Environmental Management
DOI 10.1007/s00267-014-0372-1

Potential of Native Shrubs *Haloxylon salicornicum* and *Calligonum Polygonoides* for Restoration of Degraded Lands in Arid Western Rajasthan, India

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Received: 17 December 2013 / Accepted: 8 September 2014

Abstract Shrub-induced soil property spatial heterogeneity is common in arid and semi-arid ecosystems and aids desertified land restoration. However, the effectiveness of this technique may rely on the plant species used and the habitat conditions present. To assess the degree to which planting two native species, *Haloxylon salicornicum* and *Calligonum polygonoides,* facilitates degraded land restoration, soil and herbaceous plant community properties were measured 7 years after planting. Soil samples were extracted at two depths (0–5 and 5–20 cm) from three sub-habitats, i.e., under the shrub canopy, from alleys between shrubs and from the open area. Shrub planting increased the quantity of silt + clay content (30–39 %); enhanced water holding capacities (24–30 %); increased the levels of organic carbon (48–69 %), available nitrogen (31–47 %), available phosphorus (32–41 %), and electrical conductivity (21–33 %); and decreased the pH (7–12 %) and bulk density levels (5–6 %) in the surface layer of soils beneath the canopy. Soil property changes were more significant at the surface (0–5 cm) than in the deeper layer (5–20 cm), and were more pronounced under *H. salicornicum* than under *C. polygonoides*. Furthermore, the density and biomass levels of herbaceous plants were 1.1 to 1.2 and 1.4 to 1.6 times greater, respectively, in the shrub alleys than in open area. *H. salicornicum* induced more robust soil amelioration and herbaceous plant facilitative properties than did *C. polygonoides*. Artificially planting these shrubs may thus be employed to restore degraded areas of arid regions.

Keywords Arid areas · Shrub effects · Soil properties · Herbaceous plants

Introduction

Arid, semi-arid, and dry sub-humid climatic areas cover approximately 40 % of the global land surface (UNEP 1997). Desertification is a major form of land degradation in these climatic areas (Kassas 1995), which seriously threatens the sustainability of agriculture and economic development. Desertification is impairing the abilities of local peoples to effectively utilize biological, physiological, and ecological resources in these areas (Wezel and Rath 2002). Vegetation restoration is a common practice that is used to combat desertification (Su et al. 2005, 2007). Because shrubs represent a major component of arid and semi-arid vegetation (Facelli and Temby 2002), this vegetation group may therefore be used as an ideal functional group for facilitating restoration. Certain shrub species native to these areas exhibit drought hardiness, wind erosion resistance, and adaptive responses to partial sand

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burial. Such shrub species are often planted to remediate desertification (Su et al. 2002; Zhao et al. 2007).

Numerous studies have shown that the shrub planting enhances soil fine particle content (Zhao et al. 2007), water holding capacities (Su et al. 2005), nutrient content (Titus et al. 2002; Zhao et al. 2007), and microbial biomass and functions (Cao et al. 2011) and improves micro-climatic conditions (Titus et al. 2002) beneath canopies than in open spaces, particularly in arid and semi-arid areas. Favorable soil and micro-climatic conditions underneath shrub canopies act as '*resource islands*' for understory herbaceous plants (Reynolds et al. 1999). These 'resource islands' are critical to desertified land rehabilitation because they may spur natural succession by facilitating the growth of other plants (Gomez-Aparicio et al. 2004). Soil and micro-climatic amelioration by shrub planting results in higher degrees of diversity, density, cover, and biomass in herbaceous species (Facelli and Temby 2002; Zhao et al. 2007). Although fertile islands provide optimal conditions for native plant proliferation, they also provide hospitable environments for several exotic species (Allen et al. 2011). Abella and Smith (2013) reported that in arid areas such as the Mojave Desert in North America, the majority of native perennial species facilitates exotic annual species. Therefore, the degree to which exotic plant growth is aided by native perennials is important to consider when selecting native perennial species for degraded arid land restoration. To effectively realize arid land ecological restoration, the selected species should facilitate native plant recruitment while minimizing exotic species facilitation (Abella et al. 2012).

Although changes in soil properties underneath shrubs are consistent across soil types, climatic conditions, and plant species, the magnitude of such changes is highly variable (Cortina and Maestre 2005). The formation and development of fertile islands are shaped by a range of interacting physical and biotic concentrating mechanisms that are closely related to a number of factors (Li et al. 2007; Schlesinger et al. 1996) that includes shrub species characteristics, canopy size, nutrient uptake via roots and litter deposition (Li et al. 2007), aeolian dust deposition, stem-flow (Whitford et al. 1997), microbial population and rhizosphere root activity, accelerated biogeochemical cycling underneath the canopy (Li et al. 2007), habitat, and climatic conditions (Cortina and Maestre 2005). Shrub species (Li et al. 2007; Titus et al. 2002) and habitat (Li et al. 2008; Su et al. 2004) represent the principle factors that affect the formation and concentration of resource islands. The levels of nutrient enrichment underneath shrubs may vary among species due to differences in vegetative cover (Li et al. 2008), *N* absorption and mineralization, stem runoff, and mineral nutrient absorption (Wezel et al. 2000). At the same time, the concentration of fertile islands may differ across habitats due to differences in water availability, temperature, and nutrient limitation of *N* in particular (Ruiz et al. 2008).

The spatial heterogeneity of soil properties and the facilitation of desertified land restoration by shrubs have been well documented in various regions of the world (Schlesinger et al. 1996; Whitford et al. 1997; Stock et al. 1999; Wezel et al. 2000; Su et al. 2004). However, most studies that describe shrub effects on soil properties have been observational and thus cannot establish cause–effect relationships (Binkley and Giardina 1998). Most studies also lack information on plant age (Jeddi et al. 2009). For example, soils beneath vegetated patches may differ from those underneath open areas where plants are not yet established; thus, differences in soil properties between vegetated patches and open areas may erroneously be attributed to the presence of shrubs alone. An alternative approach to observational study is common garden experimentation, in which species are simultaneously planted under the same growing conditions. This design has successfully been applied to evaluate plant effects on soil properties under a broad range of climatic conditions (Jeddi et al. 2009). However, the use of this technique in dry lands, particularly in arid regions of western Rajasthan, India, has been limited.

