Abiotic processes are insufficient for fertile island development: A ten-year artificial shrub experiment in a desert grassland

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Abstract

The relative importance of biotic and abiotic processes in the development of "fertile islands" in dryland systems has rarely been investigated. Here, we approached this question by using artificial shrubs, which exclude plant litter production and soil nutrient uptake, but retain the functions of trapping windblown material, funneling of stemflow, and differential rain splash. We conducted a vegetation manipulation study more than a decade ago in the desert grassland of southern New Mexico, and subsequently revisited the site in 2012 and 2015. The results show that no notable soil mounds were observed under the artificial shrubs, however, soil texture under the artificial shrubs has gradually changed to resemble the patterns of soil particle-size distribution under natural shrubs. Our results highlight that with the exclusion of direct biotic additions, soils captured by shrub canopies are not necessarily fertile and thus do not themselves contribute to the development of fertile islands.

Keywords: Shrub encroachment, Ecosystem change, Soil carbon, Soil nitrogen, Windblown sediment, Resource heterogeneity

Key Points:
- Artificial shrubs were used to study the relative importance of biotic and abiotic processes in fertile islands development
- No notable fertile islands were observed after 10 years
- Aeolian processes are not efficient in fertile island development in the absence of biotic additions

1. Introduction

The desert grasslands of the southwestern United States have undergone extensive woody shrub encroachment in the last 150 years [*Van Auken*, 2000; *Gibbens et al.*, 2005]. Along with the shrub encroachment is the increase of soil resource heterogeneity, in which soil resources (e.g., nutrients, organic matter, fine soil particles) move from the shrub interspaces to the area beneath shrub canopies, forming "fertile islands" or "resource islands" [*Schlesinger et al.*, 1990; *Schlesinger et al.*, 1996; *Reynolds et al.*, 1999]. Fertile islands have been documented in desert habitats on all continents, but they are particularly well described in the desert grassland of the southwestern United States [e.g., *Schlesinger and Pilmanis*, 1998; *Okin and Gillette*, 2001; *Shade and Hobbie*, 2005; *Thompson et al.*, 2005; *Ravi and D'Odorico*, 2009; *Ravi et al.*, 2011; *Allington and Valone*, 2014]. The conversion of perennial grasslands into desert shrublands and the consequent redistribution of soil resources have important implications for local pastoral economics, regional and global climate, biogeochemical cycles, biodiversity, and human health [*Schlesinger et al.*, 1990; *Jackson et al.*, 2002; *Ravi et al.*, 2009; *Eldridge et al.*, 2011; *D'Odorico et al.*, 2012].

Both biotic and abiotic processes have been invoked to explain the initiation and persistence of fertile islands in the desert grassland of the southwestern United States (Figure 1a). Biotic processes may include the deposition of litter in the localized areas beneath shrubs, and plant uptake of essential nutrients, whereas abiotic processes primarily include trapping of windblown materials, and directional transport of soil materials by differential rainsplash [e.g., *Schlesinger and Pilmanis*, 1998; *Wainwright et al.*, 1999; *Ridolfi et al.*, 2008]. Numerous studies have examined the recovery trajectories of microsites located undershrub and in shrub interspace in response to physical and biological manipulations in shrub deserts [e.g., *Li et al.*, 2008; *Sankey et al.*, 2011; 2012; *Minick and Alward*, 2015]. No study to date, however, has explicitly studied the relative importance of biotic versus abiotic

processes during the formation of fertile islands, although *Schlesinger et al.* [1996] pointed out the important role of physical (abiotic) processes in the accumulation of non-limiting elements such as chloride (Cl) and sulfur (S) in desert ecosystems.

