

Chapter

The Role of Pre-Desert Vegetation in the Rehabilitation of Degraded Soil

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Abstract

In arid and Saharan zones, drought and human activities accentuate the risk of degradation of pre-desert rangelands. Some plants disappear, while others persist and adapt. In this study, we aimed to list the plants that can grow in a sandy environment and investigate their distribution levels and effect on sand dunes. We conducted vegetation inventories in Laghouat province in Algeria, and we calculated the ecological parameters using the transect method. The height of fixed windblown deposits was measured under all inventoried plants. Under three perennial plants (*Retama raetam*, *Aristida pungens*, and *Astragalus armatus*), soil texture, and physical and microbiological characteristics were analyzed. We found that the area studied is species-poor but has certain diversity, so the plant biological type influenced sand fixation. Fixed Aeolian deposits stabilized by plants ranged in height from 28 to 63 cm. Micro-dunes stabilized by *R. raetam* exhibited higher nitrogen, carbon, and bacterial richness compared to those stabilized by *A. pungens*. In contrast, *A. pungens* micro-dunes had greater calcium carbonate, electrical conductivity, and fungal richness. Our findings highlight the distinct contributions of each species to soil rehabilitation. Moreover, the complementary effects of these plants suggest their potential for synergistic wind erosion control.

Keywords: vegetation, soil, Saharan, dune, restoration

1. Introduction

North Africa is one of the regions most vulnerable to the consequences of climatic aridity and the impact of human activities on the natural environment. The steppe areas of North Africa are particularly affected by the problems of desertification [1]. In Algeria, Morocco, and Tunisia, the proportion of national territory affected by desertification was estimated at over 80% in the early 1980s [2]. Similarly, the desertification sensitivity map drawn up by the Algerian National Center for Space Technology reveals that 53% of the total Algerian steppe area is classified as very sensitive to desertification [3]. In Algeria, outside the Saharan zone, it is above all the high plains that are most affected by the phenomenon of silting-up, with 500,000 ha of aeolian formations extending to the north of the Saharan Atlas [4]. Wind erosion is a major physical factor in the depletion of agricultural land [5], and causes severe

environmental degradation by impoverishing soils and reducing their production [5, 6]. Nearly 600,000 hectares of land in the steppic zone are totally desertified, with no possibility of biological recovery, and almost 6 million hectares are threatened by the effects of wind erosion [7]. The Algerian steppe is subject to ecologically unsustainable exploitation. Desertification is gaining ground due to recurrent drought, overgrazing, and the extension of rain-fed and sometimes irrigated agriculture, which is unsuited to the conditions of the natural environment [8]. The extension of plowing and the introduction of mechanization are just as important parameters of degradation as overgrazing. The plowing techniques used by agropastoralists have an erosive action, destroying the superficial horizon and sterilizing the soil, often irreversibly. The woody species that hold the soil in place are destroyed and replaced by adventitious species that promote wind erosion [9]. Psammophyte steppes are linked to the sandy texture of the surface horizons and to aeolian inputs. They follow the silting corridors and are also distributed in the depressions formed by the chotts, they are more frequent in arid and pre-Saharan zones, forming steppes with *Stipagrostis pungens* and *Thymelaea microphylla* or shrub steppes with *Retama raetam*, and their pastoral values vary from 200 to 250 FU/ha [10]. According to the results of the 2003 ROSELT program, psammophytic vegetation, which was non-existent in 1978 in the west, has expanded due to greater silting during the drought period of 1981–1987. The cover of psammophytic vegetation often exceeds 30%, thanks to the proliferation of annual species [11]. Sand dunes are characterized by the presence of plant cover, of variable density, which fixes their sand to a greater or lesser extent. Dune soils are generally poor in nutrients and water [12]. Houyou et al. [13] have demonstrated that sandstorms cause (64.32 t/ha/year) of land loss in the Mokrane area of Laghouat, accentuated by plowing and wind speed (7.3 m/s). In view of the silting-up of this cereal-growing and sheep-breeding site, we set out to draw up an inventory of the plant species colonizing the sandy accumulations and assess the pastoral value of these rangelands. In arid areas, plowing and overgrazing increase the risk of degradation of steppe rangelands, leading to sand encroachment and wind erosion. Some plants disappear, while others persist and adapt. What are soil characteristics of the plants canopy that can grow on sandy accumulations? In this study, we aimed to identify steppe plants that can grow in a sandy environment and to investigate their distribution levels on sand dunes and their effects on dune soil.

2. Material and methods

2.1 Study area

The studied site is named Mokrane, situated 4 km from Laghouat, the capital of Laghouat Province (N 33°48'–E 2°48') (**Figure 1**).

Mokrane is an alluvial plain characterized by steppe vegetation. Frequent sandstorms, coupled with agricultural activities, and extensive grazing, exacerbate wind erosion and sedimentation (**Figure 2**).

