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ORGANIC CARBON AND ALKALINITY INCREASE IN TOPSOIL AFTER RANGELAND RESTORATION THROUGH *ATRIPLEX NUMMULARIA* PLANTATION

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ABSTRACT

This research studied the impact of fodder shrub plantations (*Atriplex nummularia* Lindl.) on topsoil properties, with particular reference to organic carbon, nitrogen, and soluble salts, in the Marrakech region (central Morocco). The studied plantation interventions were carried out to rehabilitate degraded rangeland and to mitigate desertification. The field experiment was conducted by drawing seventeen 50-m-long transects designed according to the ecological patch–interpatch approach defined by the Landscape Function Analysis. The top soil (0–5 cm) was sampled in 134 microsites, covering the main patch and interpatch types in plantation and control plots. The following variables were determined: pH, carbonates, organic carbon, total nitrogen, electrical conductivity, and soluble ions (Na^+, K^+, Ca^{2+}, Mg^{2+} Cl^-, NO_3^-, SO_4^{2-} and PO_4^{3-}). Statistical analyses were carried out to analyse changes between sites and between patch types. Most of the studied properties were strongly affected by the spatial pattern defined by the plantation, particularly when the sites with higher biomass production were considered. Organic carbon increased by around 63% and 117% when the under canopy patches were compared, respectively, to the between-plants interpatches and to the control plots, a strong positive effect considering the aridity of the study area. On the other hand, a stronger increase was detected under canopy for most soluble salts and sodium adsorption rate. On average, the latter increased by 350% and up to 450% under the best developed plants, a stronger impact than observed in previous research, highlighting the very strong plant effect on the soil surface alkalinity. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: desertification; rehabilitation; fodder shrub; Landscape Function Analysis (LFA); salinity; old man saltbush

INTRODUCTION

Land degradation and desertification are increasingly seen as a consequence of land mismanagement (Reynolds & Stafford-Smith, 2002; Geist, 2005; D'Odorico *et al*., 2013). These processes are particularly severe in dry rangelands (Reynolds & Stafford Smith, 2002; Bedunah & Angerer, 2012). Population growth and growing demand for meat increase pressure on these systems, where the grazing lands that are saved from conversion into arable lands are often overexploited (Turner, 2011; Tessema *et al*., 2014). Intensification and sedentarization policies, along with the increased availability of water (e.g. through the establishment of permanent sources of water in locations where this resource was not historically available), also contributed to increase grazing pressure, often resulting in overgrazing and soil degradation (D'Odorico *et al*., 2013).

A wide range of options are applied to restore and or rehabilitate degraded rangelands (Schwilch *et al*., 2011). These span from passive approaches such as grazing exclosure (e.g. Gökbulak & Hizal, 2013; Mekuria & Aynekulu, 2013) to active strategies such as managed and rotational grazing, control of shrub encroachment (Fulbright, 1996), natural vegetation rehabilitation (e.g. Zhao *et al*., 2013), vegetation reseeding (Wiedemann, 1987), (re)introduction of selected and adapted species (e.g. Kargar Chigani *et al*., 2012) and afforestation programmes including fodder shrub plantations (Le Houérou, 2000). However, limited evaluation has been conducted on the effectiveness of the restoration efforts.

The evaluation of land restoration is a research priority for the scientific community committed to land degradation mitigation (Schwilch *et al*., 2011; Zucca *et al*., 2013a). The 'zero net land degradation' target, recently adopted by the United Nations Convention to Combat Desertification, suggested that the progress made with restoration activities could counterbalance the negative impacts of land degradation, further stressing the importance of a quantitative evaluation process (Chasek *et al*., 2014). The Millennium Ecosystem Assessment stated that the measurement of the persistent change in the capacity of ecosystems to supply services provides a robust way to quantify land degradation and improvement (MEA, 2005). This measurement is a challenging task, because both land degradation and restoration processes may produce complex and contrasting effects on the different ecosystem services involved (MEA, 2005; D'Odorico *et al*., 2013).

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There is then a need for integrated research and evaluation. However, the increasing international emphasis on carbon management seems to polarize the scientists' attention on the carbon sink potential of land restoration, sometimes overlooking other positive or negative effects (Barbera *et al*., 2012; Barua & Haque, 2013; Roa-Fuentes *et al*., 2013; Fialho & Zinn, 2014; Guzman *et al*., 2014).

