

# Trade-offs between vegetation recovery and soil fertility under semi-arid rangeland rehabilitation: insights from Central Tunisia

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## Research Article

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# Abstract

## Background and aims

Rangeland rehabilitation becomes necessary when structural and functional degradation has exceeded the ecosystem's capacity for natural recovery. This study investigates and compares the long-term effects of two rehabilitation approaches—shrub plantation and water-harvesting interventions—on vegetation composition and structural attributes and soil fertility in a semiarid rangeland ecosystem of central Tunisia.

## Methods

Four experimental areas were defined alongside a control zone (natural rangeland), representing different rehabilitation techniques: cactus plantation, Acacia plantation, scarification, and bund construction. Vegetation monitoring and soil sampling were conducted in spring. Measured parameters included total vegetation cover (TVC), plants density and diversity, carrying capacity (CC) and soil physicochemical properties, including soil organic carbon (SOC) and key nutrients (N, Mg, K, and CaO).

## Results

Scarification significantly enhanced plant density and diversity, particularly of perennial species, indicating a trajectory toward ecosystem recovery. Diversity metrics, including richness and evenness, increased significantly under all rehabilitation treatments compared to the control, with the strongest improvements observed under scarification. *Cactus* plantation showed the highest TVC ( $85.3 \pm 6.8\%$ ) and CC ( $0.86 \pm 0.16$  Sheep Unit  $\text{ha}^{-1} \text{ year}^{-1}$ ), likely due to greater annual species abundance. However, SOC and key nutrients declined under most treatments, whereas bunds remained comparable to the control.

## Conclusions

Findings suggest that although rehabilitation techniques promote vegetation recovery, they may also result in a decline in soil fertility. Scarification appears most effective in restoring perennial vegetation and enhancing ecosystem function, despite concurrent nutrient depletion. These findings highlight important trade-offs and guide for selecting appropriate rangeland rehabilitation strategies in semi-arid environments.

## Introduction

Rangelands are the largest terrestrial biome, covering approximately 54% of the Earth's land surface (Ellis et al. 2010). They provide the primary livelihood for hundreds of millions of pastoral and agro-pastoral households, especially in the arid and semi-arid regions of the Mediterranean Basin, the Sahel, and West Asia (Reid et al. 2014; Eldridge and Fisher 2026). In these environments, chronic overgrazing, increasing erratic rainfall, land-use change, and the erosion of traditional mobility-based grazing systems have driven widespread structural and functional degradation of rangeland ecosystems (von Wehrden et al. 2012; Reid et al. 2014; Gaitán et al. 2018). When degradation exceeds ecological thresholds, dryland ecosystems can shift into persistent low-productivity states characterized by reduced vegetation cover, declining plant density, and dominance of annual or unpalatable species. These regime shifts are reinforced by

vegetation–soil feedback that constrains natural recovery and may require active restoration to restore ecosystem functions (Suding et al. 2004; Kéfi et al. 2007; Roy et al. 2026). Identifying effective rehabilitation strategies that reverse degradation while enhancing long-term ecosystem resilience remains a critical challenge in global dryland management (Bestelmeyer et al. 2017; Maestre et al. 2016; He et al. 2026).

Natural rangelands occupy more than one-third of Tunisia's territory and support extensive livestock systems in arid and desert regions. However, low and variable rainfall, combined with overgrazing, reduced pastoral mobility, and increasing reliance on supplementary feeding, have contributed to vegetation degradation and declining forage productivity in steppic and pre-desert ecosystems (Jauffret and Lavorel 2003; Gamoun 2016). Since the early 1990s, Tunisia has implemented rangeland rehabilitation programs through the "Office de l'Élevage et des Pâturages" (OEP, a public development organization), integrating soil and water conservation measures, grazing management, and drought-adapted shrub plantations to restore ecosystem productivity and resilience (Louhaichi et al. 2021).

Rangeland rehabilitation in Tunisia has largely relied on two complementary approaches: biological restoration through drought-tolerant shrub plantations and hydrological restoration through water-harvesting techniques. Plantations of *Opuntia ficus-indica* and *Acacia spp.* are widely used for their high drought resistance, rapid establishment, and ability to provide valuable forage during dry periods while improving soil protection and vegetation recovery (Le Houérou 2000; Nefzaoui et al. 2002). In parallel, mechanical interventions such as soil scarification and traditional runoff-harvesting structures (jessour and tabias) enhance infiltration, reduce runoff losses, and promote sediment and nutrient accumulation. These measures create favorable microsites for plant regeneration and help restore ecosystem productivity and resilience in water-limited Mediterranean drylands (Critchley and Siegert 1991; Ouessar et al. 2009).

Although rangeland rehabilitation techniques have been shown to improve vegetation cover, plant density, and forage production (Le Floch et al. 1999), their long-term effectiveness remains uncertain because direct comparisons among rehabilitation approaches under similar environmental conditions are still limited. Most assessments have focused on aboveground vegetation responses, while changes in soil physicochemical properties and belowground ecosystem functions have received comparatively little attention. This is a critical gap because soil organic carbon and nutrient pools regulate ecosystem productivity, stability, and recovery potential (Lal 2004; Conant et al. 2017; Zhang et al., 2025). Increased biomass following rehabilitation does not necessarily indicate sustainable restoration if improvements are accompanied by declines in soil organic matter or nutrient availability. Therefore, identifying interventions that enhance both vegetation recovery and soil functioning is essential for distinguishing genuine ecosystem restoration from short-term resource redistribution and for developing sustainable rangeland management strategies (Hobbs and Harris 2001; Gann et al. 2019).

The Oueslatia rangeland in the semi-arid area of Tunisia provides a valuable natural setting for addressing this knowledge gap. For nearly two decades, this landscape has been subjected to a series of rangeland rehabilitation interventions, including cactus and *Acacia* plantations, soil scarification, and bund construction. In contrast, adjacent unmanaged rangelands have remained untreated. The long-term

implementation of these parallel rehabilitation approaches provides a unique opportunity to assess the effects of different rehabilitation techniques on vegetation dynamics and soil properties under comparable climatic, edaphic, and management conditions.

The present study addresses these gaps by evaluating the long-term ecological and productive outcomes of Tunisia's national rangeland rehabilitation program. Specifically, this study aims to compare different rehabilitation methods applied to degraded rangelands in semi-arid areas by assessing their effects on vegetation structure, ecosystem productivity, and soil fertility. The research questions that justify this study are (i) how does each rehabilitation approach affect the structure and functioning of pastoral ecosystems in the target area? (ii) Which rehabilitation method(s) provide the greatest benefits compared with the control area, and are vegetation indicators alone sufficient to evaluate their effectiveness? (iii) Based on the overall assessment of the advantages and limitations of each technique, which combinations of rehabilitation practices can be recommended to support sustainable rangeland management?

## Materials and methods

### Study area

The study was conducted at the Experimental Station of the National Institute of Agricultural Research of Tunisia (INRAT) in Oueslatia, governorate of Kairouan, in central Tunisia (Fig. 1; 35°50'57.0" N, 9°37'39.7" E). The study area is characterized by a semi-arid Mediterranean climate (BSk according to the Köppen–Geiger climate classification), with a mean annual rainfall of approximately 347 mm (based on local measurements collected between 1983 and 2025), a mean annual temperature of 19.2°C, and an estimated mean annual potential evapotranspiration of approximately 1,680 mm. The climate is characterized by hot, dry summers, with precipitation occurring mainly during autumn and spring. Over the past two decades, rainfall has become increasingly irregular, with drought events occurring frequently (Bousbih et al. 2017).