In spring 2004, we established a landscape-scale, vegetation manipulation experiment to investigate the role of aeolian processes in ecosystem change in the desert grassland of southern New Mexico [see *Li et al.*, 2007]. While the results of this experiment speak strongly for the importance of erosion, redistribution, and deposition of aeolian materials in the rapid change of the spatial distribution of soil resources, the layout of the experiment cannot control the potentially independent roles of abiotic and biotic processes [*Li et al.*, 2007; 2008; 2009a; 2009b]. Consequently, the relative importance of biotic and abiotic processes in the development of soil resource heterogeneity is still unknown. With the recent advent and use of abiotic barriers for restoration of arid and semiarid systems [*Rachal et al.*, 2015; *Fick et al.*, 2016], an understanding of the longer-term effects of these types of interventions is critically needed.

The objective of this study is to address a fundamental question of ecosystem changes in the desert grassland of the southwestern United States: would abiotic processes alone, be able to form soil resource islands in this landscape? Our overall hypothesis is that physical barriers to aeolian sediment movement can trap nutrient-rich fine particles, therefore, creating resource islands beneath the barrier in the absence of biotic additions (e.g., litter fall and root turnover). We approached this question by using artificial shrubs, which exclude plant litter production and soil nutrient uptake, but retain the functions of trapping windblown material and funneling of stemflow movement (Figure 1b). In this study, we monitored soil resources that are indicative of fertile island development, including soil nitrogen (N), soil carbon (C),

and soil particle-size distribution, under and outside the artificial shrubs as well as a number of natural shrubs located nearby.

2. Materials and Methods

2.1. Experimental sites

The study was conducted at the Jornada Experimental Range (JER), located in a desert grassland of the Chihuahuan Desert, southern New Mexico. This area has an annual mean temperature of 15.6°C and mean annual precipitation of 247 mm. The JER experiences highly consistent southwesterly winds from March to May, which cause substantial transport of windblown material [e.g., *Li et al.*, 2007; *Bergametti and Gillette*, 2010]. Elevation of the JER varies between 1,200 to 1,300 m. The invasion of honey mesquite (*Prosopis glandulosa*) at the experimental site was light compared to other areas at the JER. The dominant grasses at the site are genus *Sporobulus*, with a moderate cover of black grama (*Bouteloua eriopoda*) and yucca (*Yucca elata*). The experimental plots are located on a "sand sheet" geomorphic surface with a relatively flat terrain. As a result, transport of soil nutrients and particulate matter is strongly dominated by wind compared to water.

2.2. Experimental design

Five replicated artificial shrub experimental plots were set up in June 2005. No shrubs or notable dunes were observed on the replicated experimental plots at the time of the experimental setup. The five replicated experimental plots were aligned in a direction perpendicular to the prevailing wind, separated by a distance of ~ 35 m. Each experimental plot has the size of 5 × 5 m and was enclosed by a barbed wire fence. At approximately the geometrical center of each experimental plot, an artificial shrub was placed in unvegetated bare patches and installed 30-40 cm deep into the ground. The exact location of the artificial shrubs within the experimental plots varied slightly in order to avoid direct contact or placement immediately downwind of an existing shrub or bunch grass. The artificial shrubs,

purchased from a local store, were made of polyvinyl chloride (PVC) and closely resemble miniature ponderosa pines. Upon the installation, the artificial shrubs had a dimension of approximately 65 cm (W) × 50 cm (H). To prevent the growth of existing plants under the "canopy" of the artificial shrubs, seedlings were removed by hand upon the experimental setup.

A natural shrub plot, located within 200 m of the artificial shrub plots and established in 2005, was also identified and monitored. This plot was created by the grass manipulation experiment, and it enclosed an area of 25 × 50 m with a number of natural mesquite shrubs [*Li et al*., 2007; 2008]. No dunes were present at these sites in 2005 but by July, 2105, dunes under these mesquite shrubs had an average width of 3.3 m and height of 0.51 m. More information about the artificial and natural shrub plots is listed in Table 1.