This study addresses the contrasting effects produced on the soil by *Atriplex nummularia* Lindl. (Amaranthaceae) plants used to rehabilitate degraded rangelands in the Marrakech province (Figure 1). Such species, native to Australia, was introduced in the northern Mediterranean area as a fodder shrub due to its palatability and resistance to aridity and grazing (Le Houérou, 1992; Mulas & Mulas, 2007; Ben Salem *et al*., 2010). *A. nummularia* is a halophyte that actively accumulates soluble salts in the leaves in relation to its drought tolerance mechanism (Sharma *et al*., 1972; Ramos *et al*., 2004; Bazihizina *et al*., 2012; Belkheiri & Mulas, 2013; Alharby *et al*., 2014). It is known that plant litter can modify the top soil salinity, along with other soil properties, but few studies analysed these effects in the field in the context of restoration interventions (Sharma, 1973; Sharma & Tongway, 1973; Lailhacar *et al*., 1989; Cepeda-Pizarro *et al*., 1992; Sameni & Soleimani, 2007; Maganhotto de Souza Silva *et al*., 2008; Zucca *et al*., 2011b). The changes induced by the plants are spatially discontinuous, in relation to the high patchiness of the agro-ecosystem established by the plantation, and their study requires suitable methods able to deal with such patchiness (Cerdà, 1997; Kröpfl *et al*., 2013).

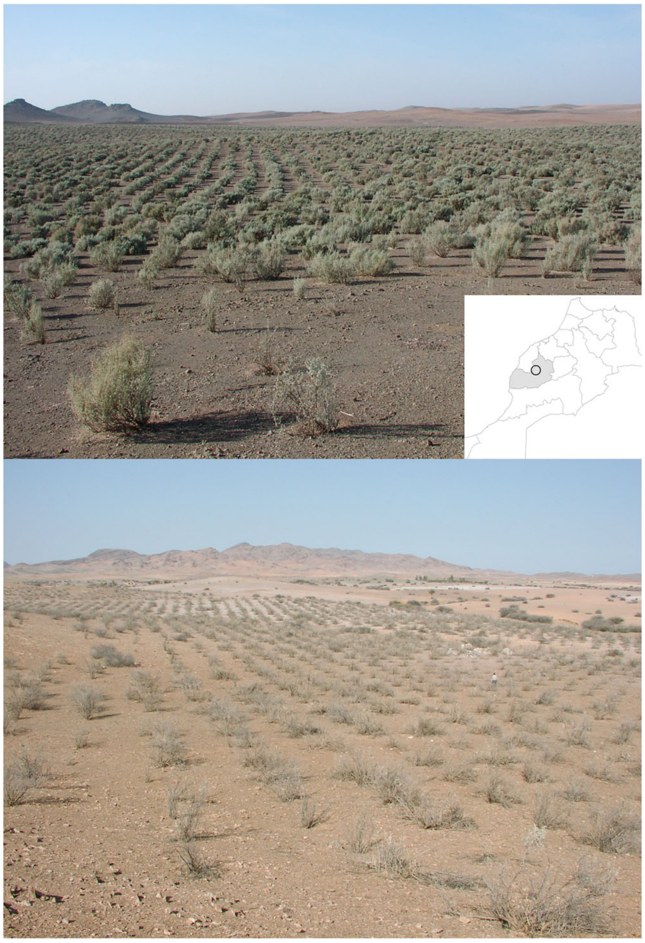

Figure 1. Two examples of *Atriplex nummularia* Lindl. plantations in the study area, a very productive one (up) and a moderately developed and intensively grazed one (down). Inset map: location of the study area (Rural Municipalities of Ouled Dlim and M'nabha, in grey-shaded Marrakech-Tensift-El Haouz Region). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

The specific objective of this research was to study the influence of the plants' development on the topsoil properties, with particular reference to organic carbon, nitrogen, and soluble salts, as part of an interdisciplinary evaluation based on both field and remote-sensing data (Zucca *et al*., 2013b, 2015). This study was innovative and complementary with regard to the previous ones dealing with the plant impact on soil, because (i) a large dataset was used, coming from ten different plantations, (ii) the sampling strategy was based on micro-ecological zoning performed according to the Landscape Function Analysis (LFA) approach (Tongway & Hindley, 2004), (iii) the under-canopy sites were compared with both the between-plants area and control areas outside the plantations, (iv) both soluble cations and anions were analysed, and (v) a shallower topsoil layer was sampled (0–5 cm), allowing emphasizing the sharp surface changes detected by Sharma & Tongway (1973) and Sharma (1973), who found the strongest changes in the 0–7·5 cm top layer.

STUDY AREA AND EXPERIMENTAL SETTING

Study Area

The study area is located in central Morocco (Marrakech region, Rural Municipalities of Ouled Dlim and M'nabha). The climate of the area is arid, with average annual rainfall of 212 mm, and marked by a long dry season (April–October). The landscape is characterized by the Palaeozoic schist formations of the Jebilet range (Huvelin, 1970), with rounded or gently undulating relieves. The natural vegetation cover is characterized by sparse trees and shrubs (*Ziziphus lotus* L, Rhamnaceae; *Acacia horrida* L., Mimosaceae; *Peganum harmala* L., Nitrariaceae). The loam to sandy loam textured soils are shallow and degraded because of overgrazing linked to the traditional extensive grazing systems. Subsistence cropping practices (rainfed cereals, mainly barley and wheat) are also present in the area. Although cereal harvesting is performed only in particularly rainy years, in part of the area soil is ploughed almost every year for fodder production.

