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African Journal of Range & Forage Science 2021: 1–10
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This is the final version of the article that is
published ahead of the print and online issue

AFRICAN JOURNAL OF
RANGE & FORAGE SCIENCE
ISSN 1022-0119 EISSN 1727-9380
https://doi.org/10.2989/10220119.2020.1838608

Assessment of soil surface scarification and reseeding with sulla (*Hedysarum coronarium* L.) of degraded Mediterranean semi-arid rangelands

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Climate change and degradation of natural resources pose daunting challenges in arid and semi-arid rangelands of southern Mediterranean region. Overcoming these challenges requires considerable management actions efforts. In this context, the current two-year (2017/2018 and 2018/2019) study investigated the effects of soil surface scarification and reseeding of rangelands with sulla (*Hedysarum coronarium* L.) on botanical composition, biomass production, water productivity and pastoral value in the Sbaihia community, Tunisia. The experimental design consisted of a randomised complete block design with six replications. The treatments were: (i) soil surface superficial scarification; (ii) reseeding sulla following soil scarification; and, (iii) control. Despite the relatively important interannual variation, the highest aboveground net primary production (2 307 and 5 330 kg dry matter ha^{-1}), water productivity (9.5 and 11.8 kg DM mm^{-1}), and pastoral value (2 099 and 4 853 forage units ha^{-1}) values were recorded in the rangelands reseeded with sulla in both growing seasons. Sulla contribution in the species composition of reseeded rangelands increased from 1.7% in 2018 to 2% in 2019. Although soil surface scarification increased the vegetation cover, its effect on biomass production was not significant. Therefore, combined soil scarification and reseeding well-adapted native forage species has a great potential to improve productivity of semi-arid rangelands.

Keywords: management, soil scarification, pastoral value, Tunisia

Introduction

Rangelands extend over 800 million ha land in the Middle East–North Africa region. They are located in arid or semi-arid climates that are characterised by low and unpredictable precipitation and wide temperature fluctuations (Thomas 2008). The rangeland ecosystems in the region are threatened by population pressure, overgrazing, recurrent droughts, degradation of natural resources and recently a changing climate. These pressures are more acute in areas with climates that are marginal for existing practices of overgrazing and cultivation (Ouled Belgacem and Louhaichi 2013). In general, degraded ecosystems are less resilient to climate change than intact and healthy ecosystems (Kaeslin et al. 2012). The current abiotic factors with other biotic factors e.g. grazing pressure pose major threats to the persistence of plants and species diversity and richness, as a result of repeated and unexpected periods of drought under heavy grazing (Louhaichi et al. 2009). Climate change could also have a major impact on rangeland vegetation, such as low emergence and survival of annual species, changes in phenology and timing of reproduction, reduced biodiversity, low plant cover, and decline in productive capacity of pastoral systems (Ouled Belgacem and Louhaichi 2013; Louhaichi et al. 2019a). Therefore, land degradation can result in losses of livelihood and trigger tension and conflict over critical resources of water and rangeland (Homer-Dixon and Blitt 1998).

Alleviating rangeland degradation ecosystems and increasing their productivity are crucial for both environmental and social sustainability. Filling the gap in feed resources is a high priority to improve the livelihoods of the agro-pastoral communities. Therefore, there is an urgent need for cost-effective management actions to reverse rangeland degradation trends in order to improve livestock productivity and increase resilience to climate change (FAO 2017; Ouled Belgacem et al. 2017). Rehabilitation of deteriorated pastoral ecosystems may include a wide range of interventions, such as controlling soil erosion, harvesting rainwater, reseeding rare and endangered native species and shrub species (Louhaichi et al. 2016).

Soil surface scarification under arid climate conditions improves the water balance of the soil and thus facilitates plant succession and enhances ecosystem health (Gauthier et al. 2016). This simple technique breaks up the crusted surface soil to improve soil respiration, infiltration of water, seed germination and seedling emergence. Breaking up the surface soil creates narrow furrows that trap moisture and improve seedbed conditions. If the soil seedbed is depleted, this practice is combined by seeding, which represents a cost-effective technique for rehabilitating severely degraded rangelands (Louhaichi 2019; Louhaichi et al. 2019b).

Sulla (*Hedysarum coronarium* L.) is a legume species native to the Mediterranean basin that has high nutritive value and contains bioactive compounds, such as condensed tannins, that help to reduce the gastrointestinal nematode burdens of livestock and oxidative stress from diseases and from some physiological stages (Niezen et al. 1998; Le Houérou 2001; Burke et al. 2004; Di Trana et al. 2015). Although, it is highly underutilised, there is a growing interest among agropastoralists, because of its agronomic and nutritional traits (Ates et al. 2014; Porqueddu et al. 2016; Slim et al. 2018). Several studies in northern Mediterranean region and New Zealand have indicated that grazing sulla improves the productivity of sheep and goats and provides a suitable base for increasing the supply of animal products (Niezen et al. 1998; Bonanno et al. 2011, 2016; Molle et al. 2009; Tibe et al. 2011). Although sulla has been tested in cultivated pastures, no studies have ever explored the role and potential of sulla in rangeland rehabilitation. Accordingly, the purpose of this study is to investigate the effects of soil surface scarification and reseeding rangelands with sulla on biomass production and pastoral value of rangelands in the semi-arid zone of Tunisia.