2.3. Sampling and measurements

The artificial shrub plots were revisited in July 2012 and July 2015. Upon the initial experimental setup and subsequent revisits, soil samples from under and outside of the shrub canopies were collected. In particular, a number of soil samples (*n*>3) were collected from different directions beneath the artificial shrub canopy (hereafter called "under canopy") and these soil samples were composited to form one single sample to represent the soil under the shrub canopy on each of the artificial shrub plots. Soil samples outside of the artificial shrubs canopies (hereafter called "interspace") were collected at directions parallel and perpendicular to the prevailing winds, within a 2 m diameter of the artificial shrub. A total of 8 soil samples (2 from each direction) were collected from the interspace of each artificial shrub. Similar soil sampling was also conducted in the natural shrub plot in 2015. A total of 6 mesquite shrubs were identified and sampled. All soil samples were collected from the top 5 cm of the soil profile.

2.4. Laboratory analysis

In the laboratory, all soil samples were air-dried and then sieved to remove roots and debris >2 mm. Soil samples were first analyzed for particle-size distribution using an automatic sieve (Gilson Company Inc., Gilsonic, GA-6). This automatic sieve separates soil particles using acoustic energy to create continuous agitation and add horizontal and vertical tapping to reorient particles to the mesh surface. The automatic sieve generates 3600 sonic pulses per minute and the operation time for each sample was 5 minutes.

Carbon and N analysis was conducted using an elemental analyzer (Costech Analytical, ECS 4010) coupled under continuous flow to a stable isotope ratio mass spectrometer (Thermo Scientific, Delta V Plus). The elemental composition (in wt %) of total C (TC) and total N (TN) were determined by thermal conductivity detector (TCD) in the elemental analyzer. The C isotope ($\delta^{13}C$) for all soil samples was also analyzed. Values of $\delta^{13}C$ were expected to indicate the relative contribution of fertile island organic matter from shrubs (C3 plants with lower $\delta^{13}C$) and grasses (C4 plants with higher $\delta^{13}C$). The $\delta^{13}C$ values were reported in standard δ-notation and normalized relative to Vienna Pee Dee Belemnite (VPDB). Analytical precision for $\delta^{13}C$ was within 0.2‰ based on replicate measurements of internal (Buffalo River Sediment, SRM 8704) and international standards (USGS-40 and IAEA CH6). *Li et al*. [2007] showed that inorganic C only accounts for a very small portion (e.g., <1%) of TC in the soil of the study area. Therefore, inorganic C was not removed from the soil samples prior to C isotopic analysis.

2.5. Data analysis

The mean and standard deviation of soil particle size in each size fraction, soil TC, TN, and $\delta^{13}C$ were calculated for samples taken under and in the interspaces of artificial and natural shrubs. A t test was conducted to deduce significant difference between these means. In addition, an enrichment index (F_i) was calculated to quantify the difference between soil resources (e.g., grain size distribution, TC, and TN) located under and in the shrub interspace:

$$F_i = \frac{U_i}{I_i}$$

where U_i and I_i are the i_{th} soil resource measured under shrub and in the shrub interspace, respectively. In general, $F_i > 1$ indicates the accumulation of that soil resource under the shrub relative to the interspace and therefore the reinforcement of fertile islands, whereas $F_i < 1$ signifies the loss of that soil resource under the shrub relative to the interspace and therefore the dissipation of fertile islands.

3. Results

Upon the revisits in 2012 and 2015, the artificial shrubs were slightly damaged and some of the leaves were lost. No notable soil mounds were observed under the artificial shrub canopies, and no natural shrubs or dunes were present in the artificial shrub plots. Soil particles with diameter >1 mm only accounted for a small percent of the total soil mass and they were not subject to further analysis. The recoveries of soil samples after the particle-size analysis averaged 99.5% of sample weight.