Extensive Atriplex plantations were established in the study area since the mid 1990s, on the initiative of the government of Morocco, to mitigate desertification (Zucca *et al*., 2011a). Seedlings were planted in manually dug planting holes, along furrows made through rippers. Plant density varied between around 1000 and 700 plants per hectare, with plants on somewhat regular 3 × 3 or 4·5 × 3 m grids. Typical plantation time was March–April. Two irrigations were carried out, the first immediately and the second a few months after planting.

Plantations were opened to sheep grazing 3 years after planting, and preferably grazed starting from late summer, when there was no natural forage left outside the planted perimeter. When the plants were 10–12 years old, they became senescent and their green to woody biomass ratio decreased consistently (Zucca *et al.*, 2013b).

Sampling

This study was conducted by following the experimental setting designed by Zucca *et al.* (2013b) in March 2012. Those authors drew 50-m-long transects to assess the impacts of the plantations on the soil functions by means of the LFA method (Tongway & Hindley, 2004). They identified 'patch' and 'interpatch' areas along the transects, where patches are defined as long-lived features that obstruct or divert water flow and, or, collect or filter out material from runoff, for example, perennial grass plants, rocks and tree branches in contact with the soil (Tongway & Hindley, 2004). They distinguished the following patch and inter-patch types: (i) the 'plant' patch, where Atriplex branches were in close contact with the soil, which generally included a portion of the under-canopy zone; (ii) the 'furrow' patch, including the furrow area intercepted by the transect; (iii) the 'furrow + plant' patch, within the furrow and under the canopy cover, corresponding to the maximum water and nutrient sink potential; and (iv) the 'bare soil' interpatch. The same authors recorded semi-quantitative field indicators, along with soil texture, in a number of 50 × 50 cm query zones corresponding to the different patch and inter-patch types, with an average of three repetitions per each type in each transect (Figures 2 and 3). Soil texture was determined in laboratory on samples collected in the 0–5 cm layer, which was considered as the reference soil layer to study the soil surface functions (according to Tongway & Hindley, 2004). The same soil samples were used for the laboratory analyses conducted in this study.

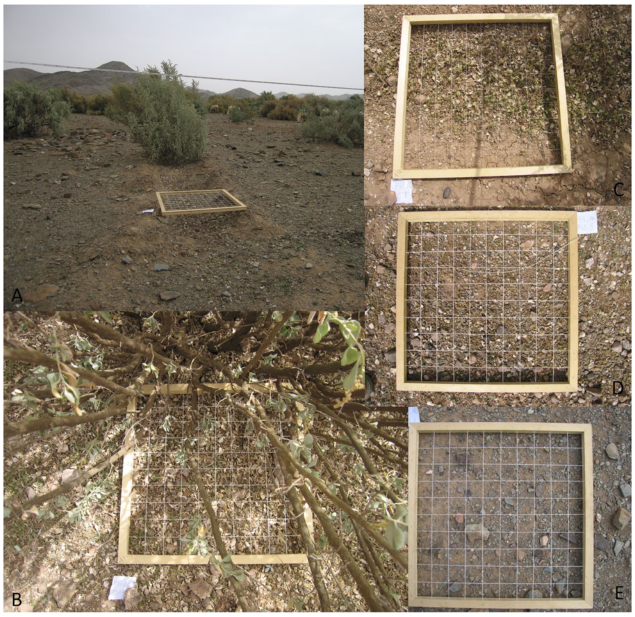

Figure 2. Examples of the patch and interpatch types and of the query zones ('quadrats') defined to perform soil surface assessment and sampling. Furrow patch (A and C); plant + furrow patch (B); bare soil interpatch, with poor grass cover (D) and without any grass cover (E). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