Materials and methods

Experimental site

The Sbaihia Community site (36°27′34.86″ N, 10°13′52.17″ E) is located in the Zaghouan Governorate in Tunisia (Figure 1). The study area is characterised by a rugged terrain with structural surface limestone outcrops and marl (Ben Rhouma et al. 2018). The altitude ranges from 180 to 200 m above sea level. Soils are shallow (0.5 to 1 m), poorly permeable and often showing crusts, with silt loam texture (47% silt, 29% sand and 24% clay) (Khelifa et al. 2017). The natural vegetation is highly degraded Mediterranean garrigue with very sparse individuals of *Olea europea*, *Eryngium campestre* and *Rosmarinus officinalis*. The climate is semi-arid with annual rainfall ranging from 350 to 600 mm (PDC 2017). In year one (2017/2018), rainfall quantities were below the long-term average during the period from September 2017 to April 2018. However, in the second year, the recorded monthly rainfall was 60 mm in September 2018, 161 mm in October 2018, and 85 mm in March 2019, respectively. These registered quantities were greater than the long-term monthly average, which were 41, 62, and 49 mm for September, October and March, respectively. The precocity of precipitations and its distribution in time in the second year will have a beneficial effect on the emergence of seedlings of annual plants and the early growth and development of the perennial plants, as well as higher biomass production (ONAGRI 2019) (Figure 2).

Most of the community of Sbaihia consists of smallholder farmers. Agricultural expansion and increased demand for feeding livestock have led to rapid land degradation of collective and private lands in the region, which together with poor management practices, cutting down forest trees and planting olive trees *Olea europea*, have aggravated soil erosion and rangeland degradation (Ben Rhouma et al. 2018).

Experimental design and management

A two-year experiment was carried out in the Sbaihia community site during 2017 to 2019 to assess the efficiency of rehabilitation practices by soil surface scarification and reseeding with sulla.

The experimental design consisted of a randomised complete block design (RCBD) with six replications and three different treatments, a total of 18 sampling plots covering each an area of 30 m × 50 m. Although the overall landscape is characterised by uneven topography, the selected plots were similar in terms of slope gradient, exposition to sun and soil depth, in order to minimise the bias caused by confounding variables. The treatments were:

(i) Soil surface superficial scarification
(ii) Reseeding sulla in combination with soil scarification
(iii) Control (no reseeding or soil scarification), during which it was left to natural regeneration for two seasons.

Mechanical soil scarification was undertaken prior to broadcasting during October 2017 to improve seeding success. However, the reseeding of sulla was applied on 5 December 2017, just after the commencement of the first rainfalls. Seed broadcasting was done manually at a sowing rate of 40 kg ha^{-1}, followed by covering the seeds with soil using a spike tooth harrow. The sulla seeds were acquired from the Office of Livestock and Pasture and were not inoculated, because as the target site represents a natural development area for sulla. The viability of the seeds was tested at the national laboratory. Facultative seed germination was 69% with a specific purity of 89.63%. One thousand seeds' weight was 10.94 ± 0.32 g. The experimental area was completely protected from livestock grazing and cutting.

Measurements and data analysis

Botanical composition

The characterisation of vegetation in terms of its botanical composition was estimated using the point intercept method during May 2018 and 2019 (Daget and Poissonet 1971). Intercept measurements were collected along three, randomly located 20 m long transects for each treatment. Measurements were recorded at 20 cm intervals in order to record 100 readings per transect line. At each contact point along each transect, the ground cover (plant species, litter, bare ground) were recorded. From these data, the percentage cover for each attribute was calculated as the proportion of the transect line covered by each species (Peratoner and Pötsch 2019).

Aboveground net primary production (ANPP)

Aboveground net primary production (ANPP) was measured toward mid-May of 2018 and 2019. This corresponded to the peak of growth of the vegetation, including sulla. In total, three quadrats (1 × 1 m) were randomly placed within each