2.2 Floristic study

A vegetation survey was conducted in March 2009 using the Braun-Blanquet method [14, 15]. Twelve linear transects were established based on vegetation

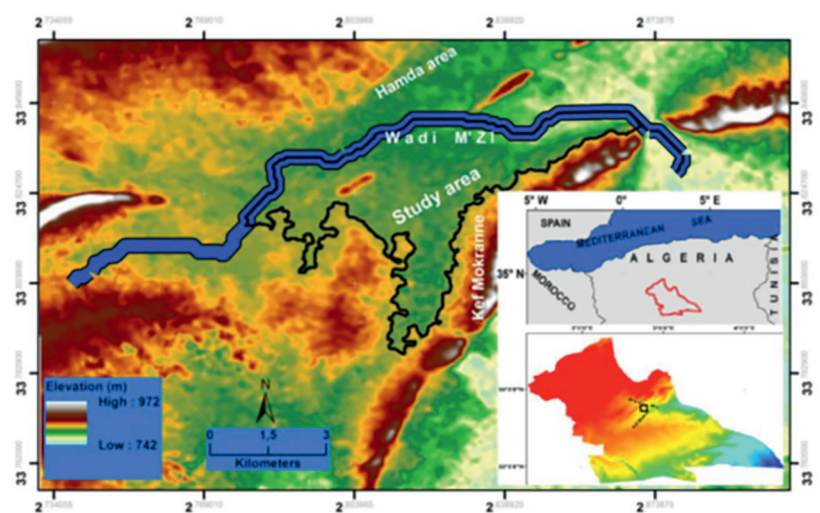


Figure 1.
 Location of the study area in Algeria.



Figure 2.
 Appearance of vegetation in the study site.

physiognomy and the Djebaili method [15], covering areas ranging from 128 to 420 m². Each 20-meter transect involved recording data at 20 cm intervals, totaling 100 data points per transect.

Floristic richness, Shannon diversity index (H'), equitability (J), sand cover, and vegetation cover were assessed. A higher H' value indicates greater diversity. Equitability helps detect changes in community structure, especially those of anthropogenic origin. These indices are sensitive to frequent species rather than overall richness [15]. Plant identification followed the flora of Quezel and Santa [16]. Simpson's index (1-D) and others indexes were calculated according to Krebs [17] as below:

a. *Richness* (S) is just the number of species in the sample.

b. *Dominance* index (D): Dominance index values range from 0 to 1.

$D = \sum (n_i/N)^2$, With: n_i = individual number of a species, N = individual number all species.

c. *Equitability or Pielou's measure of species evenness*, $J = H' / \ln(S)$ where H' is Shannon Weiner diversity and S is the total number of species in a sample.

d. *Simpson diversity index* ($1-D$) represents the probability that two individuals randomly selected from a sample will belong to different species. It is a measure of diversity that considers both Richness (the number of species per sample) and Evenness (the relative abundance of the different species making up the richness of an area). Formula: $1 - D = 1 - \sum (n/N)^2$. The results can be from 0 (less diverse) to 1 (most diverse).

e. *Shannon diversity index* (H') is a measure of the average degree of uncertainty in predicting to what species and individual chosen at random from a collection of species and individuals will belong. Formula: $H' = - \sum (P_i * \ln P_i)$. The values can range from 0 (less diverse) to $\ln(1/S)$, but usually they will fall between 1.5 and 3.5 and rarely above 5.

f. *Berger-Parker dominance index* ($1/d$), is the number of individuals in the dominant taxon relative to n . Its value does not take into account the number of classes but it is highly influenced by equity. It is a simple measure of the numerical importance of the most abundant species. Formula: $1/d = N_{\max}/N$. An increase in the value of the index accompanies an increase in diversity and a reduction in dominance.

To evaluate rangeland degradation, a disturbance index (DI) was computed using the ratio described by Hébrard et al. [18]:

$$DI = \frac{\text{Chamaephytes number} + \text{Therophytes number}}{\text{Total number of species}} \quad (1)$$

2.3 Pastoral productivity of Mokrane's grazing land

Pastoral productivity represents the vegetation's energy output per unit area and time, expressed as Forage unit per hectare and year ($FU \text{ ha}^{-1} \text{ t}^{-1}$). The formula used in numerous Algerian steppe studies [19] was adopted (Eq. (2)). It correlates pastoral value with forage productivity.

$$P_p = 6.74 P_v + 14.77 \quad (2)$$

Where:

- P_p : Pastoral productivity of the facies in FU/ha
- P_v : Pastoral value

According to Aidoud [19], pastoral value is an allometric assessment suitable for estimating rangeland forage production. It is calculated by multiplying each species' contribution by its corresponding index and summing the results. To determine pastoral value, we employed Eq. (3), previously used by Hirche et al. [20] for Algerian steppe rangelands. This equation originates from Daget and Poissonet in [21].

$$Pv(\%) = 0.1 \times VC \times \sum SCI \times SI \quad (3)$$

Where:

- SCI: Specific contribution of plant species
- SI: Specific index of plant species
- VC: Overall vegetation cover

The specific vegetation indices for the Algerian steppe are empirically derived using a numerical scale developed by Aidoud [19]. This scale considers factors such as bromatological quality, digestibility, and assessments by steppe breeders. Each species is assigned a score or grade, which we adopted for this study.

Animal load refers to the livestock carrying capacity of a grazing area, often expressed as the number of animals per unit area.