The study area is dominated by poorly developed soils, which are mostly silty or calcareous. The landscape consists of agricultural land, including cereal crops alternating with fallow fields and orchards, mainly olive (*Olea europaea*) and almond (*Prunus dulcis*) trees. It also includes rangelands composed of shrublands dominated by Aleppo pine (*Pinus halepensis*) forests, ranging from dense stands to degraded woodlands; carob (*Ceratonia siliqua*) and mastic (*Pistacia lentiscus*), and steppes characterized by *Stipa tenacissima* and *Seriphidium herba-alba* (Asso) Soják. Land use in the region is primarily dedicated to livestock production, cereal cultivation, olive growing, and beekeeping. Historically, livestock farming has been dominated by small ruminants, with sheep remaining the predominant species, while camel husbandry, once practiced on a limited scale, and gradually disappeared by the end of the twentieth century.

### Experimental design

At the Experimental Station of the INRAT at Oueslatia, several rangeland rehabilitation measures have been implemented for nearly two decades to improve the dynamics of the pastoral ecosystem. Five management areas were delineated according to the rehabilitation practice applied: (i) spineless cactus

(*Opuntia ficus indica* f. *inermis*) plantation, (ii) *Acacia saligna* plantation, scarification, and contour bunds, and (v) a control area representing the natural rangeland.

The cactus plantation follows a continuous linear pattern with 5-meter spacing between rows. The *Acacia* plantation features 10-meter spacing both within and between rows. Scarification involves scraping the topsoil layer with a ploughshare to create parallel furrows—spaced 50 cm apart—running perpendicular to the low slope. As for the bunds, these are small earthen embankments, 1 meter high and 2 meters width at the base, arranged in a large crescent shape, perpendicular to the low slope and spaced approximately 100 meters apart.

Within each treatment, three adjacent, distinct and independent areas were selected, resulting in a total of 18 sampling plots. Vegetation surveys and soil sampling of the upper soil layer (0–20 cm depth) were conducted in each plot during the spring of 2025. All study areas (treatments and control) were subjected to continuous grazing by sheep and goat flocks, both before and after the implementation of the rehabilitation measures being tested.

## Vegetation cover and plant density

Vegetation monitoring was carried out using the quadrat point method described by Daget and Poissonnet (1971). In each plot, a randomly positioned 20-m line transect was established. A fine pin was inserted vertically at 20-cm intervals along the transect to record contacts with vegetation and ground surface components. In addition, four subplots were established within each plot to determine the density of perennial (PD) plants using a 20 m<sup>2</sup> sampling area and annual (AD) plants using three replicated 1-m<sup>2</sup> subplots. Total vegetation cover (TVC) was calculated as follows:

$$TVC = \frac{n}{N} \times 100$$

1

With *n* representing the number of points with vegetation presence and *N* representing the total number of points.

## Diversity metrics

To evaluate the effects of rehabilitation on ecosystem structure, health, and dynamics, three biodiversity metrics were calculated: the Shannon–Wiener diversity index (*H'*), True Diversity (TD), and Evenness (*E*). The Shannon–Wiener diversity index (*H'*) was used to assess habitat heterogeneity by accounting for both species' richness and relative abundance. True Diversity (TD) was calculated to estimate the effective number of species, thereby overcoming the non-linearity associated with conventional diversity indices. Evenness (*E*) was used to evaluate the uniformity of species abundance distributions within the community. These metrics were calculated for each sampling plot based on the recorded species abundance data using the following formulas:

$$H' = -\sum_{i=1}^s p_i \ln p_i$$

2

$$TD = e^{H'}$$

3

$$E = \frac{H'}{\ln(S)}$$

4

With  $S$  being the total number of species (richness), and  $P_i$  is a proportion of individuals belonging to the  $i^{\text{th}}$  species ( $n_i/N$ ).

## Biomass and pastoral productivity

Within all treatments, natural vegetation biomass was estimated by cutting aboveground vegetation within triplicate subplots of 4 m<sup>2</sup> each. The fresh weight (FW) was determined on-site using a digital balance. Samples were then oven-dried at 65°C for 72 hours and weighed to obtain their dry weight (Jones et al., 1990). The percentage of dry matter (DM) was calculated as:

$$DM (\%) = \frac{DW}{FW} \times 100$$

5

Furthermore, data collected on each line transect were used to calculate the specific frequency of presence ( $SFP$ ) according to the following formula:

$$SFP_i = \frac{n_i}{N} \times 100$$

6

(where,  $n_i$  is the number of hits of the  $i^{\text{th}}$  species). The specific contribution of presence ( $SCP$ ) of species  $i$  was calculated as:

$$SCP_i = (SFP_i / \sum_{i=1}^n SFP_i) \times 100$$

7

Grazing value (GV) was calculated using the following formula:

$$GV = 0.2 \times \sum_{i=1}^n (SCP_i \times I_{si}) \times VC$$

8

Where  $I_{si}$  is the acceptability index of  $i$  species (Le Hou  rou and Ionesco, 1973). Thereafter, Pastoral Productivity ( $PP$ ) was calculated as:

$$PP \left( \text{FU ha}^{-1} \text{year}^{-1} \right) = 7.52 \times GV$$

9

According to A  doud et al. (1983), with forage unit (FU) being the energy equivalent of 1 kg of barley. Carrying Capacity ( $CC$ ) was calculated as

$$CC \left( \text{SU ha}^{-1} \text{year}^{-1} \right) = \frac{PP}{\text{FU needs for head per year}}$$

10

According to Bouamar (1987), annual forage unit needs for sheep in the Mediterranean Basin were estimated around 350 FU head<sup>-1</sup> year<sup>-1</sup>.

## Soil parameters

Soil samples were air-dried at room temperature and sieved through a 2-mm mesh before analysis. Soil electrical conductivity (EC) was determined in the saturated paste extract using a conductivity meter (InoLab Cond Level 1). Soil organic matter (OM) was determined according to the method of Anne (1945), which is based on the complete oxidation of organic carbon with potassium dichromate in sulfuric acid under boiling conditions. Soil organic carbon (SOC) was calculated from organic matter using the equation: SOC = OM / 1.725. Total nitrogen (N) was determined using the micro-Kjeldahl method (ISO 11261), while active limestone was measured using the Drouineau–Galet method (NF X 31–106). Potassium (K) and magnesium (Mg) concentrations were determined using an atomic absorption spectrophotometer (Shimadzu AA-6800, Shimadzu Corporation, Kyoto, Japan).

## Statistical analysis

Shapiro-Wilk test was applied to check data normality. In order to evaluate the effect of different rehabilitation types on measured vegetation and soil parameters a One-way ANOVA was performed to detect significant differences. Duncan's test was used to find different groups.

To explore the relationships between used parameters in this study, a correlation matrix was calculated for all variables and a heatmap was generated to visualize rehabilitation types with similar profiles and groups of correlated variables. A Redundancy Analysis (RDA) was used to model the combined response of soil

and vegetation variables to the rehabilitation types. Data analysis was conducted using open-source R software (version 4.5.1) by connecting a set of packages.