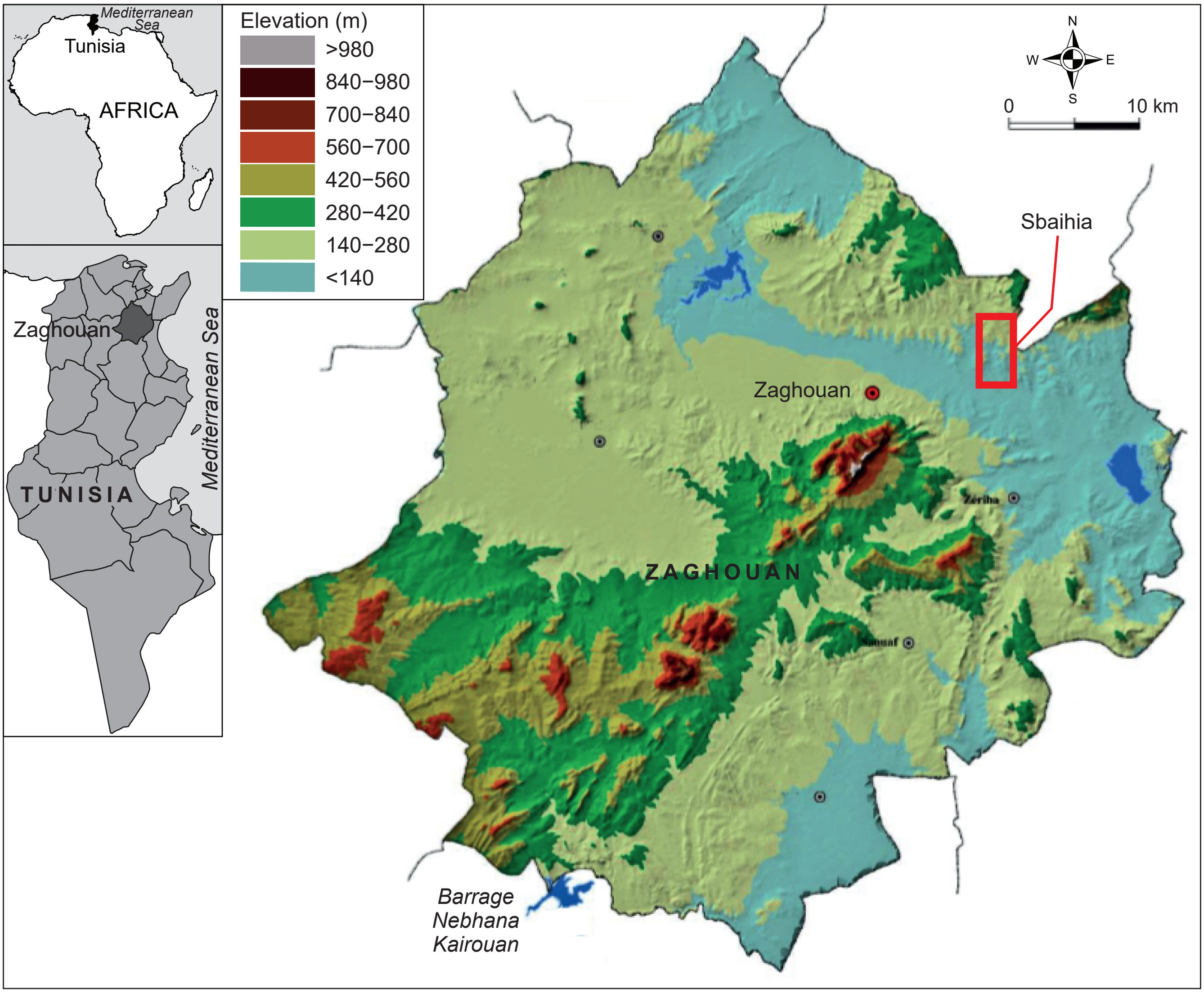

Figure 1: Geographical location of the study area (Sbaihia) in the Zaghouan Governorate, Tunisia (SDAD 2018)

plot of the three treatments. All forage biomass inside the quadrats was clipped to a stubble height of 50 mm. The total fresh material from each quadrat was immediately weighed by a field electronic scale (Ohaus Valor 7000). The dry matter (DM) content was determined by drying a subsample in an air-forced oven at 60 °C for 72 h.

Pastoral value (PV) and nutritive value (NV)

The pastoral or the net energy values of the feed per kg DM expressed in forage units (FU kg DM^{-1}), were predicted by the equations of Andrieu and Weiss (1981) used for legumes and adopted by INRA (2018). The INRA system, like most other feeding unit systems for ruminants, is based on net energy (NE). In practice, NE is expressed in FU, based on the reference barley value (1 FU = 1 760 kcal for 1 kg of raw barley). The pastoral value per hectare is equal to the amount of FU/kg of DM per hectare.

$$PV\ (FU\ ha^{-1}) = (FU_{treatment}) \times [AGB\ (kg\ DM\ ha^{-1})]$$

where, PV is pastoral value, FU is forage unit and AGB is above-ground biomass.

Crude protein (CP%)

Total nitrogen (TN) was measured by the Kjeldahl method (AOAC 1999) and results converted to crude protein content using a factor of 6.25 (i.e. percentage crude protein = percentage TN × 6.25).

Crude fibre (CF%)

Samples were homogenised and ground to particles of <0.5 mm. Crude fibre content was determined by dissolving the samples in 0.255 N-H_2SO_4 and 0.13 N-NaOH, following AOAC (1999).

Water productivity

Water productivity for biomass production is defined as the ratio between aboveground net primary production (ANPP) and total rainfall (R) (Zwart and Bastiaannssen 2004;