2.4 Sediment height measurement under and outside the canopy

Sediment height measurement was conducted concurrently with vegetation surveys. Using a modified differential leveling method [22], sediment accumulation at the study site's ground surface was measured. Altitude differences were determined every 20 cm along the transect using a leveling instrument aimed at a graduated rod placed on the accumulated sediment.

2.5 Soil analysis

Soil samples were collected from eight randomly selected sediment accumulation points associated with each host species (fixed soil) and eight points without vegetation (unfixed soil). Samples were taken in March 2014, at the end of the rainy season, using a hand auger to collect the top 30 cm of sediment, approximately 10–15 cm from the host plant center [23]. The following soil parameters were measured: moisture content (determined by drying at 105°C for 24 hours), particle size distribution, total nitrogen, limestone content, electrical conductivity (EC), pH, and organic matter content. Soil particle size distribution was determined by sieving and sedimentation to obtain percentages of sand, silt, and clay [24]. Organic matter content was estimated through loss on ignition at 600°C for 5 hours. Soil pH and electrical conductivity (EC) were measured in a 1:5 soil-to-water suspension after shaking for 30 minutes using a digital conductivity meter (YSI Inc., OH, USA). Total nitrogen (N) was quantified using the Kjeldahl method. Calcium carbonate (CaCO₃) content was determined according to the procedures of the United States Salinity Laboratory (Jackson, 1962). For microbial enumeration, PDA (Potato Dextrose Agar) and LPGA (Yeast Peptone Glucose Agar) media were used for fungi and bacteria, respectively [25].

2.6 Statistical data

Floristic diversity was assessed using Paleontological Statistics software (version 2.17c). Soil parameters were compared using ANOVA in XLSTAT software (version 3.5) at a significance level of $P \leq 0.05$. Principal component analysis (PCA) was conducted using XLSTAT to examine relationships between soil parameters and vegetation.

3. Results and discussion

3.1 Vegetation

All the plant species inventoried in the Mokrane area have already been reported by other authors interested in the plant biodiversity of North African steppes [26, 27]. The floristic analysis of the sandy agricultural zone of Mokrane allowed us to identify the dominance of seven steppe plants: *Bromus rubens*, *Schismus barbatus*, *Thymelaea microphylla*, *Echinops spinosus*, *Retama raetam*, *Aristida pungens*, and *Astragalus armatus* (Figure 3).

We recorded the dominance of three families: Asteraceae, Fabaceae, and Poaceae (Table 1). Aidoud [19] has already confirmed the dominance of the families Asteraceae, Poaceae, Fabaceae and Chenopodiaceae in the desert flora. Similar observations have been noted in the floristic description of the North Algerian Sahara [28]. Asteraceae, Poaceae, and Fabaceae are three families that represent 35–40% of the flora in each Saharan sector [29, 30]. This predominance is justified since these are cosmopolitan families that are widespread throughout the steppe and the Saharan Atlas [31].

On a physiognomic and floristic level, Djebaili [15] defines the variation in the floristic composition of the grouping according to the nature of the lithological substrate. When it develops on heavily sanded erosion glacia, this grouping forms facies with psammophyte species, such as *Retama raetam* and *Thymelaea microphylla*. According to Benaradj et al. [31], sandblasting favors the installation of psammophyte species, such as *Retama raetam* and *Malcolmia aegyptiaca*. Pouget [32] indicated

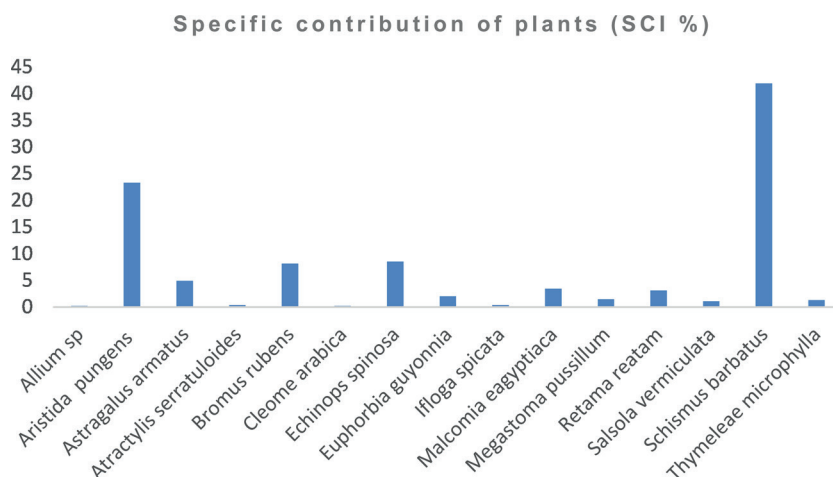


Figure 3.
Specific contribution of plants.