3.1. Change of soil texture

At the time of the experimental setup (June 2005), soils in the artificial shrub plots were dominated by sand (>90%) and no significant differences were observed between soils collected under the artificial shrub canopies and the shrub interspaces (Figure 2a, 2e, Table 2). After 7 to 10 years, despite the fact that no systematic soil texture changes were observed, the relative abundance of soil particles at certain size ranges has changed significantly in the

artificial shrub plots (Figure 2). In both 2012 and 2015, the fraction of soil particles ranging from 0.212-0.5 mm was significantly higher under the artificial shrub canopies compared to the shrub interspaces ($p<0.05$). The fraction of particles finer than 0.053 mm, however, was lower for soils collected from under shrub canopies than those of the interspaces, corresponding to the enrichment index of 0.62 and 0.65 for 2012 and 2015, respectively (Figure 2f, 2g, Table 2). Overall, the pattern of soil particle-size distribution in the artificial shrub plots closely resembled that of the natural shrub plot, particularly for soil particles <0.5 mm (Figure 2h).

3.2. Change of soil C, N

In the artificial shrub plots, at the beginning of the experiment in 2005, little difference was observed for soil TC, TN, C/N ratio, and δ^{13}C between the soils collected from under canopies and in the canopy interspaces. Upon the revisits in 2012 and 2015, both soil TC and TN in the artificial shrub plots were slightly more abundant in the canopy interspaces relative to those of under canopies (Figure 3, Table 2). However, soils from the interspaces had slightly lower δ^{13}C values than those of under canopies in the artificial shrub plots. Soil C/N ratio, however, was significantly higher under artificial shrub canopies than that of the interspaces by 2015 (Figure 3). With the exception of δ^{13}C, these soil C and N properties did not resemble the pattern observed in the natural shrub plots.

The enrichment indices of C and N in the artificial shrub plots are significantly different from those of the natural shrub plot. Since the experimental setup, the enrichment indices of C and N in the artificial shrub plots have decreased steadily to well below 1 (Table 2).

4. Discussion

Disentangling biotic versus abiotic factors in the formation of fertile islands has been the focus of a number of studies concerning woody shrub encroachment in the desert grassland of the southwestern United States and elsewhere in the world. Other studies, however, either lack long-term observations [e.g., *Schlesinger et al*., 1996; *Schlesinger and Pilmanis*, 1998, *Stock et al*., 1999] or are limited by the experimental setup that cannot exclude the biotic additions [e.g., *Reynolds et al*., 1999; *Walker et al*., 2001; *Li et al*., 2007; 2008].

We approached this fundamental question by resampling areas associated with an experiment initiated in 2005 that involved placement of artificial shrubs in a wind-susceptible shrubby grassland in the north Chihuahuan Desert. The application of artificial shrubs allowed us to exclude biotic processes such as litter deposition and plant uptake of nutrients, and to focus only on the abiotic factors including directional movement of water and the trapping of windborne materials (Figure 1). The reported time scales for fertile islands and nebkha dune development varies in different systems with different characteristics of soil, wind, and disturbance. For example, Graham *Gadzia and Ludwig* [1983] revealed that it would take <20 years to form a dune with a volume of 1 m^3 under mesquite shrubs at the JER. A study in semi-arid northern China found that nebkha dunes may be formed 5-6 years after the land was reclaimed [*Wang et al*., 2006]. A most recent study by *Kidron and Zohar* [2016] showed that it would take up to 150 years to form a coppice dune of 60 cm-high in the Negev Desert of Israel. At the JER, the experimental period of 10 years is likely long enough for the development of fertile islands and nebkha topography as *Li et al*. [2008] showed that substantial fertile islands could be formed in a period of 3 years under natural mesquite shrubs. This site was installed in the same year as the artificial shrubs discussed here, and significant (~ 1 m) soil mounds (nebkhas) have developed at this site since the beginning of the experiment.

For the case of artificial shrubs, however, we did not observe measurable soil mounds under the shrubs. Nevertheless, the relative distribution of soil particles under artificial shrub canopies and shrub interspaces suggests that soil materials have begun to accumulate under the artificial shrubs. In general, the spatial distribution of soil particles in the artificial shrub plots has gradually changed to resemble the patterns of soil distribution in the natural shrub plot, i.e., the accumulation of fine sand, silt, and clay in the shrub interspaces and the accumulation of relatively coarse sand under shrub canopies (Figure 2). Such an alteration in soil particle-size distribution along the formation of fertile islands has also been observed by other studies in the Chihuahuan Desert and elsewhere in the world [*Cross and Schlesinger*, 1999; *Titus et al.*, 2002; *Dunkerley*, 2000; *Wezel et al.*, 2000]. The accumulation of silt and clay particles in the interspace of the artificial shrub plots, and the high similarity of $\delta^{13}C$ between artificial and natural shrubs indicates that artificial shrubs, similar to natural shrubs, direct fine soil particle movement from under canopies to interspaces in response to the action of wind or rain.