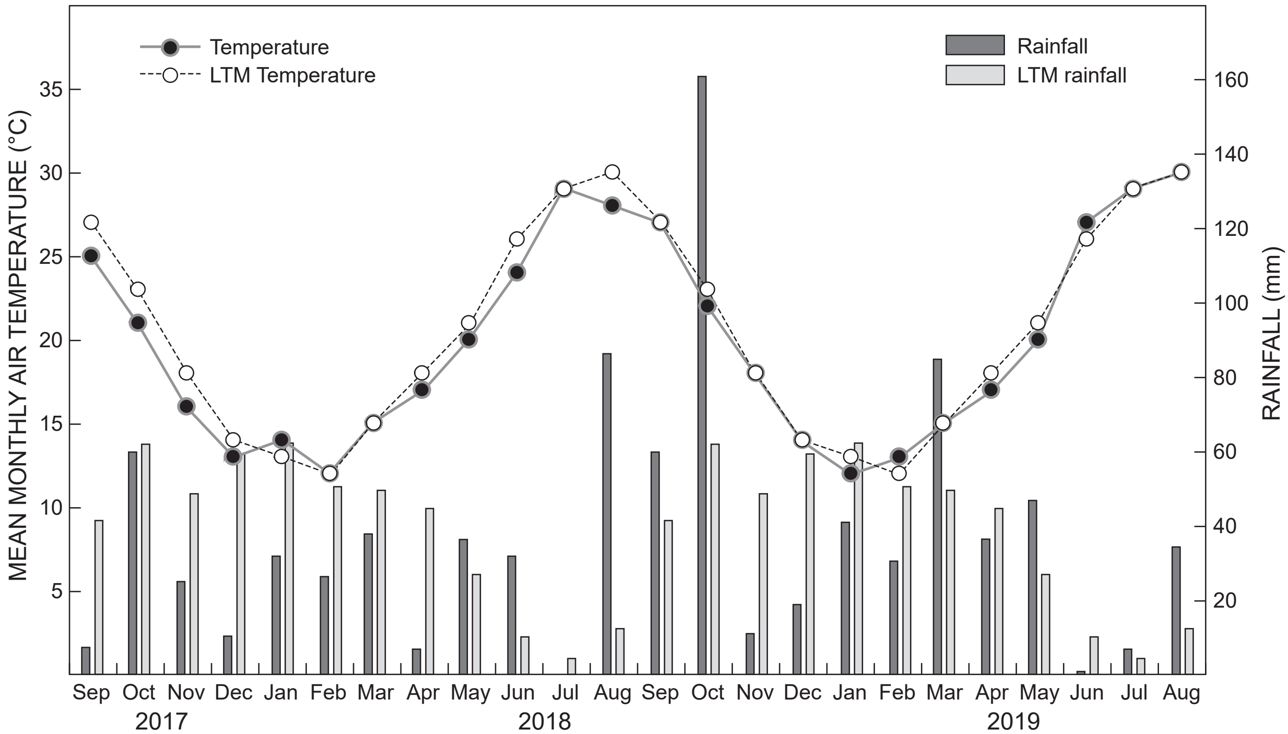

Figure 2: Monthly mean rainfall and air temperature in Zaghouan recorded during the experimental period (from 1 September 2017 to 31 August 2019). Long-term means (LTM) are for the period 1985 to 2012. The meteorological data were obtained from http: //www.onagri.nat.tn/pluviometrie and https: //www.historique-meteo.net/

Mellouli et al. 2006). Water productivity was measured by harvesting plants, determining dry weight of the vegetative portion, and dividing that by the rainfall over the same growing season (Kirkham 2005). It is worth noting that lost water through evaporation, surface runoff; erosion factors and deep drainage, were not taken into consideration, likely resulting in underestimation of WP.

$$\text{Water productivity (kg DM mm}^{-1}\text{)} = \text{ANPP. R}^{-1}$$

where, ANPP is the aboveground net primary production and R is the annual precipitation (mm) recorded according the daily records of ONAGRI (2019) for both growing seasons (from September to May).

Statistical analyses

All data were analysed by analysis of variance (ANOVA) in randomised complete block design for each measurement period. Scarification and sulla reseeding were considered fixed effects. Treatment effect was evaluated using the LSMEANS procedure in SAS v. 9.2 software (SAS Institute, Cary NC, USA). Pearson correlation analysis was used to assess the relationship between different variables. Prior to statistical analysis, botanical composition of the rangelands was log transformed (Log(x + 1)) to improve normality and preserve extreme values. The data presented are back transformed means. The computations were carried out using SPSS statistical software (SPSS IBM 20). Significant differences among treatment means were compared by Fisher's protected least significant difference at $p = 0.05$.

Results

Botanical composition

The numbers of species that make up the vegetation of rangelands were significantly affected ($p < 0.05$) by the scarification and in particular by reseeding with sulla (Table 1). The exceptions were *Scorpiurus muricatus*, *Silybum marianum* and *Allium tricoccum* contributions to total ground cover, which remained similar across the treatments. Similarly, a significant interaction of rainfall and treatments ($p < 0.05$) on *Stipa capensis*, *Euphorbia helioscopia* and *Emex spinosa* cover. The presence of *Stipa capensis* in the control plots remained stable in both years (~7%), whereas it decreased in the reseeded plots with sulla (from 4% in 2017/2018 to 1% in 2018/2019) and increased in the scarified plots (from 5.33% in 2017/2018 to 11.67% in 2018/2019). *Euphorbia helioscopia* was only recorded in the scarified plots (0.33%) and absent both in the Control and in the reseeded rangelands during the season 2017/2018. Although *Emex spinosa* presence did not change and seems to be indifferent to scarification, it increased in control rangelands and disappeared from the reseeded plots over the course of the study. Overall, the effect of year on the botanical composition was minimal, except the content of *Silybum marianum* was greatly reduced in 2018/2019. Scarification had a positive effect ($p < 0.01$) on *Ferula communis, Eryngium campestre, Catapodium rigidum, Reseda alba and Hedysarum spinosissimum.* The effect of reseeding sulla on botanical composition was various. In most cases, the number of species remained stable if not

Table 1: Plant family, life form and livestock palatability (Le Houérou and Ionesco 1973) index and plant composition under different treatments (soil surface scarification and reseeding of rangelands with sulla (*Hedysarum coronarium* L.), Sbaihia community, Tunisia