Species	Family	Abbreviation	Cycle	Biological types	Biogeography
<i>Aristida pungens</i> Desf.	Poaceae	<i>A. pungens</i>	P	Hemicryptophyte	Saharo South Africa
<i>Astragalus armatus</i> Willd.	Fabaceae	<i>A. armatus</i>	P	Chamaephyte	Mediterranean
<i>Atractylis serratuloides</i> Sieber ex Cass	Asteraceae	<i>A. serratuloides</i>	p	Chamaephyte	Saharan
<i>Bromus rubens</i> L.	Poaceae	<i>B. rubens</i>	A	Therophyte	Mediterranean
<i>Cleome arabica</i> L.	Capparidaceae	<i>C. arabica</i>	A	Therophyte	Saharo Sindian
<i>Echinops spinosa</i> L.	Asteraceae	<i>E. spinosa</i>	P	Chamaephyte	Mediterranean
<i>Erodium glaucophyllum</i> L.	Geraniaceae	<i>E. glaucophyllum</i>	P	Hemicryptophyte	Endemic Mediterranean
<i>Eruca vesicaria</i> (L.)Thell.	Brassicaceae	<i>E. vesicaria</i>	A	Therophyte	Mediterranean
<i>Euphorbia guyoniana</i> Boiss & Rent.	Euphorbiaceae	<i>E. guyoniana</i>	P	Hemicryptophyte	Endemic N. Africa
<i>Evax desertorum</i> Pomel.	Asteraceae	<i>E. desertorum</i>	A	Therophyte	Mediterranean
<i>Helianthemum getulum</i> Pomel.	Cistaceae	<i>H. getulum</i>	P	Chamaephyte	Mediterranean Saharan
<i>Iflogia spicata</i> Vahl.	Asteraceae	<i>I. spicata</i>	A	Therophyte	Saharo Sindian
<i>Launaea resedifolia</i>	Asteraceae	<i>L. resedifolia</i>	P	Hemicryptophyte	Mediterranean Saharo Arab
<i>Malcomia aegyptiaca</i> Syr.	Brassicaceae	<i>M. aegyptiaca</i>	A	Therophyte	Saharo Arabo Subtropical
<i>mediterraneanicago laciniata</i> L.	Boraginaceae	<i>M. laciniata</i>	A	Therophyte	Mediterranean. Saharo Sindian
<i>Megastoma pusillum</i> Cos. & Durieu	Boraginaceae	<i>M. pusillum</i>	A	Therophyte	Mediterranean
<i>ononis pusilla</i> L.	Fabaceae	<i>O. pusilla</i>	P	Hemicryptophyte	Mediterranean
<i>Peganum harmala</i> L.	Zygophyllaceae	<i>P. harmala</i>	P	Hemicryptophyte	Irano-Turanian
<i>Plantago albicans</i> L.	Plantaginaceae	<i>P. albicans</i>	P	Hemicryptophyte	Mediterranean
<i>Retama raetam</i> Forsk.	Fabaceae	<i>R. raetam</i>	P	Nanophanerophyte	Saharo Sindian
<i>Salsola vermiculata</i> L.	Chenopodiaceae	<i>S. vermiculata</i>	P	Chamaephyte	Saharo Mediterranean
<i>Schismus barbatus</i> L. Thel.	Poaceae	<i>S. barbatus</i>	A	Therophyte	Mediterranean
<i>Silene arenarioides</i> Desf.	Caryophyllaceae	<i>S. arenarioides</i>	A	Therophyte	Endemic N. Africa

Species	Family	Abbreviation	Cycle	Biological types	Biogeography
<i>Stipa tinassicima</i> L.	Poaceae	<i>S. tinassicima</i>	P	Hemicryptophyte	Endemic
<i>Thymelaea microphylla</i> Coss et Dur.	Thymelaeaceae	<i>T. microphylla</i>	P	Chamaephyte	Endemic N. Africa

Table 1.
List of steppe plants in the Molerane area (P: perennial, A: annual).

that *Aristida pungens* and *Malcomia egyptiaca* are found on fixed micro dunes. On the other hand, non-fixed dunes are colonized by *saccocalyx saturoides*; *Euphorbia guyoniana*, and *Ononis natrix*; these species are resistant to water shortage and are best adapted to this type of ecosystem. According to QUEZEL [33], on mobile dunes a few species can survive under 50 mm of rainfall, such as *Euphorbia guyoniana* and *Aristida pungens*.

Killiain [34] has already indicated that *Euphorbia guyoniana* releases roots 15 cm from the wet horizon. Therophytes like *Bromus rubens* and *Lolium rigidum* require a certain percentage of water. Pouget [35] indicated the presence of *Malcomia aegyptiaca*, *Aristida pungens*, and *Retama reatam* in the coarse texture of the soils. In our case, we investigated the existence of plants linked to fixed micro dunes, the species linked to sandy sails and unbound dunes.

The results of the analysis of the biological type (**Table 1**) showed the dominance of therophytes in the Mokrane pasture. The observed therophytization is linked on the one hand to the harshness of the climate and on the other hand to human activities which increasingly degrade the conditions for the establishment of new species.