The accumulation of soil particles in the range of 0.212-0.5 mm under both the artificial and natural shrubs suggests that the shrubs are more effective in catching windblown sediments in certain size ranges. This preferred deposition of soil particles under the shrubs may be explained by the characteristics of aeolian transport and the structure of the shrub canopies at the experimental site. Studies have shown that the average background level of horizontal sediment flux in the study area is ~0.25 g cm^{-1} day^{-1} [*Li et al.*, 2007; *Bergametti and Gillette*, 2010]. These windblown sediments are produced primarily by saltation, a mechanism of aeolian sediment transport that occurs close to the ground (e.g., <1 m), for particles with diameter in the range of 0.02-0.5 mm [*Gillette et al.*, 1997; *Field et al.*, 2010]. In the same natural shrub plot, *Li et al.* [2009b] found that the saltation layer was between 0.30 to 0.45 m and the particle size at this height was mainly the 0.25-0.5 mm fraction. These

sediments, thus are the primary available particles that may be captured by the artificial shrubs. Silt and clay particles, on the other hand, travel primarily by suspension at the height of over 1 m [*Bagnold*, 1941], therefore are less likely to be trapped by either the artificial or the natural shrubs in this study.

The interception of windblown sediments by the artificial shrubs did not necessarily increase soil fertility under the shrub canopies. Our experimental results show minimal changes in soil TC and TN beneath the artificial shrubs. The relative concentration between the shrub canopy and interspace was different from the natural shrub plot, where both C and N are more concentrated under the shrub canopies than the interspaces. *Li et al.* [2009b] analyzed C and N content of windblown sediments collected at the height of 0.3 m and the authors found that sediments with particle size in the range of 0.25-0.5 mm contain disproportionately less amounts of C and N relative to their total mass. The insignificant change of soil C and N under the artificial shrubs observed in the current study was therefore related to the interception of low-nutrient saltating sands, as most of the effective biotic additions are missing. The accumulation of C and N under natural mesquite shrubs, on the other hand, is the result of windblown sediment interception and more importantly, the biotic additions including litter decomposition, root uptake, and nitrogen-fixing in their rooting system [*Schlesinger and Pilmanis*, 1998; *Reynolds et al.*, 1999].

The aeolian sediment transport in the artificial shrub plots was much lower than that of the natural shrub plot monitored in this study (Table 1). The high aeolian sediment transport in the natural shrub plot has resulted in a notable growth of shrub islands under the mesquites, i.e., from an aveage width of 1.5 m in 2005 [*Li et al.*, 2008] to 3.3 m in 2015. The slow formation of soil mounds under the artificial shrubs may be the net consequence of a number of factors: 1) the aeolian sediment flux was low in the artificial shrub experimental sites, 2) the directional movement of soil particles from under shrub canopy to shrub

interspace may also partially counteract the accumulation of soil particles under the shrub, and 3) very importantly, the disconnection of the positive feedback to the growth of shrub dunes and the development of fertile islands that is essential in the natural shrub dune systems [*Schlesinger et al.*, 1990; *D'Odorico et al.*, 2012]. With regard to vegetation structure, *Raupach et al.* [2001] concluded that the efficiency of entrapment of windborne particles was related to optical porosity. Although optical porosity was not measured in this experiment, visual inspection indicates that the optical porosities of the real and artificial shrubs is not much different. Thus, the efficiency of entrapment between the two structures is also not likely considerably different. As a result, we do not believe that structural differences between the two is a major contributor to the differences in mound development between the real and artificial shrubs.