## Results

### Dry biomass, total vegetation cover and carrying capacity

Variations in DM, TVC, and CC among the rehabilitated areas and the control are presented in Fig. 2. Analysis of variance followed by Dunn's test revealed significant differences ( $p < 0.05$ ) for DM and CC, and highly significant differences ( $p < 0.001$ ) for TVC. The highest DM values were recorded in the control area ( $63.2 \pm 2.5\%$ ) and the bund construction treatment ( $60.1 \pm 5.3\%$ ). In contrast, the highest TVC ( $85.3 \pm 6.8\%$ ) and CC ( $0.86 \pm 0.16 \text{ SU ha}^{-1} \text{ year}^{-1}$ ) values were observed in the cactus plantation area.

### Plant density

A comparison of the mean densities of annual and perennial species is presented in Fig. 3. Analysis of variance revealed a highly significant difference in perennial density ( $p < 0.001$ ) and a significant difference in annual density ( $p < 0.05$ ) between the rehabilitated areas and the control. Perennial density (PD) in the bund construction and cactus plantation treatments was comparable to that of the control, with values of  $3.1 \pm 1.7$ ,  $4.0 \pm 0.8$ , and  $4.8 \pm 1.4 \text{ plants m}^{-2}$ , respectively. The highest PD was recorded in the scarified area ( $9.2 \pm 1.3 \text{ plants m}^{-2}$ ), whereas the lowest was observed in the Acacia plantation ( $2.2 \pm 0.3 \text{ plants m}^{-2}$ ), representing a significant decrease. In contrast, annual density (AD) was significantly higher in the cactus plantation ( $76.7 \pm 15.3 \text{ plants m}^{-2}$ ) and bund construction treatments ( $73.2 \pm 25.1 \text{ plants m}^{-2}$ ). The lowest AD values were recorded in the Acacia plantation ( $35.8 \pm 9.0 \text{ plants m}^{-2}$ ) and the scarified area ( $46.5 \pm 15.3 \text{ plants m}^{-2}$ ), both of which were comparable to the control ( $40.7 \pm 13.5 \text{ plants m}^{-2}$ ).

### Diversity

Variation in true diversity (TD) and evenness (E) values under the different rehabilitation techniques and the control treatment is presented in Fig. 4. Mean comparison revealed a significant increase in the effective number of species ( $p < 0.001$ ) in all rehabilitated areas compared with the control, demonstrating the positive impact of rehabilitation on species establishment and diversity. The highest TD values were recorded in the scarified area ( $12.1 \pm 1.3 \text{ species}$ ) and the cactus plantation ( $10.9 \pm 0.5 \text{ species}$ ). Intermediate TD values were observed in the Acacia plantation ( $9.0 \pm 2.8 \text{ species}$ ) and the bund construction treatment ( $6.9 \pm 2.2 \text{ species}$ ). In contrast, the control area exhibited the lowest species diversity, with only  $2.9 \pm 1.2$  effective species.

Similarly, species evenness differed significantly among treatments, with all rehabilitation techniques showing significantly higher mean E values than the control ( $p < 0.01$ ). While the control area had an evenness value of  $0.56 \pm 0.12$ , rehabilitated areas exhibited E values ranging from  $0.78 \pm 0.04$  in the bund construction treatment to  $0.84 \pm 0.02$  in the scarified area.

### Soil properties

Soil parameter variations between rehabilitated areas and the control site are presented in Table 1. Mean comparisons revealed significant differences among treatments for electrical conductivity (EC), total nitrogen (N), and soil organic carbon (SOC) ( $p < 0.001$ ), as well as for Mg and CaO ( $p < 0.001$ ), while potassium (K) showed a significant difference ( $p < 0.05$ ). The highest mean values of SOC, N, and K were recorded in the control area ( $1.91 \pm 0.09\%$ ,  $1.93 \pm 0.30\%$ , and  $22.77 \pm 1.51$  ppm, respectively). These values were maintained only in the area with bund construction, where SOC, N, and K reached  $2.14 \pm 0.13\%$ ,  $1.92 \pm 0.09\%$ , and  $21.37 \pm 4.34$  ppm, respectively. In contrast, these parameters decreased significantly in the scarified area, reaching the lowest mean values of  $0.83 \pm 0.31\%$ ,  $0.57 \pm 0.25\%$ , and  $17.20 \pm 1.61$  ppm, respectively.

The highest CaO concentration was observed in the control area ( $3.50 \pm 0.50\%$ ), followed by a significant decline in all rehabilitated areas, where values ranged from 2.00 to  $1.33 \pm 0.58\%$ . This reduction suggests increased utilization of free lime in chemical reactions promoted by the rehabilitation practices.

Table 1

Electrical Conductivity (EC), Total Nitrogen (N), Soil Organic Carbon (SOC), Potassium (K), Magnesium (Mg) and Active limestone (CaO) variation under tested rehabilitation techniques (Acacia plantation, bunds, Cactus plantation and scarification) compared to control area (natural rangeland). Values are mean  $\pm$  SD ( $n = 3$ ).

| Rehabilitation type                                             | EC (mS.cm <sup>-1</sup> )   | N (%)                       | SOC (%)                      | K (ppm)                       | Mg (ppm)                      | CaO (%)                     |
|-----------------------------------------------------------------|-----------------------------|-----------------------------|------------------------------|-------------------------------|-------------------------------|-----------------------------|
| Acacia plantation                                               | $1.47 \pm 0.66$<br><b>b</b> | $1.49 \pm 0.12$<br><b>b</b> | $1.75 \pm 0.33$<br><b>ab</b> | $16.82 \pm 5.17$<br><b>ab</b> | $20.70 \pm 8.16$<br><b>b</b>  | $1.33 \pm 0.58$<br><b>b</b> |
| Bunds                                                           | $2.89 \pm 0.19$<br><b>a</b> | $1.92 \pm 0.09$<br><b>a</b> | $2.14 \pm 0.13$<br><b>a</b>  | $21.37 \pm 4.34$<br><b>a</b>  | $34.15 \pm 5.88$<br><b>a</b>  | $2.00 \pm 0.00$<br><b>b</b> |
| Cactus plantation                                               | $2.51 \pm 0.16$<br><b>a</b> | $1.50 \pm 0.16$<br><b>b</b> | $1.43 \pm 0.11$<br><b>b</b>  | $14.28 \pm 0.40$<br><b>b</b>  | $19.48 \pm 0.47$<br><b>bc</b> | $1.67 \pm 0.58$<br><b>b</b> |
| Scarification                                                   | $0.71 \pm 0.06$<br><b>c</b> | $0.57 \pm 0.25$<br><b>c</b> | $0.83 \pm 0.31$<br><b>c</b>  | $17.20 \pm 1.61$<br><b>ab</b> | $11.77 \pm 1.47$<br><b>c</b>  | $1.67 \pm 0.58$<br><b>b</b> |
| Control                                                         | $1.46 \pm 0.05$<br><b>b</b> | $1.93 \pm 0.30$<br><b>a</b> | $1.91 \pm 0.09$<br><b>a</b>  | $22.77 \pm 1.51$<br><b>a</b>  | $20.39 \pm 1.22$<br><b>bc</b> | $3.50 \pm 0.50$<br><b>a</b> |
| <i>F value</i>                                                  | 23.204                      | 23.294                      | 15.607                       | 3.615                         | 9.311                         | 8.733                       |
| <i>P value</i>                                                  | 0.0000                      | 0.0000                      | 0.0003                       | 0.0452                        | 0.0021                        | 0.0027                      |
| Significance                                                    | ***                         | ***                         | ***                          | *                             | **                            | **                          |
| Significance : '***' $p < 0.001$ '**' $p < 0.01$ '*' $p < 0.05$ |                             |                             |                              |                               |                               |                             |