Species	Family	Characteristics	Palatability index	Plant composition (%) 2017/2018 CON	SCF	SRR	2018/2019 CON	SCF	SRR
Emex spinosa	Poligonaceae	Annual herb, TH	2	2.00	9.33	7.67	7.33	12.00	0.00
Scorpiurus muricatus	Fabaceae	Annual herb, TH	3	1.33	2.00	1.00	1.00	0.33	0.00
Plantago albicans	Plantaginaceae	Perennial herb, HM	5	13.33	12.00	0.67	15.00	15.00	0.33
Stipa capensis	Poaceae	Annual grass, TH	2	7.00	5.33	4.00	6.00	11.67	1.00
Eryngium campestre	Apiaceae	Perennial herb, HM	0	0.33	8.67	1.00	1.33	10.00	0.00
Lolium rigidum	Poaceae	Annual grass, TH	4	1.67	5.00	0.33	2.33	3.33	0.00
Silybum marianum	Asteraceae	Annual herb, TH	1	0.33	1.33	0.67	0.00	0.00	0.00
Hedysarum spinosissimum	Fabaceae	Perennial herb, HM	3	0.67	3.00	0.67	2.67	4.00	0.00
Hedysarum coronarium	Fabaceae	Perennial herb, HM	5	5.33	2.67	48.00	4.67	3.00	89.7
Rosmarinus officinalis	Lamiaceae	Perennial woody, SH	3	1.67	1.67	0.00	2.33	1.67	0.00
Carduncellus pinnatus	Asteraceae	Perennial herb, HM	0	1.33	2.33	0.00	1.33	2.00	0.00
Diplotaxis muralis	Brassicaceae	Annual herb, TH	2	4.67	0.00	0.00	4.67	0.00	0.00
Olea europaea	Oleaceae	Perennial woody, TR	4	1.33	0.00	0.00	1.67	0.00	0.00
Carthamus tinctorius	Asteraceae	Annual herb, TH	1	1.33	0.00	0.00	2.33	0.00	0.00
Catapodium rigidum	Poaceae	Annual grass, TH	3	1.33	9.33	2.00	1.67	7.67	0.00
Euphorbia helioscopia	Euphorbiaceae	Annual herb, TH	0	0.00	1.67	5.33	0.00	0.33	0.00
Allium tricoccum	Alliaceae	Perennial herb, GP	1	0.00	0.00	1.33	0.00	0.00	0.00
Reseda alba	Resedaceae	Annual herb, TH	1	0.00	1.00	0.00	0.00	1.33	0.00
Ferula communis	Apiaceae	Perennial herb, HM	0	0.00	1.67	0.00	0.00	1.00	0.00
Dead material	–	–	–	14.00	10.67	12.33	15.67	8.67	8.67
Bare ground	–	–	–	42.33	22.33	15.00	30.00	18.00	0.33

CON: Control, SCF: Scarification, SRR: Sulla reseeded rangelands, TH: Therophyte, HM: Hemicryptophyte, SH: Shrub, TR: Tree, GP: Geophyte
Palatability index: 0: Refusal or Toxic; 1: Occasionally palatable; 2: Few palatable; 3: Palatable; 4: Very palatable; 5: Extremely palatable.

reduced. The exceptions were with *Hedysarum coronarium* and *Euphorbia helioscopia*, which increased in the sulla reseeded rangelands.

Aboveground net primary production (ANPP)

A treatment × year interaction ($p < 0.01$) was detected for the ANPP of rangelands (Figure 3). Overall, total annual ANPP of rangelands increased from 1 426 kg ha^{-1} in 2017/2018 (dry) to 2 967 kg ha^{-1} in 2018/2019 (wet). However, the increase was more prominent in the sulla reseeded rangelands where it reached 2.7 and 3.4 times the control and scarification treatments averaged across years, respectively, and 2.3 times the reseeded area during the drier season 2017/2018. The highest ANPP of 5 330 kg ha^{-1} was recorded in the sulla reseeded rangelands during the wetter season, whereas the lowest ANPP of 810 kg ha^{-1} was obtained in the scarified rangeland sites during the drier season.

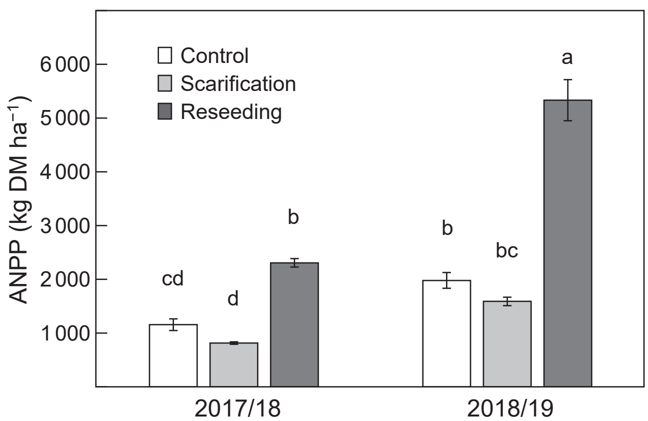

Figure 3: The effect of rehabilitation techniques on annual aboveground net primary production (ANPP, t DM ha^{-1}) in 2017/2018 and 2018/2019

Water productivity (WP)

The results of the statistical analysis emphasised a significant ($p < 0.05$) interannual variation of the WP in relation to the rehabilitation techniques (Figure 4a). The WP recorded in the sulla reseeded rangeland plots increased from 9.5 in 2017/2018 to 11.8 kg DM mm^{-1} in 2018/2019, whereas it did not change in control and scarified rangeland plots. The highest WP value was registered in the sulla reseeded rangeland plots in 2018/2019 (11.8 kg DM mm^{-1}), whereas the scarification resulted in the lowest WP in 2017/2018 (3.3 kg DM mm^{-1}). When plotted together, a strong and positive relationship is present between ANPP and WP in 2017/2018 and 2018/2019 (R^2 = 0.99, root mean square error (RMSE) = 4.71) and R^2 = 0.93, (RMSE) = 5.61), respectively (Figure 4b). The relationship between ANPP and WP was linear as ANPP increased, so too did the WP of rangelands.

