J. S. Singh. 2005. Lantana invasion: An overview. *Weed Biology and Management* 5:157–65. doi:10.1111/j.1445-6664.2005.00178.x

Singh, G., and S. Shukla. 2012. Effect of *Prosopis juliflora* (DC.) tree on under canopy resources, diversity, and productivity of herbaceous vegetation in Indian Desert. *Arid Land Research Management* 26:151–65. doi:10.1080/15324982.2012.656178

Sodha, M. S., R. Chandra, K. Pathak, N. P. Singh, and N. K. Bansal. 1991. Techno economic analysis of typical dryers. *Energy Conservation and Management* 31 (6):509–13. doi:10.1016/0196-8904(91)90085-W

Sparling, G. P., K. N. Whale, and A. J. Ramsay. 1985. Quantifying the contribution from the soil microbial biomass to the extractable P levels of fresh and air dried soils. *Australian Journal of Soil Research* 23:613–21. doi:10.1071/SR9850613

Syomiti, M., H. Hoag, G. Getachew, M. Beatrice, and D. Wamae. 2015. Medicated *Prosopis* spp. based feed-blocks-for anthelmintic efficacy and performance of weaner lambs. *Live Research Rural Development* 27:50.

Tegegn, G. G. 2008. *Experiences on Prosopis juliflora management case of Afar region*. London: FARM-Africa.

Tessema, Y. 2012. Ecological and economic dimensions of the paradoxical invasive species *Prosopis juliflora* and policy challenges. *Ethiopian Journal Economical Sustainable Development* 3 (8):62–70.

Tewari, J. C., P. J. C. Harris, L. N. Harsh, K. Caboret, and N. M. Pasiecznik. 2000. *Managing Prosopis juliflora (vilayati Babul): A technical manual*. Jodhpur, India: Central Arid Zone Research Institute; and Coventry, UK: HDRA.

Turc, C. O., and B. E. Cutter. 1984. Sorption and shrinkage studies of six Argentine woods. *Wood and Fiber Science* 16:575–82.

Van Wilgen, B. W., D. C. Le Maitre, and R. M. Cowling. 1998. Ecosystem services, efficiency, sustainability and equity: South Africa's working for water programme. *Trend in Ecology and Evolution* 13:378. doi:10.1016/S0169-5347(98)01434-7

Wakie, T. T., D. Hoag, P. H. Evangelista, M. Luizz, and M. Laituri. 2016. Is control through utilization a cost effective *Prosopis juliflora* management strategy? *Journal of Environmental Management* 168:74–86. doi:10.1016/j.jenvman.2015.11.054

Walker, K. 2011. Prosopis, an alien among the sacred trees of south India. PhD Dissertation, University of Helsinki.

Warrag, M. O. A. 1995. Autotoxic potential of foliage on seed germination and early growth of mesquite (*Prosopis juliflora*). *Journal of Arid Environment* 31:415–21. doi:10.1016/S0140-1963(05)80124-7

Wetzel, R. G., and G. E. Likens. 1979. *Limnological analysis*. Philadelphia: Saunders.

Whittaker, R. H. 1972. Evolution and measurement of species. *Taxon* 21:213–51. doi:10.2307/1218190

Wilcove, D. S., D. Rothstein, J. Dubow, A. Phillips, and E. Losos, 1998. Quantifying threats to imperilled species in the United States. *Bioscience* 48:607–15. doi:10.2307/1313420

Wise, R. M., B. W. van Wilgen, and D. C. Le Maitre. 2012. Costs, benefits and management options for an invasive alien tree species: The case of mesquite in the Northern Cape, South Africa. *Journal of Arid Environment* 84:80–90. doi:10.1016/j.jaridenv.2012.03.001