The highest Mg concentration was recorded in the bund construction treatment ( $34.15 \pm 5.88$  ppm). Mg concentrations in the cactus and Acacia plantation treatments ( $19.48 \pm 0.47$ ,  $20.70 \pm 8.16$ , and  $20.39 \pm 1.22$  ppm, respectively) were comparable to those of the control area, whereas the scarified area exhibited a marked decline, with the lowest mean value of  $11.77 \pm 1.47$  ppm. EC showed a pattern closely associated with Mg concentrations, with the highest value recorded in the bund construction area ( $2.89 \pm 0.19$  mS

cm<sup>-1</sup>) and the lowest in the scarified area ( $0.71 \pm 0.06$  mS cm<sup>-1</sup>), indicating a strong positive relationship between these two parameters.

## Heatmap analysis and correlation between variables

Heatmap-based hierarchical clustering of control area and rehabilitation treatments, together with the correlations among the measured variables, are presented in Fig. 5. Clustering analysis revealed distinct patterns, highlighting two major groups of variables related to vegetation structure (E, TD, PD, AD, TVC, and CC) and soil fertility (K, CaO, EC, Mg, N, and SOC). Furthermore, the analysis distinguished four groups of areas. Three groups were represented by individual treatments: cactus plantation, scarification, and control (non-rehabilitated area), while the fourth group combined bund construction and Acacia plantation.

The cactus plantation was characterized by substantial increases in total vegetation cover (TVC) and canopy cover (CC), whereas scarification promoted greater species diversity and evenness and facilitated the establishment of perennial species. However, both treatments showed limited levels of key nutrient elements and soil organic carbon (SOC). Intermediate values of both vegetation and soil characteristics were observed in Acacia plantations and banded areas. In contrast, the control area was clearly differentiated by low vegetation diversity, reduced species evenness, and low productivity, with vegetation strongly dominated by *S. herba-alba*. Despite these poor vegetation characteristics, the control area exhibited the highest soil fertility levels, indicating greater nutrient availability, although it was associated with a relatively high CaO content (3.5%). Strong positive correlations were observed between TVC, CC, and AD, suggesting that productivity increases were mainly driven by increases in aboveground density (AD), particularly in cactus plantations and banded areas. Additionally, strong positive relationships were detected between CaO, dry matter (DM), and K, as well as between SOC, N, and Mg. Conversely, strong negative correlations were found between CaO, DM, and K with total diversity (TD) and evenness (E).

## Redundancy analysis

A redundancy analysis (RDA) was conducted to assess the relationships among variables and to evaluate the combined effects of rehabilitation techniques on vegetation and soil characteristics compared with the control treatment. The results showed that the first two principal axes (PC1 and PC2) together explained 79.2% of the total variance (Fig. 6). PC1 accounted for 49% of the variance and represented a significant gradient distinguishing managed areas from the control. This axis separated soil fertility-related variables, particularly chemical nutrients, associated with the control and bund construction treatments (negative side), from vegetation-related variables, including species diversity and vegetation growth, associated with planted areas and scarification (positive side).

PC2 explained 30.2% of the constrained variance and mainly differentiated areas according to soil and vegetation characteristics. The positive side of this axis was associated with high values of dry matter (DM) and CaO, mainly observed in control areas, as well as high perennial density (PD) in scarified areas. In contrast, cactus plantations and bund construction areas were characterized by higher total vegetation cover (TVC) and aboveground density (AD) values.

## Discussion

The results of this long-term comparison indicate that the rehabilitation techniques applied at INRAT's experimental station in Oueslatia did not affect the rangeland ecosystem uniformly. They positively impacted vegetation structure and productivity, but also imposed measurable costs on soil chemical fertility, which varied by technique. The divergence between above- and below-ground responses is the central finding, and it has direct implications for defining and monitoring rehabilitation success.

The high total vegetation cover and carrying capacity recorded under cactus plantations and bunds were driven primarily by an increased abundance of annual species rather than by the re-establishment of a perennial-dominated plant community. This pattern is consistent with the ecological functioning of these restoration techniques. Spineless cactus (*Opuntia ficus-indica* f. *inermis*) plantations create shaded, wind-protected microsites that enhance litter accumulation and soil moisture retention, thereby facilitating the germination and growth of ephemeral and annual species beneath and around established plants (Nobel, 1988; Le Houérou, 2000). Similarly, bunds, derived from traditional Tunisian water-harvesting systems such as *jessour* (a mixed small stone and soil dam built across mountain wadis and thalwegs) and *tabias* (macro-catchment system built on low sloping plains), intercept and concentrate runoff and sediment behind small earthen embankments, creating localized areas of improved soil moisture that promote the rapid establishment of opportunistic annual species during favorable growing seasons (Calianno et al. 2020; Prinz and Singh 2000). Although both rehabilitation approaches generate a rapid and visually increase in vegetation cover, the resulting plant communities remain structurally simple and highly dependent on interannual rainfall variability. Consequently, their apparent restoration success may be transient, as annual-dominated communities are particularly vulnerable to collapse during prolonged drought periods, whereas the recovery of perennial vegetation typically requires longer timeframes and sustained improvements in resource availability (Cortina et al. 2011).

Unlike cactus plantation and bund construction techniques, in which annual species benefited mainly from the favorable microclimatic conditions created by the cactus plantation (both beneath the canopy and in inter-patch areas) and the improved soil hydraulic functioning associated with bund construction, Scarification followed a markedly different trajectory. Rather than maximizing short-term vegetation cover, it produced the greatest increases in plant density and perennial species diversity. By disrupting surface crusts and compacted soil layers, scarification enhances water infiltration and creates favorable microsites for seed capture and root penetration, thereby improving seedling establishment and root development. These conditions preferentially benefit perennial grasses and shrubs over ephemeral annuals, promoting a shift toward a perennial-dominated community (Tongway and Hindley 2004; James et al. 2013). Such a transition represents a more robust indicator of ecosystem recovery than vegetation cover alone, as perennial species provide more stable, drought-resilient forage production and continuous protection of the soil surface throughout the year (Millennium Ecosystem Assessment 2005; Maestre et al. 2012).

The results of this study also indicate a more balanced distribution of individuals among species in rehabilitated communities, reflecting improved community structure and suggesting enhanced ecosystem stability and resilience following rehabilitation. The consistent increase in diversity metrics—including effective species number and evenness—across all rehabilitation treatments relative to the control, with the largest improvements observed under scarification, further supports the interpretation that moderate

physical disturbance combined with localized improvements in resource availability can reduce the dominance of a few stress-tolerant species characteristic of degraded rangelands, creating opportunities for a more balanced and functionally diverse plant community to establish (Hobbs and Huenneke 1992; Suding et al. 2004). These findings are consistent with the Vital Ecosystem Attributes framework developed for Mediterranean and North African drylands, which recommends assessing ecosystem recovery using multiple complementary indicators—including perennial vegetation, species richness, and productivity—rather than relying solely on vegetation cover to determine whether ecosystems are moving toward recovery or further degradation (Aronson et al. 1993; Tongway and Hindley 2004; Gann et al. 2019).