Pastoral (PV) and nutritive value (NV)

As expected, during the rainy season of 2018/2019, the pastoral value (PV) significantly increased in the sulla reseeded rangeland plots ($p < 0.05$) and reached approximately three-fold more compared with the control

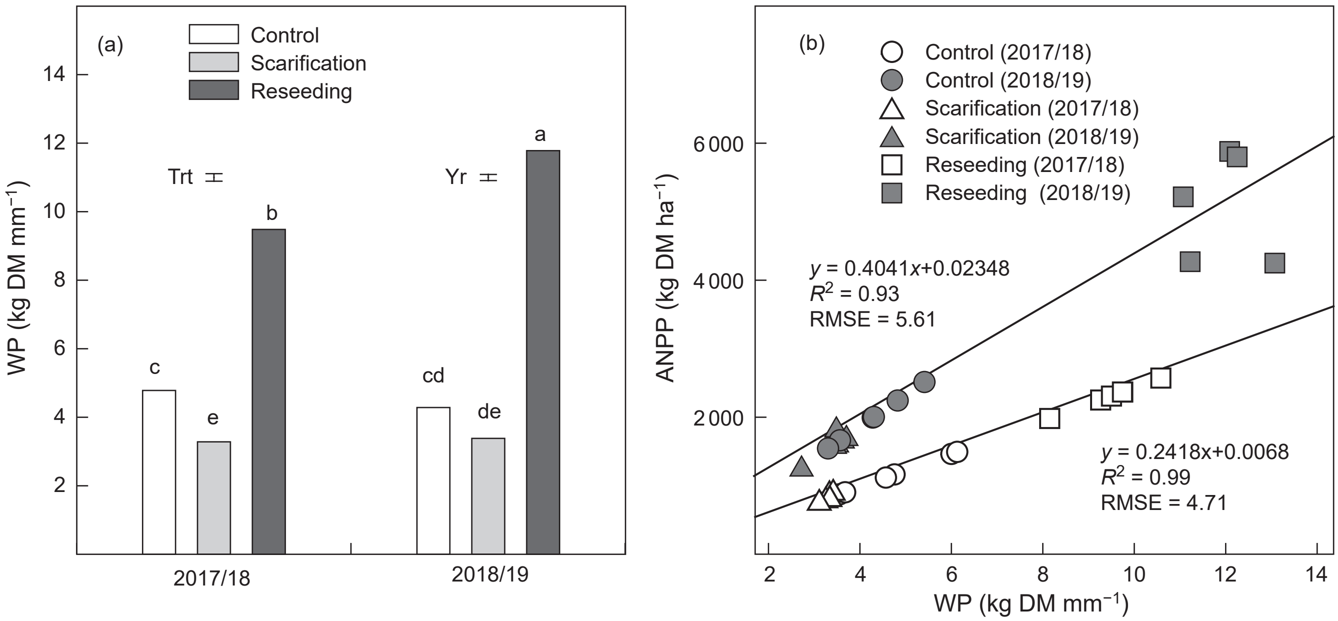

Figure 4: (a) The effect of scarification or reseeding with sulla on water productivity (WP, kg DM mm⁻¹) and (b) relationship between aboveground net primary production (ANPP, kg DM ha⁻¹) and water productivity (WP, kg DM mm⁻¹) in 2017/2018 and 2018/2019

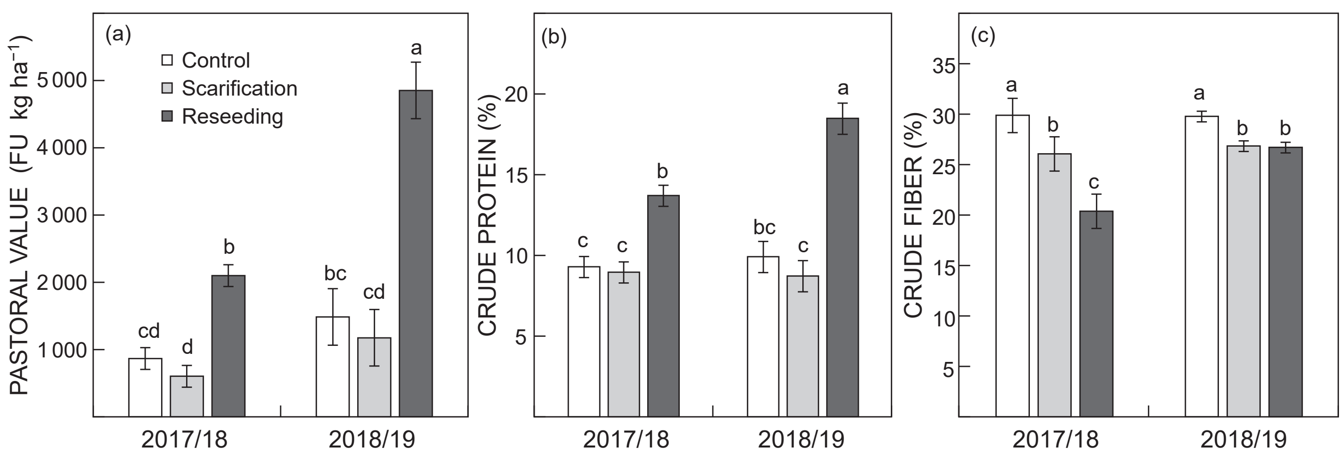

Figure 5: The effect of scarification or reseeding with sulla on (a) pastoral value (forage unit, t ha⁻¹), (b) crude protein and (c) crude fibre content of rangelands plots in 2017/2018 and 2018/2019