Emberger [36] and Daget [37] state that the rate of therophytes increases with the aridity of the environment. This richness is due to the process of the biological rise, of the reconstitution, regeneration, and reappearance of species threatened with destruction by degradation factors. About 30% of psammophyte vegetation is due to the proliferation of ephemeral plants [11]. We have thus observed the impact of climatic drought by the increase in the rate of therophytes and by the presence of Saharan affinity species such as: *Euphorbia guyoniana* and *Launaea residifolia*. Chamaephytes can also develop forms of adaptation to drought. The chamaephytization recorded in the Mokrane area has its origin in the phenomenon of aridity, according to Floret and Pontanier [26], chamaephytes adapt better to summer drought. Grazing also generally favors chamaephytes rejected by herds, such as *Thymelaea microphylla*, *Hammada scoparia*, *Anvillea radiata*, and *Gymnocarpos decander* [38], and *Astragalus armatus* according to Floret and Pontanier [26]. According to Kadi Hanifi [38], grazing generally favors chamaephytes refused by herds. Kadi Hanifi [39] confirmed that the regression of steppe formations generally results in chamaephytization by thorny species without economic interest abandoned and rejected by livestock. Le Houerou [27] also reported that the increase in woody chamaephytes in Poaceae formations is due to overgrazing by sheep and cattle. In our study area, the rangelands are mainly exploited by sheep and goats which allowed the appearance of the *A. armatus* group. Phanerophytes are less important, these decreasing gradually with the aridification of the climate. The proliferation of hemicryptophytes can also be explained by the poverty of the soil in organic matter, which has been demonstrated by soil analysis. The analysis of the phytogeographic spectrum (**Table 1**) showed the dominance of the Mediterranean, endemic, and Saharan tendencies. However, these results confirm the trends observed on the scale of the North African sub-region by Le Houerou [27] who showed that among the 2630 vascular plant species present in the Maghreb steppes, 60% are Mediterranean affinity species and 30% tropical affinity species. The high Saharan spectrum rate can be explained by the aridity of the environment.

From 2009 to 2015, the ecological indices (total richness, equitability, and species diversity) have not shown a significant difference (**Table 2**), The environment exhibited low biodiversity, with a species richness ranging from 15 to 21 taxa and Shannon index ranging from 1.8 to 2.13. Species evenness, as measured by the equitability index, fluctuated between 0.66 and 0.74.

Between 2009 and 2015, vegetation cover on the site increased significantly from 46.16% to 61.99%, coinciding with a substantial decrease in sand cover from 53.84% to 31.5% (**Figure 4**). This suggests that the fixation of sand by perennial plants contributed to the observed vegetation expansion, El-Bana et al. [40], Guerrache et al. [41], and Akkouche et al. [42] recorded the improvement of the vegetation cover on the sand dunes fixed by *Retama raetam*. *Astragalus armatus*, a chamaephyte with low pastoral value, has shown remarkable proliferation on the site, it is a species that appears in formerly cultivated areas and overgrazed areas [26]. Chaieb [43] explained this proliferation by the root architecture of this plant, favoring water absorption and also its high germination power.

Floral modifications of pastoral ecosystems in arid and desert regions, under the effect of animal pressure and water deficit, first affect palatable grasses and chamaephytes [44]. Maintaining the biological productivity of the environment remains, under such conditions, linked to the appearance of a new type of vegetation that is not very productive but in balance with this new environment [26]. However, although *Astragalus armatus* is considered to be a species marking degradation, it can contribute, even if only partially, to the process of restoring ecological balance in these degraded environments [43]. The trapping of sand and the reconstitution of the wind veil by the highly developed clumps lead to an improvement in the soil water balance and favor the germination of species hitherto rare. Finally, its ability to fix atmospheric nitrogen contributes to improving soil fertility.

3.2 Pastoral value

The Mokrane area in Laghouat rangeland (Drinn rangeland: *A. pungens* Steppe) presented an average pastoral value of 11–14%, we estimated this rate during a period

Ecological indices	Year 2009	Year 2010	Year 2011	Year 2012	Year 2014	Year 2015
Taxa_S	15.00	16.00	19.00	19.00	21.00	18.00
Dominance_D	0.25	0.21	0.20	0.16	0.09	0.16
Simpson_1-D	0.75	0.79	0.80	0.84	0.91	0.84
Shannon_H'	1.80	1.99	2.13	2.13	2.64	2.13
Equitability_J	0.66	0.72	0.72	0.72	0.87	0.74
Berger-Parker	0.42	0.40	0.38	0.26	0.15	0.27

Table 2.
The ecological indices measured through 6 years.

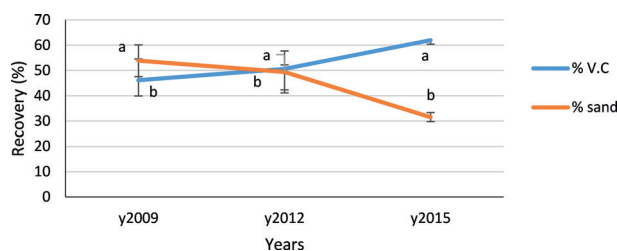


Figure 4.
Change of vegetation cover (VC) and sand cover over time.

when the vegetation was supposed to be optimal. Compared to Hirche et al. [20], they gave a value of 7% for a pasture of the South-West Algerian steppe in the Naâma region. In the same region in 2007, Benaradj et al. [31] calculated a pastoral value of 4% for a Sparte pasture (*Lygeum spartum*). On the other hand, the results established by OSS [45] on the potential of West Algerian rangelands report a higher pastoral value of around 11%, a value close to our results. The different types of vegetation and the richness in these rangelands explain the gaps recorded between the pastoral values. As well as the vegetation cover itself is always dependent on local edaphoclimatic conditions which differ from one region to another and from one year to the next.