The arid area of Western Rajasthan is one of the most severely desertified arid regions in India. Desertified lands account for approximately 84 % of the total area in this region. Wind erosion is the major driver of desertification in this region (Kar et al. 2007). From the 1960s, large areas of degraded land covered by artificial perennial plants have acted as a sand binder, causing noticeable changes to the local ecosystem. However, studies of the effects of native shrub species such as *Calligonum polygonoides* and *Haloxylon salicornicum* on the soil and herbaceous vegetation properties in this region have been scarce. This study was therefore conducted to determine the effect of two native shrub species, i.e., *H. salicornicum* (Moq.) Bunge ex Boiss. and *C. polygonoides* L., on soil and herbaceous vegetation properties 7 years after being planted in the hot, arid region of western Rajasthan, India. Our hypothesis posits that (1) soil physiochemical properties in areas where shrubs are present differ from those in unplanted areas and (2) shrubs aid the establishment of herbaceous plants.

Materials and Methods

Shrub Species

Haloxylon salicornicum (Moq.) Bunge ex Boiss. belongs to the Chenopodiaceae family. The shrub is characterized by

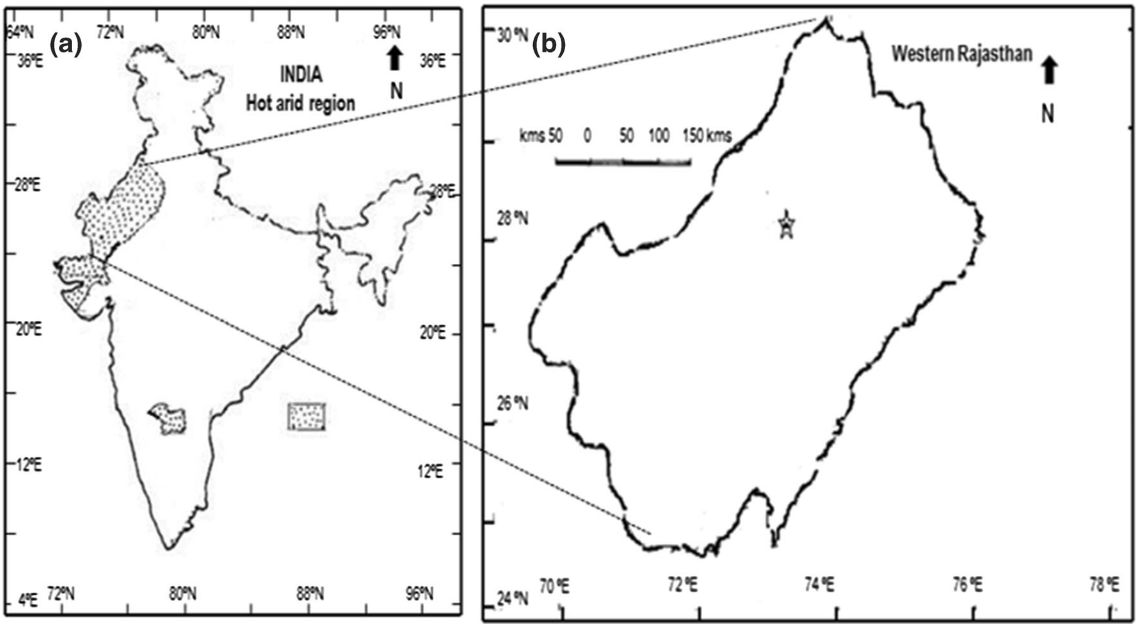

Fig. 1 Location of study area. **a** The hot arid region of India, **b** Western Rajasthan of India and study site (Bikaner, indicated by *star*)

many branches and a woody base. The shrub is generally found in sandy, undulating, and hummocky plains, dunes, and inter-dunes in western Rajasthan, India and forms productive grazing lands in the Thar Desert in association with *Lasiurus sindicus* Henr. and *Panicum turgidum* Forsk. It is frequently used as camel fodder, and fruiting twigs are often used for feeding after being mixed with cluster bean straw and phylloclade of *C. polygonoides*. *C. polygonoides* L. belongs to the Polygonaceae family and is a common woody shrub found in the Thar Desert. The shrub is found throughout western Rajasthan, India, and on sand dunes and sandy plains in particular. It is highly resistant to drought and is harvested for use as fodder, fuel wood, food and used for sand dune stabilization.

Study Site

The arid western Rajasthan (latitude 24°37′00″–30°10′48″ N, longitude 69°29′00″–76°05′33″ E), covering an area of 210,399 km^2, is one of the most severely desertified areas in India. The study was conducted at the Regional Research Station of the Central Arid Zone Research Institute in Bikaner (latitude 28°4′ N; longitude 74°3′ E; elevation 238.3 m above mean sea level), India (Fig. 1). The experimental site is characterized by hot and dry summers, a rainy season, and warm autumn and cool winter weather. The mean annual rainfall levels in the region reach 287 mm with high degrees of inter-annual variability (C.V. 47 %). The majority (~85 %) of the annual rainfall occurs during the monsoon season spanning from June to August (Rao and Singh 1998). The mean annual evaporation reaches approximately 1,800 mm, denoting a high water deficit in the region. The mean maximum temperatures reach 45 °C in May and June. The minimum temperatures range from 3 to 9 °C in December and January, and occasional periods of subfreezing surface temperature occur. The mean wind speeds range from 4 to 6 m s $^{-1}$ from April to June and reach approximately 2 m s^{-1} during the post-monsoon seasons. Southwesterly winds prevail from April to October, and northeasterly winds dominate during intermittent months. Wind erosion processes often occur during the hot summer months from April to June.