and scarification treatments (Figure 5a). However, the PV was not significantly affected by scarification compared with the control ($p > 0.05$). The PV was significantly higher ($p < 0.05$) during the wetter season of 2018/2019 than the drier season of 2017/2018 (average seasons of PV = 1 610 and 697 FU ha⁻¹, respectively). The PV was 3.3 and 4.0 times higher in the reseeded area during the wetter season, compared with the control and scarification treatments, respectively. The interaction was also significant ($p < 0.05$), because the effect of rainfall was a key determinant for higher pastoral values.

Similarly, a highly significant effect of the treatment × year interaction ($p < 0.05$) on CP content has been emphasised (Figure 5b). During both years, reseeding sulla resulted in greater CP content than scarification and control treatments, with the difference being more substantial in the wetter year 2018/2019, which was wetter by 7% than the drier year.

Conversely, crude fibre (CF) contents were similar in both scarified and sulla reseeded plots, but significantly ($p < 0.01$) lower than the content recoded in the control plots (Figure 5c).

Discussion

Degradation of rangelands highlights a critical requirement for the development of appropriate management strategies that enhance the sustainable use of natural resources. In the current study, we tested the effect of soil surface scarification and reseeding with a native legume species, *Hedysarum coronarium* L. as a mean of abating the degradation of rangelands and increasing high quality forage production. The current findings suggest that variation in rangeland productivity was greatly influenced by favourable rainfall conditions regardless of the nature of the intervention. However, one should note that even grazing exclusion alone, especially in favourable years, would increase forage production. This practice is often used to manage degraded rangelands (Ouled Belgacem et al. 2019). This is also consistent with previous studies conducted in other arid and semi-arid regions of the world where rangeland productivity is mainly driven by climatic factors (Fynn et al. 2000; Hein 2006; Hiernaux et al. 2009; Chang et al. 2018), and grazing exclusion significantly increased rangeland productivity (Wang et al. 2019; Liu et al. 2016, 2020). However, it is of note that long-term exclusion can also have a detrimental impact on rangeland health. Livestock hoofs break up the hard-crusted soils common to arid rangelands, allowing rainwater infiltration in the soil and seedlings emergence; and in the case of perennial grasses, grazing removes oxidised plant material that would otherwise remain on the top of plants and prevent photosynthesis, causing plant death after several years (Holechek 2006; Tarhouni et al. 2017).

Natural establishment of vegetation by reseeding may be assisted by human intervention through soil scarification that increased the vegetation cover by 12–20%, compared with control plots during the dry season of 2017/2018. The slight increase in vegetation cover can be explained that topsoil scarification probably increased rather than decreased water availability and therefore drought stress. Exposing mineral soil that often has a more stable moisture regime than the organic topsoil, is the key to achieve successful soil scarification treatment on seedling survival (Hille and den Ouden 2004; Negussie et al. 2008). The Mediterranean region is particularly prone to erosion. The reason is that it is subject to long dry periods followed by heavy torrents of intensive precipitation, falling on steep slopes with shallow soils and low plant cover (Zuazo and Pleguezuelo 2009; Wubie and Assen 2020). Keeping this in mind, one should be careful when dealing with sloping and shallow soils. Therefore, it is not recommended to disturb soil surface when the terrain is so steep, because this may accelerate soil and water erosion. Furthermore, shallow soil can damage the equipment used to implement the mechanical scarification (Lideskog and Karlberg 2016).

The vegetation cover pattern was driven mainly by changes in the relative abundance of two annual species that were already present. *Emex spinosa* and *Stipa capensis* increased in relative abundance after soil scarification. Furthermore, increasing the vegetation cover indicated that local events of soil scarification may have profound effects on patterns of seedling emergence and, consequently, on the relative abundance of the two species in the newly created habitat. The inability of buried seeds of some plants to germinate and emerge could have been caused by dormancy (Traba et al. 1998; Benvenuti et al. 2001). In addition, if seeds are buried in scarified soil, they fail to act as an effective seed bank from the first year, but forming what will be the active component of the soil bank for the next favourable years. On scarified soil without reseeding, natural regeneration was at its early stage and hence the botanical composition was small, but the ultimate outcome of pasture regeneration could be reached over the course of a longer period.