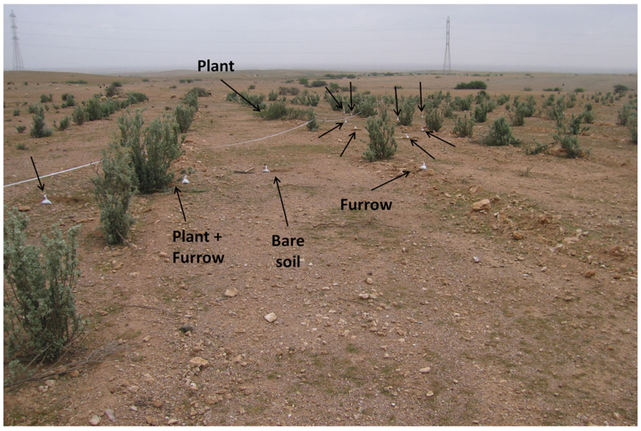

Figure 3. Soil sampling along a 50-m-long transect in a poorly developed plantation. Plastic bags on the ground (pointed by arrows) indicate sampling locations. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Overall, 134 samples coming from 17 transects were analysed (Table I). Ten transects referred to Atriplex sites belonging to two age classes (M, or mature: 10–12 years old; Y, or young: 5–6 years old). The latter group was split into two subgroups based on the total biomass production previously assessed by Zucca *et al.* (2013b): Y1, young plantation with low total dry biomass ($<$2,000 kg ha^{-1}); Y2, young plantation with high biomass (between 2,000 and 4,400 kg ha^{-1}). Finally, seven transects were drawn in control plots located nearby the studied plantations and used for either grazing (GR) or cropping (CR).

Laboratory and Statistical Analysis

The following laboratory analyses were conducted on soil samples: the pH in 1 : 2·5 water solution (pH), calcium carbonate equivalent (Carb) by gas-volumetric determination, organic carbon (OC) and total nitrogen (N) by elemental analyzer, electrical conductivity in 1 : 5 solution (EC), soluble cations (Na^+, K^+, Ca^{2+} and Mg^{2+}) and the related sodium adsorption ratio (SAR) by atomic adsorption. Soluble anions (Cl^-, NO_3^-, SO_4^{2-} and PO_4^{3-}) by high performance liquid chromatography (HPLC).

The statistical analysis was carried out through the Statistica software (Statsoft, 2004). The non-parametric Mann–Whitney *U*-test and Kruskal–Wallis test were applied to compare the analytical values. The following groups were considered for the statistic analysis: (i) patch (P) versus interpatch (I), where patch included all kinds of patches in all plantation transects, and interpatch included all interpatches in both control and plantation plots; (ii) interpatches in control transects (Ic), interpatches in plantation transects (Ip), all patches with plant canopy ('plant' and 'furrow + plant'; Pp) and furrow-only patches outside the plant canopy area (Pf); and (iii) patch (all types) versus interpatch within each of the five plantation and control subgroups: CR, GR, Y1, Y2 and M.

The correlation between selected variables was studied by means of Spearman correlation analysis. This analysis

Table I. Summary information about the 17 transects

Transect	Locality	Plant. date	Group	Total dry shrub biomass (March 2012)	Soil texture class	Mean pH	Mean carbonate	Lithology of the rock fragments
		Year		kg ha^{-1}			%	
P33_C8	El Ahntri	/	CR	/	Loam	8·4	0·7	Sandstone and quartzite
P08_C10	Mkimene	/	CR	/	Sandy loam	9·0	5·0	Sandstone and quartzite
P10_C1	DraaTouiza	/	GR	/	Sandy loam	8·9	3·7	Schist and sandstone
P11_C3	Chehibat	/	GR	/	Loam	9·0	1·4	Sandstone, quartzite and schist
P03_C5	Kdadra	/	GR	/	Sandy loam	8·9	5·9	Clay schist
P32_C6	Ouled Nejim	/	GR	/	Sandy loam	8·5	0·0	Clay schist
P21_C7	Ouled Nejim	/	GR	/	Sandy loam	8·2	0·0	Clay schist
P10_A1	DraaTouiza	2006	Y1	548 ± 21	Sandy loam	8·9	10·8	Schist and sandstone
P08_A10	Mkimene	2006	Y1	820 ± 58	Sandy loam	8·8	8·2	Sandstone and quartzite
P04_A4	Kdadra	2007	Y1	1,441 ± 95	Sandy loam	8·9	6·6	Clay schist
P21_A7	Ouled Nejim	2007	Y1	1,758 ± 70	Sandy clay loam	8·8	0·0	Clay schist
P32_A6	Ouled Nejim	2007	Y2	4,373 ± 110	Sandy loam	8·7	0·0	Clay schist
P10_A2	Chehibat	2006	Y2	2,281 ± 101	Sandy loam	9·1	3·2	Sandstone, quartzite and schist
P33_A8	El Ahntri	2006	Y2	3,019 ± 121	Loam	8·8	2·2	Sandstone and quartzite
P11_A3	Chehibat	2002	M	2,393 ± 129	Sandy loam	9·0	2·1	Sandstone, quartzite and schist
P03_A5	Kdadra	2000	M	466 ± 15	Sandy loam	9·0	13·2	Clay schist
P34_A9	El Ahntri	2000	M	3,904 ± 56	Loam	8·5	0·2	Sandstone and quartzite

Values of carbonate and pH are obtained as mean of all the available samples for each site.
CR, cropped; GR, grazed; Y1, young plantation, low biomass; Y2, Young plantation, high biomass; M, mature plantation.

also considered one LFA index calculated by Zucca *et al.* (2013b) at the query-zone level: the nutrient cycling (NC) index (Tongway and Hindley, 2004).