The decline in soil organic carbon and key nutrients (N, Mg, K, and CaO) under most rehabilitation treatments appears, at first glance, counterintuitive. A substantial body of dryland research describes the opposite pattern—the *fertility island* effect—whereby shrub canopies enrich the soil beneath them through litter deposition, root turnover, and the trapping of windborne sediments, resulting in higher concentrations of organic carbon and nutrients than in adjacent open interspaces (Schlesinger et al. 1996; Schlesinger and Pilmanis 1998; Okin et al. 2009). Several factors specific to managed rehabilitation, rather than spontaneous shrub encroachment, likely explain why this expected enrichment was not observed in the present study. First, cactus cladodes and *Acacia* foliage at Oueslatia are regularly harvested or grazed as emergency fodder, creating a continuous export of biomass and nutrients from the system. Unlike natural shrublands, where litter and senesced biomass are largely returned to the soil, nutrient pools captured by rehabilitated vegetation are repeatedly removed before they can contribute to soil organic matter accumulation. Grazing and biomass harvesting are well known to reduce litter inputs and alter nutrient cycling, particularly in water-limited ecosystems (Eldridge et al. 2011; McSherry and Ritchie 2013). Second, the soil disturbance associated with plantation establishment, and particularly scarification, likely accelerated the decomposition of previously protected soil organic matter. By breaking soil aggregates and increasing aeration, scarification exposes physically protected organic carbon to microbial decomposition, a process well documented following tillage and other mechanical disturbances (Six et al. 2000; Lal 2004; Conant et al. 2007). Consequently, although scarification may improve seedling establishment and vegetation recovery, it can also induce short- to medium-term losses of stabilized soil carbon and associated nutrients. Third, despite successful shrub establishment, large areas of inter-canopy soil remained sparsely vegetated and vulnerable to wind and water erosion. These exposed surfaces likely continued to lose fine, nutrient-rich particles, limiting the development of fertility islands and offsetting localized nutrient accumulation beneath shrub canopies. Wind and water erosion preferentially remove fine soil particles enriched in organic matter and nutrients, thereby slowing soil fertility recovery in degraded drylands (Lal 2001; Li et al. 2007). Together, these mechanisms suggest that the ecological benefits of rehabilitation for vegetation recovery do not necessarily translate into immediate improvements in soil fertility, particularly where biomass removal, soil disturbance, and continued erosion constrain the recovery of soil organic matter and nutrient stocks. These patterns support the rehabilitation inconsistency theory, which proposes that biological productivity recovers more rapidly than the soil processes responsible for supplying mineral nutrients. The higher fertility observed in the control area and in the bund construction treatment (distant tabias) may be attributed to the stability of the soil surface. This stability likely limits the

activation of biological and chemical processes that are otherwise stimulated by soil scarification and shrub plantation, thereby preserving the existing soil fertility

Bunds stand out as the only rehabilitation technique for which soil fertility remains comparable to that of the untreated control. This pattern indicates a gradient of soil modification intensity, ranging from unmanaged conditions (control) and minimally altered soils (bund construction) to actively rehabilitated soils (scarification, cactus, and Acacia plantations), which were characterized by higher plant diversity, greater perennial species density, and increased vegetation cover.

This finding is consistent with the documented function of traditional Tunisian water-harvesting structures, which capture runoff, sediment, and associated organic matter, thereby contributing to the maintenance or gradual improvement of soil fertility within treated areas (Critchley and Siegert 1991; Roose 1994; Nasri et al. 2004; He et al. 2026). Rather than causing soil disturbance or nutrient redistribution through mechanical alteration, these structures primarily modify runoff pathways, reduce erosion, and promote sediment deposition (Boers and Ben-Asher 1982; Prinz 1996). Because they function through passive processes such as hydrological regulation and sediment accumulation, rather than through soil inversion, plantation pits, or biomass removal, bunds avoid some of the main pathways of nutrient depletion associated with more intensive restoration interventions (Lal 2001; Rey et al. 2005). The contrasting responses observed among rehabilitation techniques highlight the importance of balancing vegetation recovery with long-term soil fertility conservation. Techniques involving soil disturbance, such as pitting and planting, may enhance infiltration, water availability, and vegetation establishment, particularly in dryland environments, but they can also alter soil structure and nutrient dynamics through mechanical disturbance and increased nutrient demand from growing vegetation (Whitford 2002). In contrast, bunds represent a low-disturbance restoration strategy that improves water retention and facilitates sediment and organic matter accumulation while maintaining existing soil nutrient pools (Critchley and Siegert 1991; Nasri et al. 2004). Therefore, rehabilitation planning should consider not only short-term vegetation responses but also long-term soil resource dynamics. The selection of restoration techniques should be adapted to local environmental conditions, degradation intensity, and management objectives, with particular attention to the trade-offs between rapid vegetation establishment and the conservation of soil fertility (Chazdon 2008). Combining structural measures such as bunds with complementary practices, such as organic matter additions, surface mulching, and controlled grazing management, may further enhance the recovery of ecosystems in degraded drylands while reducing the risk of nutrient depletion (Lal 2001).

Taken together, these results show that rangeland rehabilitation requires balancing ecosystem functions rather than identifying a single universally optimal technique. Scarification was the most effective treatment for restoring perennial vegetation structure, a key attribute associated with ecosystem stability, drought resistance, and long-term rangeland resilience. Perennial plant communities generally provide greater resistance to climatic variability because of their deeper root systems, persistence during dry periods, and capacity to maintain soil functions (von Keyserlingk et al. 2021). However, the increase in perennial vegetation following scarification was accompanied by a measurable decline in soil chemical fertility, indicating that intensive mechanical disturbance may accelerate nutrient redistribution or depletion if not accompanied by complementary soil management practices.

In contrast, cactus plantations and bund construction generated the fastest and most significant increases in standing vegetation cover and short-term carrying capacity. Nevertheless, the vegetation response associated with cactus plantations was largely driven by increases in annual species, suggesting that rapid biomass accumulation does not necessarily correspond to the recovery of a stable, drought-resilient rangeland community. In degraded drylands, increases in vegetation cover may represent transient improvements if they are not accompanied by improvements in soil quality, functional diversity, and perennial species recovery (von Keyserlingk et al. 2021). Moreover, the greater decline in soil fertility observed under cactus-based rehabilitation highlights the importance of evaluating rehabilitation success using both aboveground vegetation indicators and belowground ecosystem properties.

Bunds represented the most balanced rehabilitation option because they enhanced vegetation development and grazing potential without producing detectable negative effects on soil fertility. This supports previous findings that water-harvesting structures can improve dryland ecosystem functioning by reducing runoff, increasing infiltration, conserving soil moisture, and creating favourable microsites for plant establishment (Critchley and Siegert 1991; Mekdaschi and Liniger 2013). Recent studies have similarly shown that water-spreading bunds can enhance vegetation recovery in arid rangelands through improved water availability and reduced soil degradation processes (Abbas et al. 2025). Therefore, combining bunds with targeted scarification may represent a promising integrated rehabilitation strategy. This approach allows managers to benefit from the recovery of perennial vegetation stimulated by soil disturbance, while reducing potential nutrient losses through improved moisture retention and ecosystem recovery.