The experimental site is composed of soils of loamy sand texture that are taxonomically characterized as the coarse, loamy, mixed, and hyper-thermic family of typic Cambothrid according to the US soil taxonomy classification. Soils in the area are low in organic carbon, N, and P content (Table 3). Original vegetation forms that are reportedly found in the study site four decades prior include perennial grasses viz. *L. sindicus* Henr. and *Cenchrus ciliaris* L. with sparse woody plants [mainly *Capparis decidua* (Forsk.) Edgew., *Ziziphus nummularia* (Burm. f.) W. & A]. Vegetation in the area has changed considerably over the past several decades, primarily due to overgrazing by cattle. Vegetation (measured using the simple transect line method) found in the site at the beginning of the experiment included *Cenchrus biflorus*

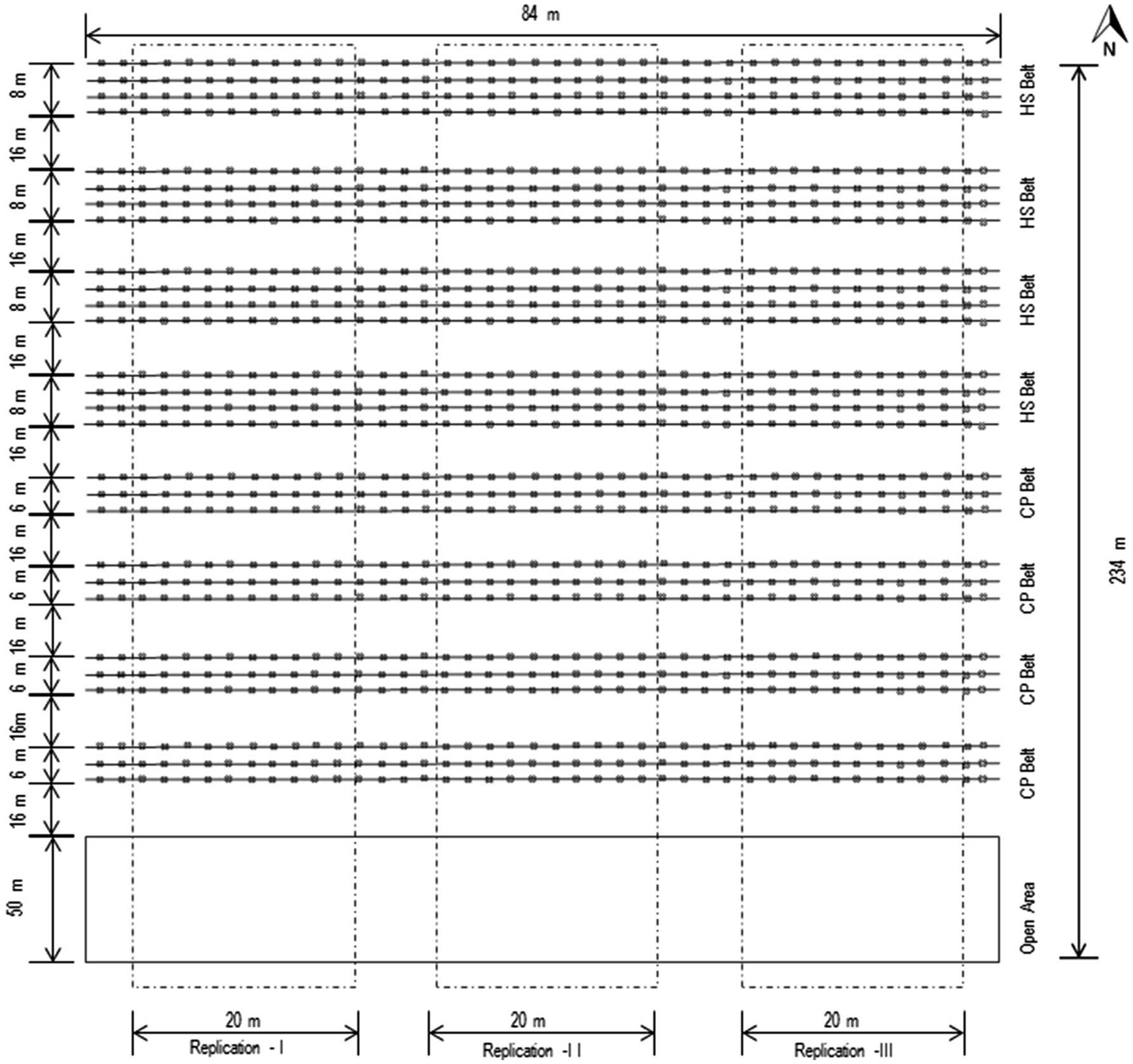

Fig. 2 Layout of experiment. (*HS* stands for *Haloxylon salicornicum* and *CP* stands for *Calligonum polygonoides*)

Roxb, *Dactyloctenium sindicum* Boiss., *Tribulus terrestris* L., *Crotalaria burihia* Buch.—Ham., *Aerva pseudotomentosa* Blatt. & Halb., and *Calotropis procera* (Ait.) R.Br.

Methods

An area of 25 ha was fenced off in 2005 with barbed wire, and grazing was prohibited. A total area of 84 × 234 m^2 was selected as the experimental site (Fig. 2). Three shrub seeds (without any pre-treatment) were sown in individual polythene bags (22 cm in length and 10 cm in diameter) filled with soil collected from the experimental site. After 20 days of emergence, one healthy seedling was kept per bag. Six-month-old seedlings were transplanted in July of 2005 (monsoon season) after a period of rainfall. Twenty-five centimeter diameter and 15 cm depth pits were created 2 × 2 m^2 apart to plant the seedlings. The plants were grown without irrigation and nutrient application. The plants were arranged in belts (rows of 2 m apart). The *H. salicornicum* belt consisted of four rows (width 8 m) of plants, and the *C. polygonoides* belt consisted of three rows (width 6 m). The area underneath each belt of *H. salicornicum* spanned 8 × 84 m^2, and those underneath each *C. polygonoides* belt spanned 6 × 84 m^2. A space of 16 m was left between the two adjacent shrub belts. One hundred sixty-eight plants were placed in the *H. salicornicum* belt, and 126 plants were included in the *C. polygonoides* belt. One hundred sixty *H. salicornicum* and 120 *C. polygonoides* plants constituted one replication. Seven years after the shrubs were transplanted; soil and herbaceous vegetation properties were recorded during the monsoon season of 2012 from three sites: (1) the 7-year *H. salicornicum* plantation area; (2) the 7-year *C. polygonoides* plantation area; and (3) the natural restoration area as a control (areas without planting shrubs are hereafter referred to as the open area).