RESULTS

PO$_4^{3-}$ values were very low for all samples, often below their specific detection limit (0·02 meq and 100 g^{-1}), and did not show any significant change in all the analyses performed. All the other variables, with the exception of Ca^{2+}, showed significant changes in one or more comparisons.

When patch and interpatch samples were compared (Table II), the strongest increase in patches was detected for SAR (+350%), K$^+$ (+360%), SO$_4$$^{2-}$ (+300%), Cl$^-$ (+250%), Na$^+$ (+114%), Mg^{2+} (+89%) and EC (+81%). The increase in OC was around 80%, whereas N increased by more than 30%. No change was observed for NO$_3$$^-$.

Most of the values showed a progressive increase (Table III) between the control interpatch samples (Ic), and, respectively, the plantation interpatches (Ip), the furrows (Pf) and the patches under plant canopy (Pp). The sharpest differences emerged when the Ic group and the Pp group were compared. In this case, the OC content was more than doubled and N increased by 50%. Much greater differences were observed for the soluble salts, which in some cases increased by around ten times (K$^+$, SAR and Cl$^-$). The other two groups (Ip and Pf) yielded intermediate values. Ic and Ip values were always statistically similar, although the Ip medians were higher. In the case of OC, Ip values (8·0 g kg^{-1}) were also statistically similar to Pf values (12·0 g kg^{-1}), and the latter were statistically similar to Pp (13·0 g kg^{-1}) values. Pf values were mostly different from Pp values, with the exception of OC, N and Mg^{2+}.

The comparison of the patch and interpatch samples within land management groups (Table IV) yielded significant differences only for the Y2 group, the most productive plantations: pH (+8%), Mg^{2+} (+190%), Na$^+$ (+142%), SAR (+457%) and SO$_4^{2-}$ (+700%). A consistent increase was also observed in this group for other values (OC, K$^+$ and Cl$^-$), although not statistically significant. Control groups CR and GR (only including interpatch samples) showed the lowest values for most variables (e.g. OC around 6·0 g kg^{-1}). These values were statistically similar to the interpatch values inside the plantations.

With few exceptions (referred to Ca^{2+}) all the variables were significantly and positively correlated with each other (Table V). The strongest relationships were observed

Table II. Comparison between all types of patch (in plantation transects) and interpatch (all transects)

		pH	EC (dS m^{-1})	OC (g kg^{-1})	N (g kg^{-1})	Sol. Ca^{++} (cmol kg^{-1})	Sol. Mg^{++} (cmol kg^{-1})	Sol. K^{+} (cmol kg^{-1})	Sol. Na^{+} (cmol kg^{-1})	SAR	Sol. Cl^{-} (cmol kg^{-1})	Sol. NO$_3$$^{-}$ (cmol kg^{-1})	Sol. SO$_4$$^{2-}$ (cmol kg^{-1})	Sol. PO$_4$$^{3-}$ (cmol kg^{-1})
I	m	8·7^{a}	0·136^{a}	7·0	0·9^{a}	0·36^{a}	0·09^{a}	0·10^{a}	0·07^{a}	0·20^{a}	0·06^{a}	0·05^{a}	0·01^{a}	0·00^{a}
N = 65	1q	8·5	0·097	6·0	0·7	0·27	0·07	0·06	0·04	0·14	0·03	0·03	0·01	0·00
	3q	9·0	0·168	9·0	1·1	0·49	0·11	0·22	0·11	0·46	0·16	0·12	0·02	0·01
P	m	8·9^{a}	0·246^{b}	12·8^{b}	1·2^{b}	0·35^{a}	0·17^{b}	0·46^{b}	0·15^{b}	0·90^{b}	0·21^{b}	0·08^{a}	0·04^{b}	0·00^{a}
N = 69	1q	8·6	0·174	8·5	1·0	0·27	0·12	0·18	0·10	0·40	0·07	0·04	0·02	0·00
	3q	9·2	0·468	15·0	1·5	0·49	0·29	1·30	0·27	2·06	0·79	0·17	0·07	0·01

Median (m) and quartile (1q and 3q) values. Superscript letters indicate statistically homogeneous groups (Mann–Whitney *U*-test, $p < 0·01$).
I, interpatch; P, patch; EC, electrical conductivity; OC, organic carbon; N, total nitrogen.