From a practical management perspective standpoint, these findings suggest that the success of rehabilitation efforts in semi-arid Tunisian rangelands should not be evaluated based solely on vegetation cover or estimated carrying capacity. Such indicators may overestimate rehabilitation success when increases in biomass are associated with annual-dominated communities or occur alongside declining soil fertility, potentially reducing ecosystem resilience during future drought cycles (von Keyserlingk et al. 2021). Therefore, rehabilitation programs should incorporate long-term monitoring of both vegetation composition and soil nutrient status. In addition, adaptive management measures—including temporary reductions in grazing pressure during establishment phases, controlled harvesting of cactus and *Acacia* biomass, and the application of organic amendments—may help maintain soil fertility and improve the sustainability of restored rangeland systems (Briske et al. 2008; Herrick et al. 2012).

## Conclusion

Overall, this study shows that the recovery of vegetation and soil fertility do not necessarily occur simultaneously during rangeland rehabilitation in semi-arid central Tunisia. Among the tested interventions, scarification was more effective in restoring perennial vegetation structure and diversity, whereas cactus plantation and bunds promoted greater short-term vegetation cover and carrying capacity largely through the development of annual species. Bunds alone, however, avoided the soil nutrient depletion observed under the other rehabilitation treatments.

These findings indicate that the selection of rehabilitation techniques should be guided by the primary management objective, whether this is the rapid provision of forage, the long-term recovery of vegetation structure and ecosystem functioning, or the conservation of soil chemical fertility. Where multiple objectives are considered important, the integration of complementary techniques may provide a more balanced and effective approach. Importantly, rehabilitation success should not be evaluated solely on the basis of vegetation indicators. Soil chemical properties and longer-term ecosystem functioning should also be incorporated into assessments to provide a more comprehensive evaluation of the effectiveness and sustainability of restoration practices.

## **Declarations**

## **Declaration of Competing Interest**

The authors have no relevant financial or non-financial interests to disclose.

## **Authorship contribution statement**

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Abderrazak Tlili. The original draft of the manuscript was written, reviewed and edited by all authors. All authors read and approved the final manuscript.

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## **Data availability statement**

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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## Figures

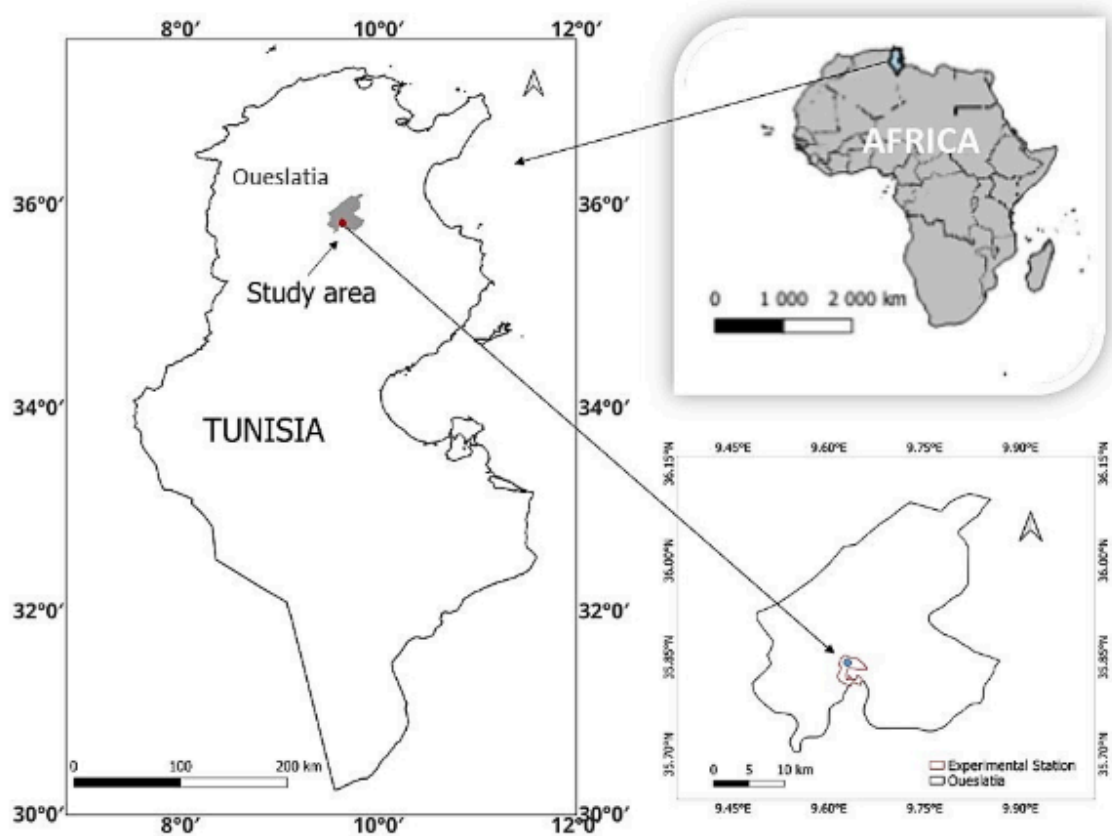


**Figure 1**

Study area localization

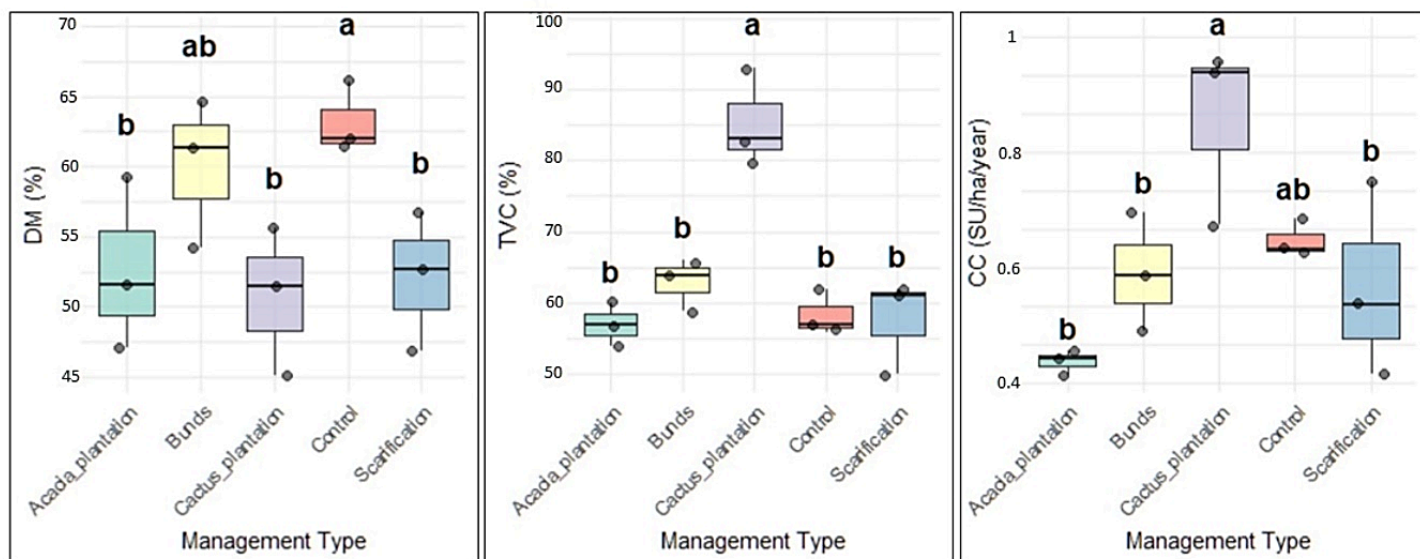


**Figure 2**

Dry matter (DM %), Vegetation Cover (VC %) and Livestock Carrying Capacity (LCC, Sheep Unit.  $\text{ha}^{-1} \cdot \text{year}^{-1}$ ) means variation between the rehabilitated areas (scarification, bunds construction, *Acacia* plantation, *Cactus* plantation) and control. Groups with different letters are significantly different (Duncan's test,  $p < 0.05$ ).