Soil Sampling and Analysis

To determine the physiochemical properties of the soil at the start of the experiment, soil samples drawn from a depth of 0–20 cm were collected from 45 randomly selected points throughout the demarcated experimental site in the second week of June 2005. After the 7-year period of shrub growth, soil sampling was conducted during the last week of June 2012. Samples were collected from three sites, i.e., underneath the shrub canopy, the shrub alley, and the open area. Soil samples were extracted from two surface layers: 0–5 and 5–20 cm. A total of 15 individual shrubs (sampling points) were randomly selected for soil sampling in each replication. For individual shrubs, soil samples were collected at depths of 0–5 and 5–20 cm from two sub-habitats, i.e., soil underneath the shrub canopy and in the alley between the rows was collected in four directions and mixed as a pooled, depth-wise sample. A total of 180 soil samples (15 shrubs × 2 sub-habitats × 2 soil depths × 3 replications) were collected for each individual shrub species planting area. The mean soil properties of the 15 individual shrubs (sampling point) from one replication were used as the replication values. To measure soil bulk density, a total of 720 soil samples (15 shrubs × 4 directions × 2 sub-habitats × 2 soil depths × 3 replications) were collected from each planted shrub area. For the open area, sampling was carried out at 15 randomly selected points in each replication. Thus, a total of 90 soil samples (15 point × 2 soil depths × 3 replications) were collected from the open area. Soil samples were air-dried and then strained through a 2-mm sieve.

Soil particle size distributions were determined via the Bouyoucos (hydrometer) method, using sodium hexametaphosphate as the dispersing agent. The soil bulk density (BD) was determined via the core method using a known core volume of 100 cm^3. The water holding capacity (WHC) of the soil was determined using Keen's box method. Soil pH and the electrical conductivity (EC) levels were measured from a soil water suspension (1:2.5 soil–water ratio) using pH and EC meters, respectively. The soil organic carbon (OC) content was measured using the $K_2Cr_2O_7{\cdot}H_2SO_4$ oxidation method through application of the Walkley and Black procedure. The available nitrogen content was measured via the alkaline permanganate method. The available phosphorus (AP) content was determined via the Olsen method, using $NaHCO_3$ (pH 8.5) as the extracting agent. The available potassium (AK) content was measured via a flame photometer, using CH_3COONH_4 (1 N) as the extracting agent (Gupta 1999). All of the above listed soil analyses were performed in duplicate.

Shrub Observations

A total of 45 individual shrub plants (15 from each replication) of each species were selected. Height, crown diameter, and branch-count for each shrub were recorded during August of 2012. To measure the crown diameter, two perpendicular diameter measurements were made. Litter on the soil surface was collected over 0.25×0.25 m^2 quadrats. The quadrats were created in July of 2011, and litter was collected at 15-day intervals until June of 2012. The collected litter was air-dried at 70 °C for 48 h and then weighed.

Herbaceous Vegetation Observations

In collecting observations on herbaceous plants at the start of the experiment, 45 quadrats (1×1 m^2) were randomly set across the experimental sites in June of 2005, immediately prior to shrub planting. To collect observations on herbaceous plants 7 years after shrub planting, we randomly placed 15 herb quadrats (1×1 m^2) in each replication across the open area and along the alleys of each shrub-planting area during August 2012. Herbaceous vegetation properties, i.e., plant density, and aboveground biomass values were measured. Vegetation samples were dried in a forced-air oven at 70 °C for 48 h to determine the oven-dry biomass values.

Statistical Analysis

All of results are reported as the mean ± standard error values. The means of the 15 sampling locations for each replication were used as the replicated values. Comparisons of soil parameters between the treatments were restricted by depth. Because two sampling locations (under the shrub canopy and along the shrub alley) were used for the two shrub treatments, and only one open area was included, analysis of variance (ANOVA) and mean comparison calculations were carried out for the five locations (Su et al. 2005) for each soil depth. With respect to herbaceous vegetation properties, comparisons were made between the three locations. One-way ANOVA tests were conducted to compare differences between the locations (Sokal and Rohlf 1995). Pearson correlation coefficients were used to evaluate relationships between soil properties. Least significant difference (LSD) tests were performed to determine the significance of treatment means. Differences reaching the $P < 0.05$ level were considered statistically significant. All of the statistical analyses were performed using the SAS software package.

Table 1 Annual maximum and minimum temperatures, rainfall, and evaporation over the study period at Bikaner (India)

Parameters	2005	2006	2007	2008	2009	2010	2011	2012
Mean annual maximum temperature (°C)	29.1	34.4	31.9	33.0	34.1	33.5	33.9	33.6
Mean annual maximum temperature (°C)	16.5	20.6	18.8	19.1	19.4	20.2	18.2	18.3
Total annual rainfall ($\mathrm{mm\ y^{-1}}$)	284.3	152.2	239.6	273.6	359.3	395.7	416.1	263.6
Total annual evaporation ($\mathrm{mm\ y^{-1}}$)	2,256.4	3,404.7	3,142.3	3,520.7	3,142.3	2,749.8	2,712.8	2,682.3

Table 2 Morphological traits and litter production of shrubs after 7 year of establishment

Trait	*H. salicornicum*	*C. polygonoides*
Plant height (cm)	95.1 ± 4.0	138.8 ± 7.5
Crown diameter (cm × cm)	157.4 ± 6.4 × 167.3 ± 7.3	166.6 ± 7.9 × 182.5 ± 5.7
Number of branches (n $\mathrm{plant^{-1}}$)	13.9 ± 1.3	8.7 ± 0.6
Litter ($\mathrm{g\ m^{-2}}$)	185.5 ± 11.7	156.1 ± 8.5

Values are mean ± SE

Results

Climatic Conditions

The annual rainfall at the study site over the study period varied from 152 to 416 mm, with an average value of 298 mm (Table 1). Less rainfall occurred during the 2006–2007 period, and the 2009–2011 period generated rainfall levels higher than the long-term average rainfall value (287 $\mathrm{mm\ year^{-1}}$) for the study site. The annual evaporation rate ranged from 2,256 to 3,521 mm, and the evaporation rate value was 8 to 22 times higher than that of annual rainfall. The period between 2006 and 2008 was drier than the 2009–2011 period. The mean annual maximum and minimum temperatures were 32.9 and 18.9 °C, respectively, over the study period.