Table III. Comparison between control interpatch and plantation (interpatch, patch with plants, and furrows outside plant canopy area)

		pH	EC (dS m^{-1})	OC (g kg^{-1})	N (g kg^{-1})	Sol. Ca^{++} (cmol kg^{-1})	Sol. Mg^{++} (cmol kg^{-1})	Sol. K^{+} (cmol kg^{-1})	Sol. Na^{+} (cmol kg^{-1})	SAR	Sol. Cl^{-} (cmol kg^{-1})	Sol. NO$_3$$^{-}$ (cmol kg^{-1})	Sol. SO$_4$$^{2-}$ (cmol kg^{-1})	Sol. PO$_4$$^{3-}$ (cmol kg^{-1})
Ic	m	9·0^{a}	0·106^{a}	6·0^{a}	0·8^{a}	0·30^{a}	0·08^{a}	0·08^{a}	0·06^{a}	0·16^{a}	0·05^{a}	0·04^{a}	0·01^{a}	0·00^{a}
N = 28	1q	8·6	0·855	5·0	0·7	0·22	0·07	0·04	0·03	0·09	0·03	0·02	0·01	0·00
	3q	9·0	0·171	7·3	1·0	0·52	0·11	0·21	0·10	0·45	0·09	0·08	0·02	0·01
Ip	m	8·7^{a}	0·137^{a}	8·0^{ab}	0·9^{a}	0·39^{a}	0·09^{a}	0·11^{a}	0·08^{a}	0·24^{a}	0·08^{a}	0·07^{ab}	0·01^{a}	0·00^{a}
N = 37	1q	8·5	0·124	7·0	0·8	0·31	0·08	0·08	0·06	0·16	0·04	0·04	0·01	0·00
	3q	9·0	0·167	10·0	1·1	0·49	0·11	0·22	0·12	0·46	0·18	0·16	0·02	0·00
Pf	m	8·8^{a}	0·188^{a}	12·0^{bc}	1·1^{ab}	0·32^{a}	0·13^{b}	0·18^{a}	0·10^{a}	0·40^{a}	0·07^{a}	0·04^{a}	0·02^{a}	0·00^{a}
N = 26	1q	8·5	0·110	8·0	0·8	0·27	0·10	0·11	0·06	0·21	0·05	0·01	0·01	0·00
	3q	9·0	0·227	14·8	1·2	0·51	0·17	0·44	0·15	0·97	0·20	0·08	0·03	0·01
Pp	m	9·0^{a}	0·340 ^{b}	13·0 ^{c}	1·2^{b}	0·36^{a}	0·22^{b}	0·79^{b}	0·22^{b}	1·50^{b}	0·53^{b}	0·12^{b}	0·06^{b}	0·00^{a}
N = 43	1q	8·7	0·221	9·3	1·1	0·27	0·16	0·33	0·11	0·59	0·15	0·06	0·03	0·00
	3q	9·3	0·543	16·0	1·5	0·48	0·33	1·56	0·36	3·47	1·02	0·20	0·10	0·01

Median (m) and quartile (1q and 3q) values. Superscript letters indicate statistically homogeneous groups (Kruskal–Wallis test, $p < 0·05$).
Ic, interpatch in control transects; Ip, interpatch in planted transects; Pp, ‘plant’ and ‘furrow + plant’; Pf, ‘furrow’; EC, electrical conductivity; OC, organic carbon; N, total nitrogen.

Table IV. Patch (P) versus interpatch (I) comparison within plantation and control subgroups. Median and quartile values