5. Conclusions

The results of this study provided new insights to the relative importance of biotic and abiotic processes concerning woody shrub encroachment in the desert grassland of southwestern United States. The exclusion of biotic processes was realized by using artificial shrubs. Over a 10-year experimental time, no notable soil mounds were observed under the artificial shrubs, however, soil texture in the artificial shrub plots has gradually changed to resemble the patterns of soil particle-size distribution in a natural shrub plot. The insufficient aeolian sediment transport, and the absence of positive feedback to the shrubs are likely the reasons why the development of fertile islands under the artificial shrubs was slow. We found that with the exclusion of direct biotic additions such as plant uptake of nutrients and litter deposition, soils captured by shrub canopies are not necessarily fertile thus further limits the development of fertile islands under the shrubs. This information is critical for the design of remediation structures in arid and semi-arid areas indicating that special attention must be

paid in their development and deployment to ensure that their performance as trappers and holders of biotic material occurs as intended.

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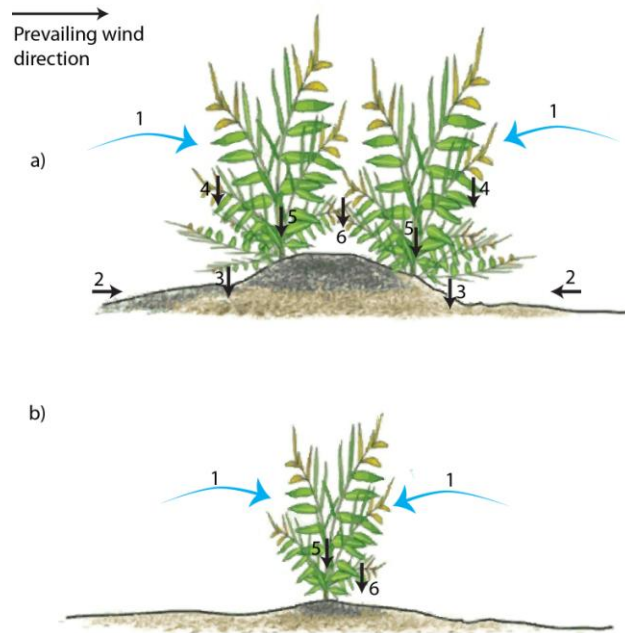