Shrub Morphological Characteristics

The two shrub species differed considerably with respect to morphological characteristics (Table 2). The average height, number of branches per plant, and crown diameter value for *C. polygonoides* were 1.38 m, 8.7, and 1.66 × 1.82 m^2, respectively. The mean values of height, number of branches, and crown diameter for *H. salicornicum* were 0.95 m, 13.9, and 1.57 × 1.67 m^2, respectively. Thus, C. *polygonoides* plants were relatively tall, less branched, and characterized by a Y-shaped crown, whereas *H. salicornicum* plants were short, heavily branched, and characterized by a compact crown. The levels of litter accumulation on the ground underneath the canopy were greater for *H. salicornicum* than for *C. polygonoides.*

Effects of Shrub Species on Soil Properties

Significant differences between most of the analyzed soil physical properties in the shrub plots and open area were observed (Table 3). The 0–5 cm soil layer in the shrub-planted areas exhibited higher silt + clay and WHC quantities and lower BD compared with the open area. The silt + clay values were highest in the 0–5 cm soil layer underneath the canopy shrub-plot sub-habitat, followed by the alley sub-habitat and open-area plots. This was expected due to arresting effect of shrub canopies on wind-eroded fine particles, which deposit underneath and around the canopy. In the 5–20 cm soil layer, differences in sand, silt, and clay content were found to be non-significant in the open area, in the alleys, and in the sub-habitats below the canopies. The bulk density of the 0–5 cm soil layer was found to be significantly higher ($P < 0.05$) in the open area than under canopies of *H. salicornicum* and *C. polygonoides* or in alleys between both shrubs. The water holding capacities in the 0–5 cm soil layer were found to be significantly higher ($P < 0.05$) under the canopy of shrubs than in the open area. Overall, the sand content and BD levels were lower, and the silt + clay content and WHC levels were higher underneath shrub canopies than in the open area. This difference is more pronounced in the 0–5 cm soil layer than in the 5–20 cm layer. It is also more pronounced under the *H. salicornicum* canopy than under the *C. polygonoides* canopy.

The soil chemical property results are presented in Table 3. Significant differences ($P < 0.05$) in the pH, EC, OC, AN, and AP levels were observed in the surface soil layers (0–5 cm) of the different sampling sites. In the

Table 3 Soil properties before planting and after 7 year of shrub establishment under shrub canopies, in alleys of shrubs, and open area at Bikaner, India

Items	Depth (cm)	Before planting	*Haloxylon salicornicum*		*Calligonum polygonoides*		Open area
			Under canopy	Alley	Under canopy	Alley	
Sand (g kg^{-1})	0–5	–	851.7 ± 8.7^{c}	$882.1 \pm 9.3^{a,b}$	$861.7 \pm 9.1^{b,c}$	$886.3 \pm 9.1^{a,b}$	893.3 ± 10.1^{a}
	5–20	–	855.3 ± 9.5^{a}	870.1 ± 11.3^{a}	861.7 ± 10.4^{a}	871.3 ± 7.2^{a}	876.3 ± 8.8^{a}
	0–20	887 ± 7	–	–	–	–	–
Silt (g kg^{-1})	0–5	–	69.7 ± 9.1^{a}	50.7 ± 5.5^{b}	64.0 ± 8.5^{a}	49.7 ± 7.5^{b}	45.7 ± 4.6^{b}
	5–20	–	67.7 ± 8.1^{a}	56.7 ± 9.4^{a}	63.3 ± 9.1^{a}	62.3 ± 9.1^{a}	58.3 ± 9.4^{a}
	0–20	52 ± 3	–	–	–	–	–
Clay (g kg^{-1})	0–5	–	78.7 ± 2.6^{a}	$67.3 \pm 3.8^{b,c}$	$74.3 \pm 3.5^{a,b}$	$64.0 \pm 3.2^{b,c}$	61.1 ± 4.7^{c}
	5–20	–	77.0 ± 4.2^{a}	73.3 ± 4.9^{a}	75.1 ± 3.2^{a}	66.3 ± 5.0^{a}	65.3 ± 3.5^{a}
	0–20	61 ± 2	–	–	–	–	–
BD (Mg m^{-3})[a]	0–5	–	1.45 ± 0.02^{c}	$1.50 \pm 0.01^{b,c}$	1.46 ± 0.01^{c}	$1.51 \pm 0.02^{a,b}$	1.54 ± 0.01^{a}
	5–20	–	1.49 ± 0.01^{a}	1.52 ± 0.02^{a}	1.48 ± 0.04^{a}	1.51 ± 0.01^{a}	1.55 ± 0.02^{a}
	0–20	1.55 ± 0.01	–	–	–	–	–
WHC (% v/v)[b]	0–5	–	8.07 ± 0.14^{a}	$7.05 \pm 0.31^{b,c}$	$7.70 \pm 0.12^{a,b}$	6.62 ± 0.22^{c}	6.20 ± 0.28^{c}
	5–20	–	7.70 ± 0.34^{a}	6.97 ± 0.29^{a}	7.00 ± 0.53^{a}	6.64 ± 0.57^{a}	6.90 ± 0.49^{a}
	0–20	6.31 ± 0.31	–	–	–	–	–
pH	0–5	–	7.47 ± 0.20^{b}	$8.03 \pm 0.18^{a,b}$	$7.88 \pm 0.07^{a,b}$	$8.07 \pm 0.15^{a,b}$	8.50 ± 0.23^{a}
	5–20	–	7.83 ± 0.20^{a}	8.13 ± 0.12^{a}	8.00 ± 0.10^{a}	8.17 ± 0.09^{a}	8.42 ± 0.22^{a}
	0–20	8.59 ± 0.11	–	–	–	–	–
EC (dS m^{-1})[c]	0–5	–	0.20 ± 0.02^{a}	$0.18 \pm 0.01^{a,b}$	$0.19 \pm 0.01^{a,b}$	$0.16 \pm 0.01^{b,c}$	0.15 ± 0.01^{c}
	5–20	–	0.19 ± 0.02^{a}	0.18 ± 0.02^{a}	0.17 ± 0.01^{a}	0.16 ± 0.01^{a}	0.15 ± 0.01^{a}
	0–20	0.16 ± 0.01	–	–	–	–	–
OC (g kg^{-1})[d]	0–5	–	1.29 ± 0.10^{a}	$0.92 \pm 0.07^{b,c}$	$1.13 \pm 0.12^{a,b}$	0.81 ± 0.05^{c}	0.76 ± 0.07^{c}
	5–20	–	0.94 ± 0.06^{a}	$0.75 \pm 0.04^{b,c}$	$0.90 \pm 0.11^{a,b}$	$0.74 \pm 0.08^{b,c}$	0.64 ± 0.05^{c}
	0–20	0.59 ± 0.03	–	–	–	–	–
AN (mg kg^{-1})[e]	0–5	–	53.8 ± 4.4^{a}	$41.2 \pm 4.5^{b,c}$	$48.2 \pm 1.5^{a,b}$	$41.7 \pm 1.4^{b,c}$	$36.7 \pm 3.4^{b,c}$
	5–20	–	49.0 ± 4.1^{a}	38.3 ± 3.8^{a}	43.5 ± 1.5^{a}	38.0 ± 2.5^{a}	34.7 ± 3.5^{a}
	0–20	27.1 ± 2.2	–	–	–	–	–
AP (mg kg^{-1})[f]	0–5	–	6.2 ± 0.4^{a}	$4.8 \pm 0.3^{b,c}$	$5.8 \pm 0.4^{a,b}$	4.7 ± 0.2^{c}	4.4 ± 0.2^{c}
	5–20	–	$5.5 \pm 0.2^{a,b}$	4.3 ± 0.3^{b}	$4.9 \pm 0.4^{a,b}$	4.0 ± 0.3^{b}	4.0 ± 0.5^{b}
	0–20	4.2 ± 0.1	–	–	–	–	–
AK (mg kg^{-1})[g]	0–5	–	133.4 ± 7.3^{a}	104.7 ± 4.9^{b}	$116.0 \pm 9.5^{a,b}$	$99.3 \pm 7.7^{a,b}$	93.8 ± 4.2^{b}
	5–20	–	116.9 ± 9.2^{a}	100.7 ± 10.5^{a}	104.3 ± 8.1^{a}	95.0 ± 8.2^{a}	100.5 ± 2.7^{a}
	0–20	93.2 ± 7.1	–	–	–	–	–