		pH	EC ($dS\,m^{-1}$)	OC ($g\,kg^{-1}$)	N ($g\,kg^{-1}$)	Sol. Ca^{++} ($cmol\,kg^{-1}$)	Sol. Mg^{++} ($cmol\,kg^{-1}$)	Sol. K^{+} ($cmol\,kg^{-1}$)	Sol. Na^{+} ($cmol\,kg^{-1}$)	SAR	Sol. Cl^{-} ($cmol\,kg^{-1}$)	Sol. NO_3^{-} ($cmol\,kg^{-1}$)	Sol. SO_4^{2-} ($cmol\,kg^{-1}$)	Sol. PO_4^{3-} ($cmol\,kg^{-1}$)
GR	m	9·0^{abc}	0·106^{a}	6·0^{a}	0·8^{a}	0·25^{a}	0·08^{a}	0·12^{a}	0·07^{ab}	0·28^{ab}	0·05^{a}	0·03^{a}	0·01^{a}	0·00^{a}
N = 20	1q	8·5	0·813	5·0	0·7	0·20	0·07	0·05	0·03	0·10	0·03	0·01	0·01	0·00
	3q	9·1	0·159	7·0	0·9	0·40	0·11	0·28	0·10	0·54	0·16	0·04	0·02	0·01
CR	m	8·9^{abc}	0·117^{ab}	6·0^{ab}	0·6^{ab}	0·42^{a}	0·08^{a}	0·04^{a}	0·04^{a}	0·10^{a}	0·08^{a}	0·08^{a}	0·01^{ab}	0·00^{a}
N = 8	1q	8·6	0·885	5·0	0·3	0·32	0·07	0·03	0·03	0·07	0·03	0·05	0·01	0·00
	3q	9·0	0·185	9·5	1·2	0·54	0·10	0·09	0·10	0·16	0·09	0·14	0·03	0·01
Y1-I	m	9·0^{abc}	0·133^{ab}	8·0^{abc}	0·8^{a}	0·42^{a}	0·09^{a}	0·10^{a}	0·06^{ab}	0·19^{ab}	0·04^{a}	0·05^{a}	0·01^{ab}	0·00^{a}
N = 15	1q	8·7	0·110	7·0	0·7	0·35	0·07	0·07	0·04	0·14	0·03	0·03	0·01	0·00
	3q	9·1	0·148	10·0	1·1	0·51	0·11	0·12	0·07	0·30	0·10	0·19	0·02	0·00
Y1-P	m	8·7^{abc}	0·197^{bc}	9·8^{bc}	1·0^{ab}	0·40^{a}	0·13^{abc}	0·25^{a}	0·09^{bc}	0·50^{bc}	0·11^{ab}	0·06^{a}	0·03^{abc}	0·00^{a}
N = 25	1q	8·5	0·153	7·8	0·8	0·26	0·11	0·15	0·05	0·28	0·07	0·01	0·02	0·00
	3q	9·0	0·468	15·0	1·2	0·60	0·21	0·76	0·10	1·32	0·54	0·19	0·05	0·00
Y2-I	m	8·5^{b}	0·150^{abc}	8·0^{ab}	1·1^{abc}	0·40^{a}	0·10^{ab}	0·11^{abc}	0·12^{ab}	0·37^{ab}	0·13^{ab}	0·07^{a}	0·01^{ab}	0·00^{a}
N = 10	1q	8·3	0·126	5·8	1·0	0·37	0·09	0·09	0·09	0·17	0·05	0·04	0·01	0·00
	3q	8·7	0·338	9·8	1·2	0·51	0·11	0·37	0·14	0·56	0·39	0·31	0·03	0·00
Y2-P	m	9·2^{c}	0·403^{c}	13·5^{bc}	1·4^{c}	0·35^{a}	0·29^{c}	1·30^{c}	0·29^{c}	2·06^{c}	0·78^{b}	0·08^{a}	0·08^{c}	0·02^{a}
N = 23	1q	8·7	0·285	9·8	1·2	0·27	0·16	0·55	0·16	1·01	0·19	0·05	0·04	0·00
	3q	9·4	0·772	15·5	1·6	0·50	0·45	2·89	0·45	4·84	1·68	0·19	0·11	0·02
M-I	m	8·8^{abc}	0·146^{ab}	8·2^{abc}	0·9^{ab}	0·35^{a}	0·09^{ab}	0·16^{ab}	0·08^{ab}	0·36^{ab}	0·13^{ab}	0·08^{a}	0·01^{ab}	0·00^{a}
N = 12	1q	8·6	0·136	7·0	0·8	0·29	0·09	0·09	0·07	0·19	0·07	0·05	0·01	0·00
	3q	9·1	0·167	10·0	0·9	0·37	0·10	0·22	0·11	0·46	0·21	0·11	0·02	0·00
M-P	m	8·9^{abc}	0·225^{abc}	13·0^{c}	1·1^{bc}	0·35^{a}	0·16^{bc}	0·32^{bc}	0·17^{bc}	0·59^{bc}	0·18^{ab}	0·10^{a}	0·04^{bc}	0·00^{a}
N = 21	1q	8·7	0·151	10·3	1·0	0·29	0·11	0·15	0·10	0·30	0·06	0·04	0·02	0·00
	3q	9·0	0·270	16·0	1·5	0·37	0·25	0·51	0·26	1·07	0·27	0·16	0·05	0·01

Superscript letters indicate statistically homogeneous groups (Kruskal–Wallis test, $p < 0{\cdot}05$).

CR, cropped; GR, grazed; Y1, young plantation, low biomass; Y2, young plantation, high biomass; M, mature plantation; EC, electrical conductivity; OC, organic carbon; N, total nitrogen; SAR, sodium adsorption rate.