The pastoral value is a synthetic index used to characterize the capacities offered by the rangelands. The Mokrane rangeland presented a pastoral value close to the alfa grass steppe but better than that of sparte and remt (**Table 3**). In our case, the low average pastoral value of Mokrane can also be explained by the low rate of soil surface cover by vegetation, by the low richness of the flora that characterizes the rangeland and by the nature of the plant species present which are not all palatable.

Among the inventoried plants, more than 68% of the species have poor specific pastoral indices (≤ 2) indicative of low energy values. About 16% of the species have average energy qualities with specific pastoral indices ($3 < I_s \leq 5$). However, some species have good forage qualities with specific indices greater than 5 (*Medicago laciniata*, *megastoma pussillum*, and *Plantago albicans*) but weakly present in the place.

The low pastoral value can also be due to the dominance of psammophytes in the rangeland, including *Thymelaea microphylla*, *Aristida pungens*, *Retama raetam*, and *Astragalus armatus*, which also have average and poor forage qualities (specific indices). In the psammophyte steppes of southern Oranian city in Algeria, Nedjraoui [46] estimated maximum pastoral productivities between 200 and 250 FU/ha. Our values for (Mokrane) Laghouat vary between 89 and 108 FU/ha, like those reported by Salemkour et al. [47] for other pastures in the Laghouat steppe. However, the productivity of the Laghouat rangeland reveals a low nutritional value of the vegetation present and the mediocrity of the grazing area. The differences in productivity between the Laghouat rangelands and those of the southern Oranais steppe can be explained by the type of vegetation that dominates, the area it covers, the nature of the rangeland soil, and especially the rainfall in the area [46]. Indeed, the amount of rainfall received is a major factor in the development of plant communities in the steppes [45, 48, 49].

The estimated pastoral values and productivities result in average pastoral loads for the rangeland varying from 3 to 5 ha/Sheep Unit. This value is close to those estimated during the same period in other places in the Algerian steppe [46, 47, 50, 51]. The estimated load for the Mokrane rangeland clearly reflects a situation of pastoral imbalance and a poor state of health of this pasture, reflecting the situation of the Algerian steppe. The calculation of the disturbance index (DI) fluctuated between 0.74 and 0.66

Year	Year 2009	Year 2012	Year 2015
Vegetation cover (%)	46.24	62.13	63.17
Pastoral value (%)	13.85	10.99	13.75
Pastoral productivity (FU/an)	108.12	88.85	107.40
Pastoral charge (hectare)	3.70	4.50	3.72

Table 3.
 Pastoral value of Mokrane area (2009–2015).

during the study years, suggesting that the Mokrane area is disturbed. Anthropogenic disturbances are largely responsible for the current state of vegetation structures in the Maghreb [52]. The natural vegetation cover is permanently subjected to a double impact, on the one hand from the soils (too dry and light) and the climate (low rainfall) and on the other hand from the actions of humans and their animals [53].

3.3 Height of accumulated sediments under and outside the canopy

The results of the statistical analysis concerning the preference of certain plants for certain elevations of accumulated sediments, allowed us to conclude that there are significant differences in this distribution ($P = 0.001$, **Figure 5**).

The three perennial species *A. pungens*, *R. raetam*, and *A. armatus* were established at a lower soil level than some annual plants that developed on the highest peaks of the sandy accumulations. The differences between the distribution levels of the inventoried plants could be due to seed dispersal modes, seed weight, wind direction, wind speed, and the phenomenon of runoff by rainwater. Bochet [54] explained that the seed dissemination capacity varies greatly between species and is mainly linked to the characteristics of the seed. In our case, seeds on and in the soil can be moved horizontally to new locations by different biotic factors (animals) or abiotic factors (wind, runoff, and gravity). Seed transport by runoff depends on soil characteristics, slope, and rainfall. Seeds can also be moved vertically by animals, in the opposite direction of the soil seed bank. Sediment movement can also explain the differences in the position levels of plant species on the accumulated sediments and their deposits in the study area. The appearance of the surface of Mokrane has been attributed to the Quaternary colluvial and alluvial deposits, and the phenomenon seems to be continuing to this day. Houyou et al. [13] observed two phenomena in Laghouat—sand burial and erosion depending on the wind speed and direction in the Mokrane area. Sandstorms in Laghouat caused the transport of seeds and their deposits with the sand. Once the seeds are deposited in the soil, they germinate, and then the plants grow if conditions are favorable. If there is a lack of water, the annual plants (ephemeral) disappear, otherwise the perennials persist. Our findings agreed with those of Cusseddu et al. [55], who reported that on coastal dunes in Sardinia, plant communities are organized in a hierarchical manner with the elevations of the

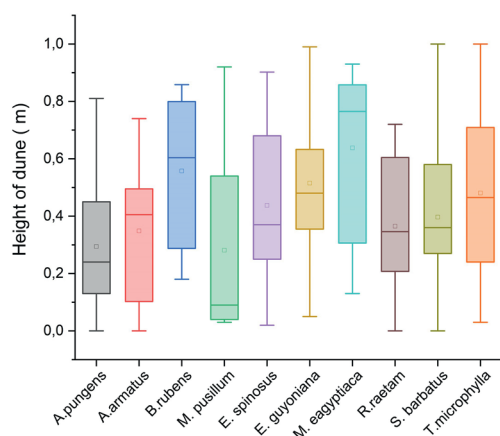


Figure 5.
Sediment depth under canopy.