Values are mean ± SE. Values with same letter within rows are not significantly different at $P < 0.05$ according to LSD test

[a] *BD* bulk density

[b] *WHC* water holding capacity

[c] *EC* electrical conductivity

[d] *OC* organic carbon

[e] *AN* available nitrogen

[f] *AP* available phosphorus

[g] *AK* available potassium

5–20 cm soil layers, most of the chemical properties were found to be statistically similar, with the exception of OC and AP content. Overall, OC content reached 0.76–1.29 g kg^{-1} in the 0–5 cm soil layer and 0.64–0.94 g kg^{-1} in the 5–20 cm soil layer. In the open area, OC levels underneath the 7-year-old *H. salicornicum* and *C. polygonoides* plants were 1.7 and 1.5 times greater in the surface (0–5 cm) layer and 1.5 and 1.4 times greater in the sub-surface (5–20 cm) layer, respectively. Using OC content in the open area as the reference level, the net OC accumulation rate was calculated [(OC content under the shrub canopy − OC content in the open area)/year after shrub planting]. Soil OC incorporation in the top 0–5 cm soil layer underneath the canopies of the two species studied ranged from 0.05 to 0.08 g C kg soil^{-1} year^{-1} for *C. polygonoides* and *H. salicornicum*, respectively. The values of EC, AN, and AP were found to be greater ($P < 0.05$) under the shrub canopies compared with the open area, but their proportional increases were lower than those of OC increases in the surface soil layer (0–5 cm). The mean AN, AP, and AK concentrations in the surface soil layer (0–5 cm) under the shrub canopies increased by 31–47, 33–41, and 24–42 %, respectively, differing from those of the open area. Additionally, EC, AN, and AP levels were lower in the deeper layer (5–20 cm) than in the surface layer (0–5 cm), irrespective of shrub species. Furthermore, in the 5–20 cm layer, differences in the EC, AN, and AK values were non-significant between the different sub-habitats. The pH levels decreased in the 0–5 cm soil layer underneath the shrub canopies but did not decrease in the open areas. Overall, the OC, EC, AN, and AP levels were higher, and pH values were lower under the shrub canopies compared with the open areas. These differences were more significant at soil depths of 0–5 cm than at depths of 5–20 cm and were more significant for *H. salicornicum* than for *C. polygonoides*. Spatial gradients for most of the soil properties were observed for sample collected from underneath the canopies and from the shrub alleys (Table 3). Instead, the OC, EC, AN, AP values were higher underneath the shrub canopy than in the alleys for both soil depths (Table 3). The soil pH and BD values followed an opposite pattern, exhibiting lower values underneath the canopies than in the shrub alleys (Table 3).

Effects on Herbaceous Vegetation

Shrub planting significantly affected the herbaceous plant community (Table 4). At the beginning of the experiment, the values for the number of species, plant density, and biomass at the study site were 8, 17 m^{-2}, and 91 g m^{-2}, respectively. Herbaceous plant density and biomass production were significantly greater ($P < 0.05$) in the *H. salicornicum* and *C. polygonoides* alleys than in the open area. After the 7-year shrub-planting period, herbaceous plant density and above-ground biomass values in the shrub alleys were 13–21 and 42–56 % higher, respectively, than the values in the open area. Herbaceous plant density and biomass values were higher in the *H. salicornicum* alleys than in the *C. polygonoides* alleys. A total of 11 species were observed in the area (Table 5). Shrub alleys exhibited the highest number of herbaceous plant species, of which ~50 % were perennials. *Dactyloctenium sindicum* Boiss., *Cenchrus biflorus* Roxb., *C. ciliaris* L., *Corochrus tridens* L., and *Digera muricata* (L.) Mart constituted the main herbaceous plant species present.