Figure 1. Diagram showing biotic and abiotic processes involved in the formation of fertile islands for the case of *a*) natural shrub, *b*) artificial shrub. These processes may include 1. Interception of windblown material, 2. Root uptake, 3. Enhanced infiltration, 4. Litter deposition, 5. Stemflow, and 6. Throughfall. Note that for artificial shrubs the processes of stemflow and throughfall do not necessary add nutrients to the soil beneath the canopy because of the absence of biotic activities. Redrawn from *Ravi et al*. [2007].
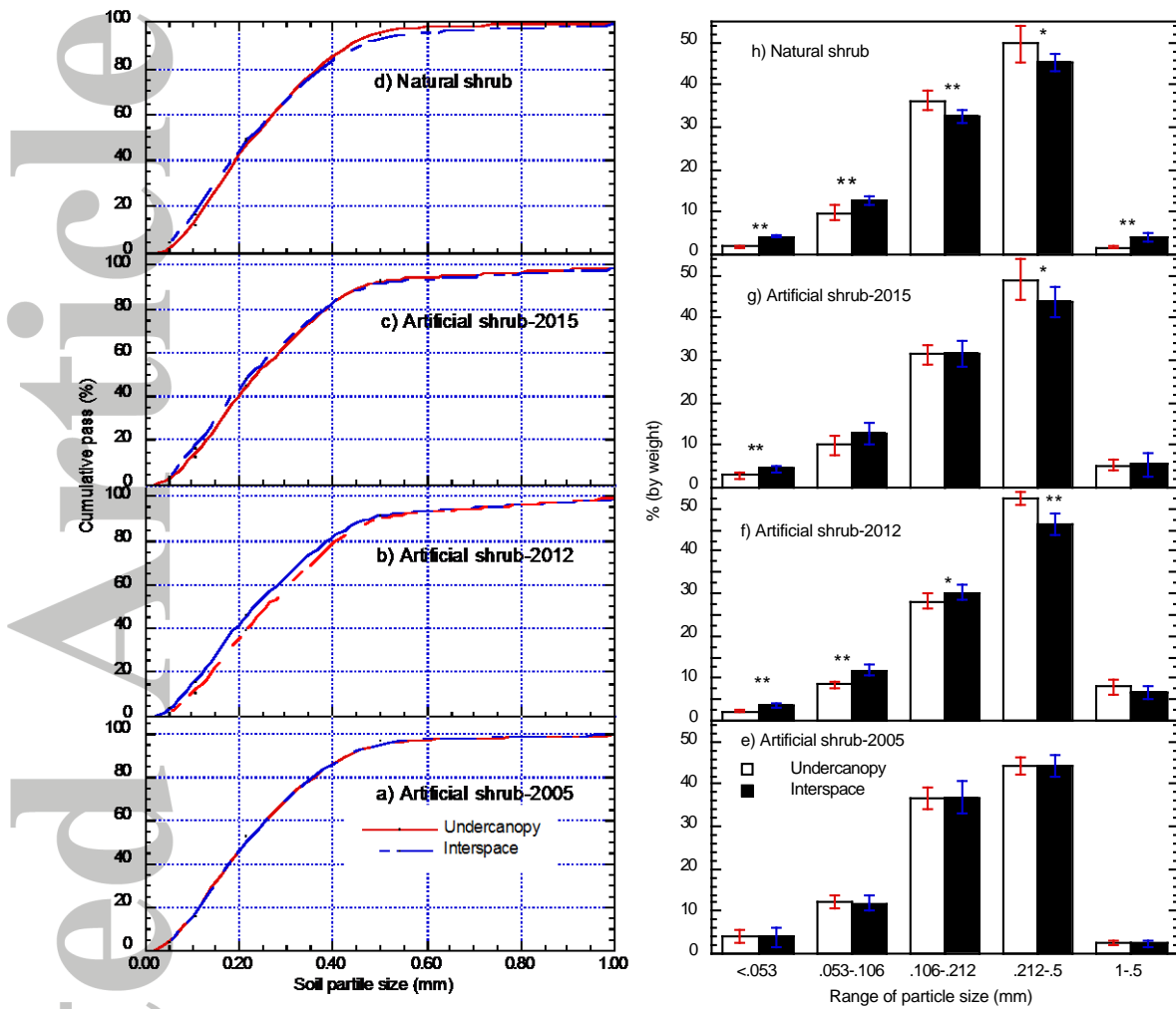
Figure 2. Characteristics of soil grain size measured under shrub canopy and between shrub interspace for both the artificial and natural shrub plots, *a-d*) Cumulative pass %, and *e-h*) Particle size distribution at different size fractions. [*] and [**] indicate significant differences within each particle-size fraction were shown at $p<0.05$ and $p<0.01$, respectively. Error bars represent $\pm$ one standard deviation.
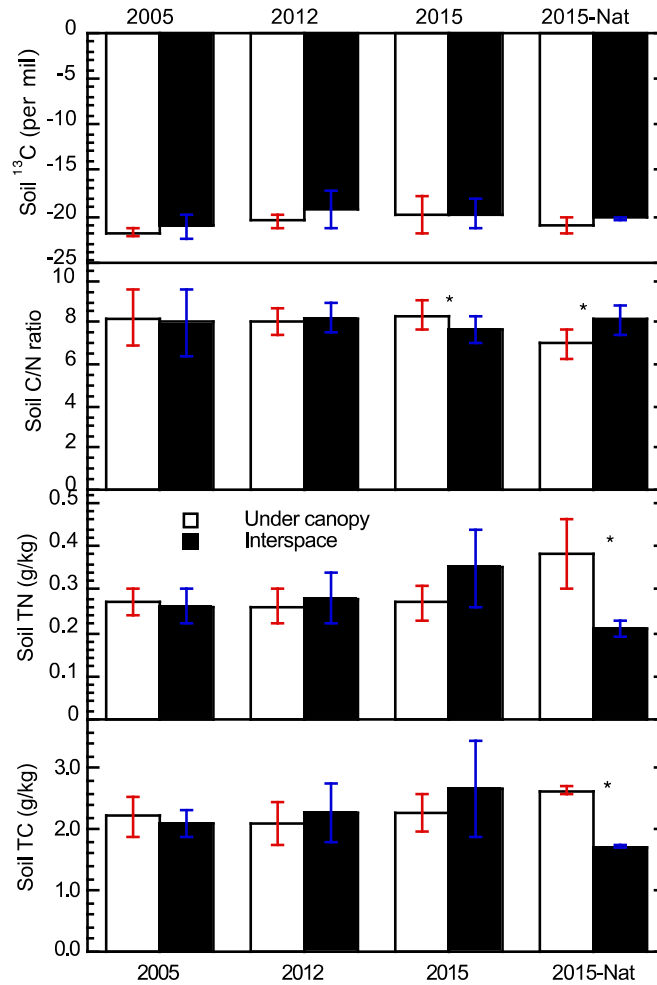
Figure 3. Properties of soil C and N measured under the shrub canopy and out of the shrub canopy (Interspace) in the artificial shrub plots and the natural shrub plot. Samples from the artificial shrub plots were collected in 2005, 2012, and 2015, and samples from the natural shrub plot were collected in 2015 (denoted as 2015-Nat). [*]Indicates a significant difference in these mean concentrations (*t*-test, p<0.05). Error bars represent ± one standard deviation.