dune. These authors added that the high summer temperatures led to a competitive dominance of woody plants on the back of the dune. In our case, although *A. pungens*, *A. armatus*, and *R. raetam* have different root architectures; they fixed the sand at similar heights, not exceeding 50 cm. The dispersal of their seeds is successively due to different processes (wind, water, and animals). The annual plants spend the bad season in the form of seeds and will be moved with the sand sediments by the wind, knowing that in the Mokrane area the wind blows all year round [13]. The new sand deposits (50–97 cm) would contain seeds of annual plants, which will then appear with the first spring rains. This behavior is different from the seeds of perennial plants that have been studied; these require specific germination conditions due to their dormancy [56]. This original method for calculating the elevations of fixed and non-fixed windblown deposits allowed us to conclude that the Mokrane area is invaded by deposits that do not exceed 1 meter in height, so we call the windblown deposits in this area micro dunes and not nebkas, given the succession observed.

3.4 Soil characteristics under and outside the canopy

The results of the soil analysis of the Mokrane area showed that the Mokrane soil generally had a sandy texture (Table 4), an alkaline pH, a low level of moisture, nitrogen, and organic matter, was slightly to moderately calcareous, had a low salinity, and a low microbial richness. Our results showed that soils under plant cover had higher moisture, organic matter, carbon, nitrogen, and microbial richness than those of soil outside the canopy. This could be due to the higher moisture content, which stimulates the growth and activity of soil microorganisms according to the statements of Hesp and McLachlan [57].

The high soil moisture content measured under the canopy in Laghouat could be influenced by the lower temperature, which also stimulates the decomposition of organic matter. In fact, Lopez-Pintor et al. [58] found that woody vegetation provides a less stressful microclimate on the environment below the cover, reducing

Soil parameters	<i>R. raetam</i>	<i>A. armatus</i>	<i>A. pungens</i>	Not fixed soil	P-value
Humidité (%)	2.39a ± 0.48	1.89a ± 0.86	2.24a ± 0.48	1.06b ± 0.64	0.01
pH	8.30b ± 0.46	8.87a ± 0.07	8.76a ± 0.07	8.72a ± 0.12	0.009
CE (ms/cm)	0.40b ± 0.07	0.39b ± 0.08	0.92a ± 0.06	0.50b ± 0.06	<0.001
C (%)	0.82a ± 0.27	0.70a ± 0.26	0.68a ± 0.29	0.25b ± 0.18	0.01
N (%)	0.08a ± 0.01	0.06ab ± 0.01	0.04bc ± 0.01	0.02c ± 0.01	0.005
CaCO ₃ (%)	1.75 ± 0.89	1.55 ± 1.11	2.37 ± 0.89	1.96 ± 0.47	0.07
M.O (%)	1.42a ± 0.48	1.21a ± 0.45	1.16a ± 0.51	0.43b ± 0.32	0.001
C/N	8.57 ± 2.06	11.25 ± 4.17	14.54 ± 11.04	13.97 ± 4.93	0.66
Coarse sands (%)	34	30	36	46	—
Fine sands (%)	62	51	64	50	—
Silt (%)	2	9	0	2	—
Clay (%)	2	10	0	2	—

Table 4.
 Soil characteristics under and out of the canopy.

the direct effects of strong solar radiation and temperature, providing greater water availability, and causing an accumulation of organic matter and nutrients. Pyke and Archer [59] indicated that the soil under the tree canopy could maintain a higher population of bacteria, conservation and accumulation of carbon and nitrogen. The statements of these latter authors agree with our results under perennials (Figure 5).

The nitrogen content in the soil under the cover of perennial plants can be explained by the presence of shrubs that fix atmospheric nitrogen such as *R. raetam* and *A. armatus*, the same findings were made by Muñozvalles et al. [60] in Spain who recorded high carbon and nitrogen contents under the canopy of *Retama monosperma*. Similarly, Halvorson et al. [61] observed a high N content in the soil under desert shrubs in the United States. Vegetation also contributes to a reduction in groundwater runoff [62] and nutrient uptake in the soil under the canopy [40, 63, 64].

Between 2009 and 2015, we observed the formation of a microbial crust on the surface of the soil in the study area. This is an important factor for conserving soil moisture, several studies have indicated that the existence of the microbial crust is necessary for the development of plant communities [65], it affects the water regime by altering runoff [62, 66] and reducing evaporation [67]. Rhizosphere microbial communities can be stimulated or inhibited by root exudate components [68]. The roots of some plants, as they develop, secrete rhizodeposits, the soluble fraction of which is rich in polysaccharides that increase aggregate cohesion [69]. Our results recorded that the three perennial species reacted differently for microbial richness at the soil level. We found that the soil under *A. pungens* contains more fungi than bacteria compared to the soils under *R. raetam* and *A. armatus* (Figure 6). Fungi are the most effective in improving aggregate stability due to their secretions with high adhesive power [69]. The N_2 fixation process of the two Fabaceae plants, involving a variable number of atmospheric nitrogen-fixing bacteria on the roots [70, 71].