Table 4 Herbaceous plant community properties in the alleys of shrubs and open area after 7 year of establishment of shrubs at Bikaner in arid western Rajasthan, India

Items	*H. salicornicum* alleys	*C. polygonoides* alleys	Open area
Species number	5.7 ± 0.6^{a}	5.6 ± 0.3^{a}	5.1 ± 0.2^{a}
Plant density (n m^{-2})	30.5 ± 1.9^{a}	28.0 ± 1.0^{a}	24.1 ± 0.5^{b}
Dry biomass (g m^{-2})	419.9 ± 22.5^{a}	382.0 ± 15.9^{a}	269.0 ± 19.6^{b}

Values are mean ± SE. Values with same letter/s within rows are not significantly different at $P < 0.05$ according to LSD test

Discussion

Plants have a strong capacity to modify the surrounding soil properties through soil-root, vegetation, and environmental interactions (Jeddi et al. 2009). The results of the present study show that planting shrubs on desertified, arid land significantly alters soil physiochemical and herbaceous vegetation properties.

Effects of Shrubs on Soil Physiochemical Properties

Our results show that in comparison to open areas, soils underneath shrub canopies are characterized by 30–39 % higher silt + clay content (Table 3). After the establishment of shrubs, the distance over which soil surface materials are transported by wind decreases, and large quantities of wind-blown, fine-soil materials are collected in the vicinity of shrubs by stem-flow and through-fall processes of dust entrapment and deposition (Wezel et al. 2000). This leads to an increase in silt and clay content in the topsoil underneath shrubs. These trends were confirmed through our particle size analysis (Table 3). In the present study, in comparison with the open area, the soil BD levels decreased underneath shrub canopies, while the WHC levels increased. Silt and clay volumes showed a negative correlation ($r^2 = -0.8$) with BD and a positive correlation with WHC ($r^2 = 0.7$). This decrease in BD levels and increase in WHC levels may be attributable to increases in the silt + clay content (Su et al. 2002; Yang et al. 2011) in soil underneath shrub canopies. Therefore, silt + clay accumulation due to wind-blown fine particle deposition may provide an explanation for the lower BD and higher

Table 5 Herbaceous species composition after 7 year of planting of *H. salicornicum* and *C. polygonoides* at Bikaner, India

Species	Family	Growth form[a]	Life history[b]	HS[f] alley			CP[g] alley			OA[h]		
				Presence/absence[c]	*N*[d]	*P* %[e]	Presence/absence	*N*	*P* %	Presence/absence	*N*	*P* %
Cenchrus biflorus Roxb.	Poaceae	G	A	1	2.7	73	1	1.9	67	1	0.9	73
Cenchrus ciliaris L.	Poaceae	G	P	1	2.5	80	1	1.7	73	1	0.9	60
Cenchrus setigerus Vahl	Poaceae	G	P	1	0.9	40	1	0.3	20	0	0	0
Dactyloctenium sindicum Boiss	Poaceae	G	P	1	10.7	100	1	8.3	100	1	8.4	100
Lasiurus sindicus Henr	Poaceae	G	P	1	1.5	27	1	1.2	53	1	0.8	60
Panicum antidotale Retz.	Poaceae	G	P	0	0	0	1	0.1	7	0	0	0
Indigofera cordifolia Heyne ex Roth	Leguminoseae	H	A	1	0.2	13	1	0.2	20	0	0	0
Corochrus tridens L.	Tiliaceae	H	A	1	3.3	87	1	7.1	100	1	6.3	100
Digera Muricata (L.) Mart.	Amaranthaceae	H	A	1	1.7	67	1	0.4	20	1	0.1	13
Tribulus pentandraus Forsk.	Zygophyllaceae	H	A	1	6.7	87	1	6.9	93	1	6.7	100
Tribulus terrestris L.	Zygophyllaceae	H	A	1	0.3	7	0	0	0	1	0.1	7

[a] *G* is grass, *H* is herb

[b] *P* is perennial, *A* is annual

[c] 1 is presence of species and 0 is absence of species

[d] *N* is number of individual per 1 m^2

[e] *P* % is frequency

[f] HS is *H. salicornicum*

[g] CP is *C. polygonoides*

[h] *OA* is open area

WHC values underneath shrub canopies compared with open areas observed in the present study.

The results of the present study denote a significant enrichment of OC, AN, and AP reserves underneath shrubs (Table 3). This mechanism likely occurs in response to two factors. First, improved vegetation cover is likely to reduce soil erosion while trapping wind-blown, nutrient-enriched, fine materials from surrounding open areas (Wezel et al. 2000). Second, OC and nutrient enhancements are largely attributable to plant litter and root mass additions to the soil (Zhang et al. 2006). In the present study, in comparison with the open areas, the OC levels were 1.7 times higher underneath *H. salicornicum* plants and 1.5 times higher underneath *C. polygonoides* plants. The soil nutrient levels (AN, AP, and AK) followed the same pattern, supporting other studies showing a high degree of co-variation between OC and nutrient levels (Whitford et al. 1997). Increases in P availability underneath shrub canopies may be a consequence of various factors such as accumulated litter and roots, animal fragmentation of particulate OM and soil aggregates, and high root phosphatase activity (Chen 2003). Significant positive correlations between OC and AN ($r^2 = 0.7$) and AP ($r^2 = 0.8$) in the soils indicate that higher concentrations of N and P are linked to higher OC content in soils, as OC is one of the most important factors contributing to nutrient storage in nutrient-poor sandy soils (Wezel et al. 2000). The change in AN content was less pronounced than the change in OC content. This may be attributable to the differing accumulation mechanisms associated with OC and N. Whereas OC is derived mainly from plant material decomposition, N is generated from mineralization, and N accumulation requires more favorable conditions than C accumulation (Cheng et al. 2004). Higher EC values in the 0–5 cm soils were observed after shrubs were established (Table 3), particularly underneath the shrub canopies, reflecting the accumulation of soluble salts in the litter material (Su et al. 2005). In this study, however, the increase in EC due to shrub establishment did not necessarily result in an increase in soil salinity because the EC values were relatively low. The EC values were positively correlated ($r^2 = 0.7$) with SOC content and likely reflected an enhancement of soil nutrient concentrations released through litter decomposition. Reduced pH levels in the 0–5 cm soil layer were most likely related to vegetative cover, as extensive secretions of organic acids and the release of CO_2 from litter, roots, and microorganisms can decrease pH levels (Tornquist et al. 1999). A review of the soil property results shows that the effect of shrub planting on soil amelioration was not appreciable in the deeper soil layer (5–20 cm depth), with the exception of OC and AP volumes underneath the shrub canopies (Table 3). This result complements previous findings (Li et al. 2008; Su et al. 2004) that fertile island concentrations underneath shrubs are greater at the soil surface than in deeper soil layers. However, in the desert of northern Namaqualand in South Africa, Stock et al. (1999) found that fertile island concentrations underneath *R. cyathiformis*, *S. utilis*, and *Ruschia* sp. did not change across soil layers. This is likely because the shrubs studied in northern Namaqualand were not yet old enough to generate vertical heterogeneity (Li et al. 2008). In natural ecosystems, soil surface littering and fine root turnover are regarded as the main pathways for the addition of OC and other nutrients derived from organic matter (Cao et al. 2011). Due to higher inputs of organic material at the soil surface, OC, AN, and AP levels decreased with soil depth. Additionally, slow litter turnovers over short plantation periods are most likely responsible for the lower OC and nutrient values in deeper soil layers in the present study.