The variability of precipitation and the shallow soil of the study area probably caused high evapotranspiration and soil erosion resulting in a poor seed bank and reduced availability of nutrients. It seems that soil scarification on uneven topography without any reseeding could rapidly increase natural erosion rates, causing loss of water and nutrients available to the plant, thereby negating the entire process of natural establishment (Weber et al. 1985; Slim and Ben Jeddi 2011). It is highly likely that the drier conditions than usual in year one (2017/2018) might have caused a quick drying of the soil surface preventing the emergence or the survival of the seedlings, because water stress is one of the abiotic factors delaying seeds germination of sulla (Ben Jeddi 2005). The results of the study also indicated the challenge of recruitment of seedlings and maintaining high forage production in rangelands with high gradients where high evapotranspiration and erratic rainfall prevail. Soil surface scarification is sought to be highly effective when surface is dominated by crusts with poor structure, although it is not recommended on sandy soils and hill sites to avoid wind and water erosion. The lower WP in the scarified areas (3.3–3.4 kg DM mm^{-1}), compared with the control and reseeded sites confirms that the regeneration was at its early stage and the success is related to the abundance of seeds spreading across the scarified areas. When appropriately done in flat areas, rainwater infiltration can double or even triple following soil surface scarification (Bainbridge 2007). Natural restoration via the seed bank of native plants is one of the main indicators for the success of rangeland management programs (Jalili et al. 2003; Nishihiro et al. 2006; Zhan et al. 2007; Williams et al. 2008; Fisher et al. 2009; Li et al. 2017). Hence, soil surface conditions must be considered with respect to rainfall effectiveness. In contrast to soil surface scarification, reseeding sulla in degraded semi-arid rangelands resulted in substantially greater ANPP, PV and WP. This result confirms the previous findings reported promising results with reseeding of rangelands that resulted in the improvement of degraded natural pasture and livestock production (Manyeki et al. 2015).

Our results indicated that reseeding locally-adapted native legumes, such as sulla on scarified soils, is one of the best options for rehabilitation to enhance the animal feed resource availability in degraded rangelands in such semi-arid areas. The high ANPP recorded in the scarified and reseeded areas could be explained by the high rate of sulla seedling establishment, survival and growth resulting from the higher soil moisture during cool season (Densmore et al. 1999; Louhaichi et al. 2014). Soil preparation through scarification enhanced seed emergence of sulla and significant improvement of WP, which reached 11.5 kg DM mm^{-1}, compared with the control (4.8 kg DM mm^{-1}) in the wetter season. Reseeding of sulla on scarified soils allowed seeds and later seedlings to get maximum profit from the favourable year and to show better productive performance, compared with the scarification and control treatments. These increased yields were consistent with results for many other experiments and studies on sulla (Martiniello et al. 2000; Ben Jeddi 2001; Bouajila et al. 2013). However, it is of note that sulla was the main component of the rangeland vegetation reaching up to 90% of the species composition in 2018/2019. Although this was highly desired from the biomass production and soil health perspectives, reduced biodiversity may be of a major concern. Accordingly, it may be important to designate only certain areas in rangelands for reseeding sulla and using these areas as forage banks or chemoscapes (Villalba et al. 2019). An additional alternative may be reseeding rangelands extensively, but at lower seeding rate of sulla than the one applied in the current study.

The WP values recorded in this study were relatively high compared with those found in arid rangeland ecosystems in southern Tunisia (Gamoun 2016). In the control areas, we found that higher annual rainfall amounts led to a slight decrease of WP, compared with other treatments. This trend can be explained by the loss of the supplementary water penetration via runoff and drainage, as a result of widespread presence of the crust all over the area (Paruelo et al. 1999; Bai et al. 2008). In light of these results, we consider that rangeland rehabilitation through implementing suitable management strategies management as well as by soil scarification can improve WP. This finding prompts us to conclude that the low WP (~4 kg DM mm^{-1}) may indicate degradation risk in this semi-arid rangeland, because of increasing disturbances, such as grazing pressure, deforestation and drought.

Conclusion

Application of reseeding techniques in scarified soils has improved the aboveground biomass production and more specifically the water use efficiency of the rehabilitated rangeland sites. Reseeding using well-adapted native legume species very rich in protein, such as sulla, also resulted in the enhanced nutritional value of silvopastoral systems, which suggests that these may be effective tools to increase forage biomass production in semi-arid environments. The main finding of this study suggests that combining soil scarification and reseeding a high nutritive forage species in degraded silvopastoral areas in the semi-arid Mediterranean rangelands, would enhance the soil water interaction and increase the water use efficiency resulting in a higher aboveground biomass. Bearing in mind that differences in vegetation characteristics across the landscape are caused by a complex of interactions of natural (e.g. soil depth, topography) and artificial (e.g. past disturbances, such as encroachment of cultivation and overgrazing) factors. However, the contributions of these factors to the spatial and temporal variations of vegetation changes could not be always uniform and cannot be easily predicted. Given these facts, because this was a short study, during which the rainfall conditions were fluctuating, we must bear in mind that these results could only serve as an effective short-term remedy to cope with the negative effects of the ongoing climate change and to increase the resilience of the silvopastoral communities. For the meantime, it is recommended that this study should be continued over the next three to five years and, if possible, duplicate it across similar environments, in order to make solid recommendations.

Acknowledgments — This work was supported by the International Center for Agricultural Research in the Dry Areas (ICARDA), the Food and Agriculture Organization of the United nations (FAO), the Direction Générale des Forets (DGF, Tunisia), the Ecole Supérieure d'Agriculture de Mateur (ESAM, Tunisia) and the CGIAR Research Program on Livestock (CRP Livestock).

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Manuscript received: 20 February 2020, revised: 9 October 2020, accepted: 14 October 2020
Associate Editor: S Bennett