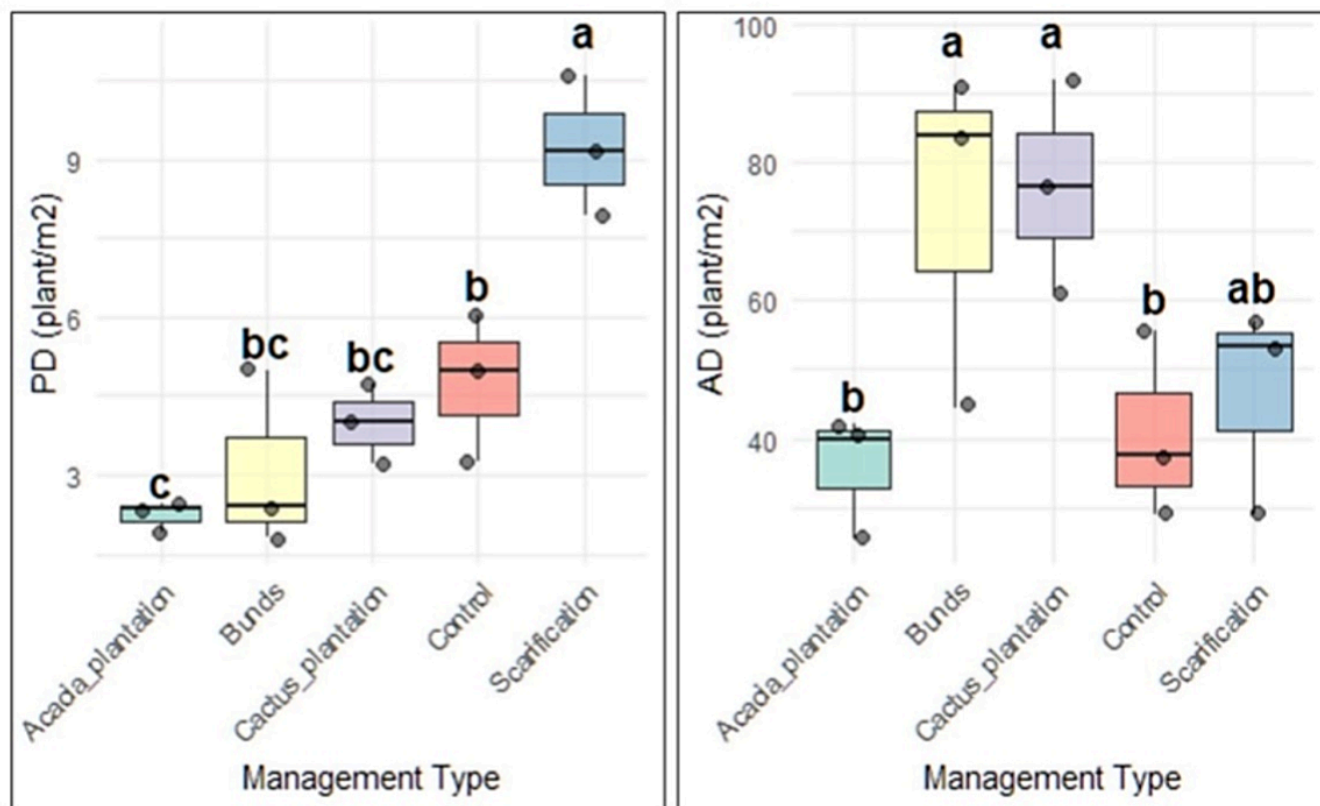


Figure 3

Comparison of annual (AD) and perennial (PD) means density between the rehabilitated areas (scarification, bunds construction, *Acacia* plantation, *Cactus* plantation) and control. Groups with different letters are significantly different (Duncan's test,  $p < 0.05$ ).

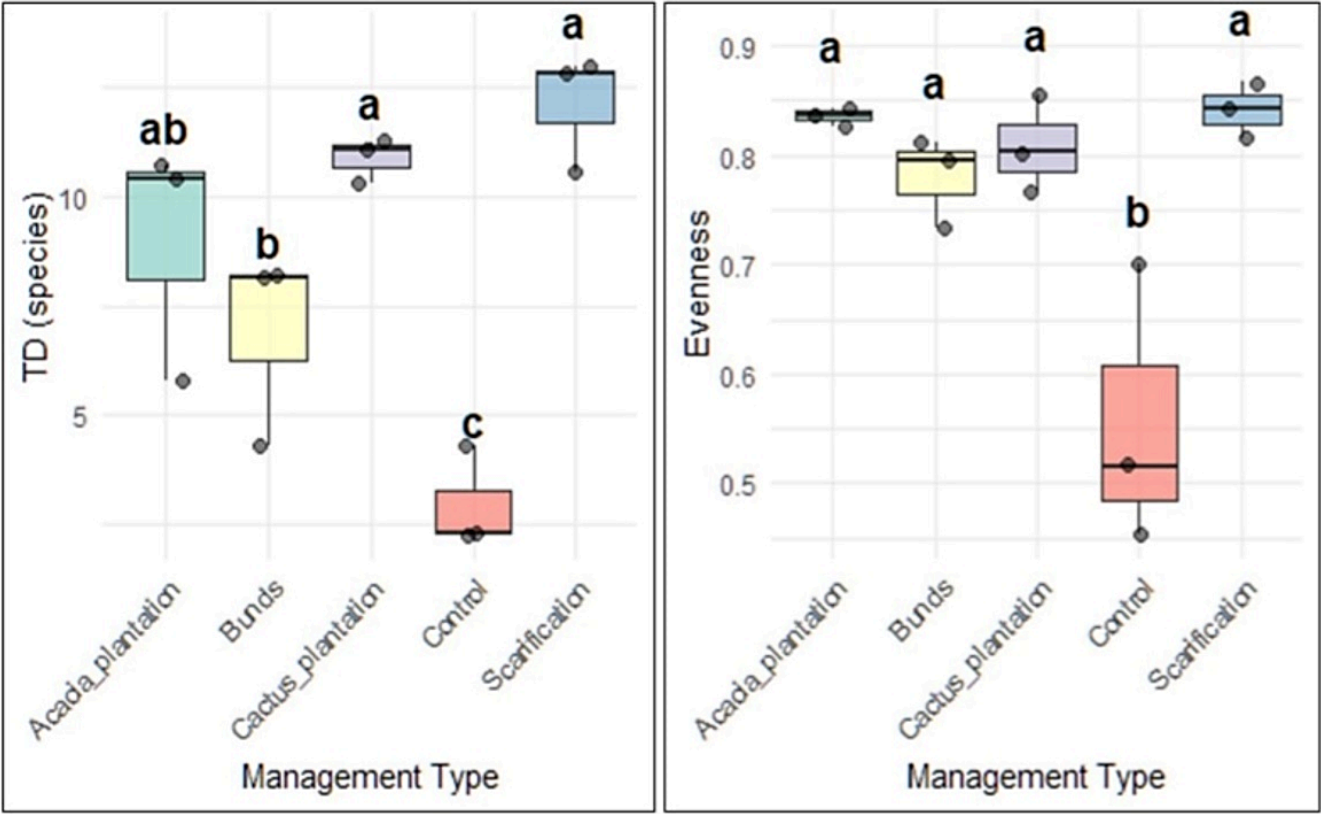


Figure 4

True diversity (TD) and Evenness variation between the rehabilitated areas (scarification, bunds construction, *Acacia* plantation, *Cactus* plantation) and control. Groups with different letters are significantly different (Duncan's test,  $p < 0.05$ ).