Table 1. Characteristics of the natural and artificial shrub plots.

Characteristics	Natural shrub	Artificial shrub
Year of setup	2004	2005
Year of revisit	2015	2012, 2015
Number of plots	1	5
Size of plot (m^2)	25×50	5×5
Number of shrubs monitored	6	5
Shrub canopy (m, means ± SD)[1]		
Length	3.30± 0.33	0.65±0.15
Width	3.30±0.42	0.63±0.17
Height	1.50±0.15	0.55±0.05
Fractional plant cover (%)[2]	23	25
Dominant species	*Prosopis glandulosa*	*Sporobolus spp.*
Estimated age (year)[3]	30-40	10
Horizontal mass flux of wind erosion[4] (g m^{-1} day^{-1}, means ± SD)	454±179	18±8

[1] Measured in July 2015. For natural shrubs, coppice dunes were formed and the shrub canopy characteristics were measured from the bottom of the dune. For artificial shrubs, no dunes were formed beneath the canopy. SD represents standard deviation.

[2] Measured during the time of plot setup, not including the artificial shrub canopy cover in the artificial shrub plots.

[3] The age of the natural shrub dunes was estimated according to *Graham Gadzia and Ludwig* [1983].

[4] Measured in *Li et al.* [2007] and *Bergametti and Gillette* [2010]. Wind erosion in the artificial shrub plots was measured from a nearby control plot with no vegetation removal and the absence of substantial shrub dunes.

Table 2. Enrichment indices of soil C, N, and soil particles at different grain size ranges calculated in both the artificial shrub and natural shrub plots.

Variables	Artificial shrub			Natural shrub
	2005	2012	2015	2015
Soil grain size (mm)				
1-.5	1.02	1.17	0.99	0.29[*]
.212-.5	1.00	1.13[*]	1.12[*]	1.08
.106-.212	0.99	0.93[*]	1.00	1.12
.053-.106	1.03	0.72[*]	0.79	0.85
<.053	1.01	0.62[*]	0.65[*]	0.45[*]
Soil C, N				
TC	1.06	0.93	0.86	1.53[*]
TN	1.04	0.93	0.77	1.81[*]

[*]Indicates a significant enrichment in these mean concentrations (*t*-test, p<0.05).