These results indicate that differences in soil properties modify the influence of *H. salicornicum* and *C. polygonoides* (Table 3). *H. salicornicum* had a stronger effect than *C. polygonoides*. It was found that the accumulation of wind-blown soil particles and litter by shrubs is heavily dependent on canopy characteristics (Li et al. 2008; Reynolds et al. 1999). *H. salicornicum* shrubs possessed higher concentrations of branches and denser canopies relative to *C. polygonoides* (Table 2). Thus, *H. salicornicum* may have trapped more transported soil and litter, which may have caused more significant changes in physical properties (higher silt + clay content, WHC, and lower BD) than those caused by *C. polygonoides*. Singh et al. (2005) found that shrub branch concentrations show the strongest positive correlation with soil deposition levels beneath shrub canopies. *H. salicornicum* caused a higher degree of OC and nutrient enrichment than *C. polygonoides*. In this case, the quantity and composition of fallen litter may be of little importance. The analysis showed that *H. salicornicum* contributed higher levels of litter than *C. polygonoides* (Table 2), and fallen litter from *H. salicornicum* contained higher levels of N content (13.4 ± 1.3 g kg^{-1}) than that of *C. polygonoides* (9.7 ± 1.4 g kg^{-1}). In addition, N and P accumulation underneath shrubs resulted to a lesser degree from the deposition of fine, wind-blown particle fractions enriched with nutrients. The soil silt + clay volumes underneath the *H. salicornicum* canopy were ~10 % higher than those underneath the *C. polygonoides* canopy. Thus, the higher degree of litter addition, nutrient content, and fine, wind-blown soil particle and plant debris entrapment may be responsible for higher degrees of nutrient enrichment underneath *H. salicornicum* shrubs than *C. polygonoides* shrubs.

These results suggest the existence of concentration gradients for sub-habitats underneath canopies in shrub alleys for OC, AN, and AP. Processes of nutrient enrichment underneath shrub canopies were greater than such processes that occurred in the shrub alleys (Table 3). This occurred due to the presence of larger volumes of accumulated litter and root biomass beneath the canopies than in sections of land far from the center of the shrub area, resulting in higher nutrient content beneath canopies than in shrub alleys Furthermore, crown soil beneath shrubs suffers from relatively weaker processes of wind erosion and is likely affected by influxes of fine particles and litter via wind-blown material trapping (Wezel et al. 2000) to a greater degree than shrub alleys.

Restoration of Herbaceous Plant Species Following Shrub Establishment

The establishment of shrubs improved the properties of the herbaceous plant community examined in our study (Table 4). Shrub establishment can aid herbaceous plant communities in desert areas by creating a suitable microclimate and soil environment and by trapping seeds (Su et al. 2004). Three principal mechanisms likely contributed to herbaceous plant community improvements over the course of sandy, desertified, land restoration. First, shrubs act as seed accumulators by shielding wind-dispersed seeds on herbaceous species, thereby enhancing possibilities for recruitment. Second, even when plant recruitment does not occur in open spaces, seedling establishment is often possible under the shade of existing ‘nurse’ shrubs, allowing for the colonization and long-term persistence of herbaceous species (Shumway 2000). Third, reduced soil erosion and improved soil properties associated with shrub development create a nutrient-rich, water-retaining substrate, thus providing a better environment for germination, seedling growth, and productivity in water and nutrient-poor environments (Shumway 2000; Su et al. 2002). In the present study, the establishment of shrubs resulted in significant accumulations of OC, AN, and AP and improved WHC levels underneath canopies, creating “*islands of resources*” surrounding shrubs, improving colonization rates and the development of herbaceous plant communities, and paving the way for vegetative expansion by ameliorating stressful environmental conditions. Our finding that biomass yields of herbaceous plants were higher in shrub alleys than in open areas is consistent with the other studies (Shmida and Whittaker 1981) of arid areas. Because *H. salicornicum* planting more effectively trapped wind-blown materials and ameliorated soils than did

C. polygonoides, vegetation restoration is more efficiently induced through *H. salicornicum* planting than through *C. polygonoides* establishment. Ecological restorations of degraded lands must compete with invasions by exotic species. A fundamental goal of restoration is to identify native species that more effectively compete with exotic species and which are capable of preventing invasion (Abella et al. 2011, 2012). In the present study, we did not find any exotic herbaceous plant species in the restored areas. Thus, the results of the present study indicate that degraded land restoration using *H. salicornicum* and *C. polygonoides* is not affected by exotic species invasion.

Conclusions

The planting of woody shrub species as a restoration tool constitutes a crucial step toward desertified arid land restoration. The results of the present study indicate that the establishment of *H. salicornicum* and *C. polygonoides* shrubs alters physical soil traits and enhances soil nutrients. Their establishment also facilitates the development of surrounding herbaceous plant communities. Of the two species studied here, *H. salicornicum* exhibited a stronger capacity to improve soil conditions and herbaceous plant communities than *C. polygonoides*. Overall, these finding imply that shrub establishment plays an important role in the reestablishment of desertified ecosystems in arid regions.

Acknowledgments This study was conducted as part of the Institute project T 02-22 funded by Central Arid Zone Research Institute, Jodhpur. We wish to thank Director, CAZRI for providing funds and necessary facilities to carry out the study, and B. M. Yadav and Bharu Singh for their assistance in data collection and laboratory work. This manuscript was improved by comments from P. Santra and R. Ravi. Our thanks also to the journal editors and three anonymous reviewers for careful and thoughtful evaluations and suggestions.

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