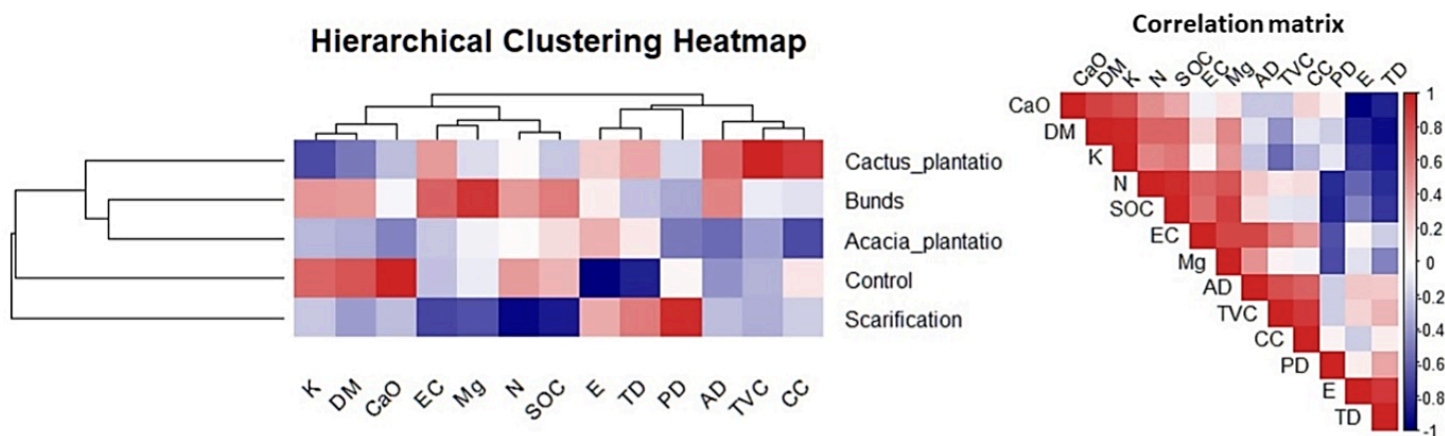


**Figure 5**

Heatmap clustering analysis of rehabilitation techniques (scarification, bunds construction, *Acacia* plantation, *Cactus* plantation and control) with correlation between measured variables with DM: dry matter, VC: vegetation cover, PD: perennial density, AD: annual density, E: evenness, TD: true diversity, LCC: livestock carrying capacity, EC: electrical conductivity, SOC: soil organic carbon, CaO: active Limestone, N: nitrogen, K: potassium and Mg: magnesium. Values are Z-scores (standardized across management types)

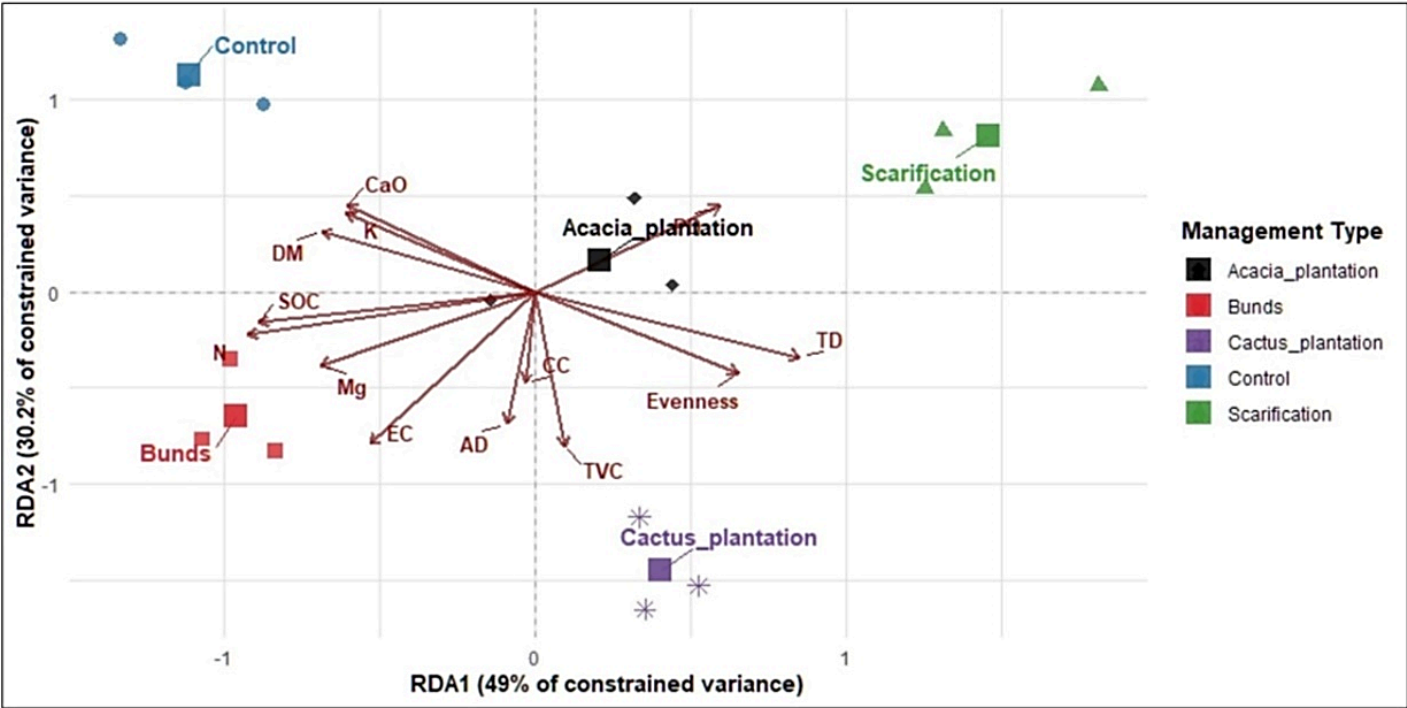


**Figure 6**

Redundancy Analysis (RDA) biplot diagram of the vegetation metrics (DM, VC, AD, and PD), diversity metrics (TD and E), soil properties (EC, SOC, CaO, N, K and Mg) and livestock carrying capacity (LCC) in different studied rehabilitation (management types) and control area. With, DM: dry matter, VC: vegetation

cover, PD: perennial density, AD: annual density, E: evenness, TD: true diversity, LCC: livestock carrying capacity, EC: electrical conductivity, SOC: soil organic carbon, CaO: active Limestone, N: nitrogen, K: potassium and Mg: magnesium.