Our results showed that the soil texture, more precisely the accumulated sediments under the plants studied, was different from that of the non-fixed sedimentary accumulations, the soil under the canopy showed higher rates of fine particles (silt and clay). El-Bana et al. [40] reported that there were significant differences in the soil texture of the nebkas fixed by *Retama raetam*, the proportion of the finest soil particles was higher under the cover than that of the soil between nebkas. The principal component analysis (PCA, Figure 7) allowed a better visualization of the behavior of the soil in the presence of vegetation and a study of the relationship between soil variables. The first axis F1 was positively correlated with N, C,

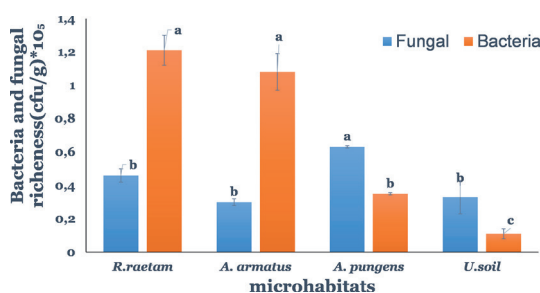


Figure 6.
Canopy influence on sediment microbial richness.

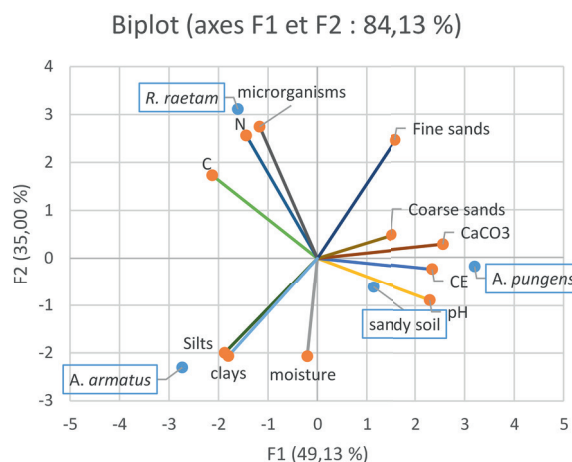


Figure 7.
 The principal component analysis demonstrating the relationship between soil variables and vegetation.

bacterial and moisture contents, this variability was linked to the presence of *R. raetam* ($r = 0.66$). Axis F1 was negatively correlated with coarse sand content, C/N ratio and accumulated sediment height, this variability was linked to the absence of vegetation on non-fixed soil ($r = 0.87$). The second axis (F2) was positively correlated with fungal content, fine sand percentage, CaCO_3 content, and soil EC, this variability was linked to the presence of *A. pungens* ($r = 0.86$). The negative side of axis F2 was correlated with silt and clay contents, this variability was linked to the presence of *A. armatus* ($r = 0.56$).

Each plant reacted differently:

- *R. raetam* provided more information on nitrogen, carbon, and bacterial richness. According to El-Bana et al. [72], the *R. raetam* nebka can improve floristic richness in areas where the soil is subjected to severe deflation. *R. raetam* branches are effective in capturing and retaining soil [40]. Danin [63] reported that this *R. raetam* shrub could survive in sand deflation cycles. Our results were similar to those of Sarig et al. [71] who explained that N₂-fixing Fabaceae trees, such as *R. raetam*, could improve nutrient content and soil structure by adding nitrogen and organic matter to the soil due to falling litter and thanks to symbiotic associations at the root level with rhizobial bacteria and mycorrhizal fungi. Through our study, we have added similar effects of *A. armatus*, which presented characteristics close to those of *R. raetam*.
- *A. armatus* had higher silt and clay values under its canopy, which could be due to the alluvial and colluvial deposits in the Mokrane area. *A. armatus* is also known as a degradation indicator plant [73].
- *A. pungens* can be considered a “facilitator” (sensu CONNELL and SLATYER [74]) rather than an initiator of the nebka. This role has already been described in Tunisia [18] for *A. pungens*, which regresses and disappears once sand fixation is complete. Our results showed that *A. pungens* had a marked effect on capturing fine sand, and the root exudates of this plant attract fungi more than the two other plants studied.

4. Conclusion

Arid and semi-arid ecosystems are particularly vulnerable to desertification due to climatic constraints and anthropogenic pressures. This study aimed to assess the role of vegetation in mitigating wind erosion and improving soil conditions in the Mokrane region of Algeria. Our findings reveal that while the plant species richness is limited, the existing vegetation plays a crucial role in stabilizing sand dunes and enhancing soil properties. The formation of fixed Aeolian deposits by selected plant species demonstrates their effectiveness in controlling wind erosion. Moreover, the observed variations in soil characteristics under different plant species highlight the importance of species diversity in ecosystem restoration. The results of this study emphasize the potential of *Retama raetam* and *Aristida pungens* for rehabilitating degraded sandy soils in arid environments. A combined approach utilizing these species could offer a promising strategy for sustainable land management and combating desertification in the region. Further research is recommended to explore the long-term impacts of these plant species on soil fertility, biodiversity, and ecosystem services.

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