Table V. Spearman correlation's coefficients for selected variables

	EC	OC	N	Sol. Ca^{++}	Sol. Mg^{++}	Sol. Na^{+}	Sol. K^{+}	SAR	Sol. Cl^{-}	Sol. NO_3^{-}	Sol. SO_4^{2-}	NC
EC	1·00											
OC	0·47***	1·00										
N	0·51***	0·67***	1·00									
Sol. Ca^{++}	0·37***	0·48***	0·17	1·00								
Sol. Mg^{++}	0·73***	0·55***	0·55***	0·24**	1·00							
Sol. Na^{+}	0·88***	0·29***	0·49***	0·04	0·68***	1·00						
Sol. K^{+}	0·72***	0·45***	0·52***	0·15	0·72***	0·66***	1·00					
SAR	0·81***	0·21*	0·47***	−0·10	0·61***	0·98***	0·63***	1·00				
Sol. Cl^{-}	0·81***	0·20*	0·38***	0·10	0·56***	0·81***	0·59***	0·78***	1·00			
Sol. NO_3^{-}	0·61***	0·34***	0·32***	0·44***	0·37***	0·38***	0·43***	0·31***	0·44***	1·00		
Sol. SO_4^{2-}	0·88***	0·41***	0·43***	0·25**	0·64***	0·82***	0·61***	0·77***	0·78***	0·54***	1·00	
NC	0·64***	0·49***	0·49***	0·12	0·60***	0·62***	0·52***	0·59***	0·47***	0·32***	0·58***	1·00

NC, nutrient cycling index; EC, electrical conductivity; OC, organic carbon; N, total nitrogen; SAR, sodium adsorption rate.
*$p = 0·05$.
**$p = 0·01$.
***$p = 0·001$.

among the cations (Mg^{2+}, Na^{+}, K^{+} and SAR) and between Cl^{-} and SO_4^{2-}. The latter were also strongly correlated with the cations. OC showed strong correlation with N and medium correlation with most of the soluble salts. Even the NC was strongly correlated with Na^{+} and the other cations, and moderately correlated with OC, N and the anions.

DISCUSSION

The comparison between all interpatch and all patch samples (Table II) showed that most of the studied properties were strongly affected by the spatial and ecological pattern created by the plantations. The results confirmed the intense salt redistribution action performed by the plants. It has to be noted that the studied soils are not saline. In one site, only three samples under bare soil showed EC values slightly higher than 4 dS m^{-1}. They are also not sodic, as the maximum observed SAR values are around 7.

Our data are comparable with the data obtained by some of the previous studies because the latter mainly compared under-canopy and between-plants sites.

The observed 81% increase in EC is rather similar in magnitude to the 125% and 178% changes measured by Sharma & Tongway (1973) in the 0–7·5 cm layer of two different plantations and to the 148% reported by Sameni & Soleimani (2007) for the 0–10 cm layer. No significant EC increase was instead observed by Zucca *et al.* (2011b) in the same study area in the 0–10 cm layer, although for fewer and different sampling sites. In agreement with Sameni & Soleimani (2007), no significant pH change was determined. The observed 114% increase in Na^{+} is similar to the 131% and 206% changes in the 0–7·5 cm layer determined by Sharma (1973), who analysed two different soils, and to the 108% reported by Sameni & Soleimani (2007). On the other hand, the 33% and 155% increase in K^{+} detected by Sharma (1973) and the 86% measured by Sameni & Soleimani (2007) are much lower than the 360% difference observed in this study and lower than the 218% increase reported by Zucca *et al.* (2011b). In general, the lower increases observed by Zucca *et al.* (2011b) compared with this study, in the same study area, can be most likely ascribed to the greater sampling depth and to the related dilution effect.

If the bivalent cations are considered, it is worth noting that Sharma (1973) determined a strong increase in Ca^{2+} (around 130%), whereas in this study, soluble calcium was not affected at all by the plants, possibly because of the higher calcium carbonate contents of the studied soils. We observed an 89% increase in Mg^{2+}, whereas a stronger increase (196% and 313%, respectively, for the two different soils considered) was detected by Sharma (1973). Finally, Sameni & Soleimani (2007) determined a 189% increase in the sum of Ca^{2+} and Mg^{2+}. The contrasting behaviour of calcium most likely influenced the SAR values, whose increase is much higher in this study (350%) compared with the others (41% and 70%, Sharma, 1973; 139%, Zucca *et al.*, 2011b).

The soluble anions were previously analysed by Sameni & Soleimani (2007), who found about 120% increase under canopy in both Cl^{-} and SO_4^{2-}, a much lower increase compared with this study (respectively, 250% and 300%). Lailhacar *et al.* (1989) also found a strong correlation between plant biomass and Cl^{-} (along with Na^{+}) content in the 0–10 cm soil layer. Finally, the OC and N changes (respectively, 83% and 33%) were higher compared with the 32% and 9% changes reported by Zucca *et al.* (2011b) and to the OC increase measured by Sharma (1973), ranging between 10% and 16%, but lower compared with the 142% and 96% increase reported by Sameni & Soleimani (2007).

The comparison of the four different types of patch and interpatches (Table III) highlighted that the impact of the plantations is mostly localized in the under canopy zone (Pp patch: plant and plant + furrow). Here, for most variables (except pH and Ca^{2+}), the values were much higher compared with the other groups (Ic, Ip and Pf). This is in agreement with Zucca *et al.* (2013b) who also observed a strong and localized plant impact contrasted by a relatively poor overall soil surface improvement along the 50-m-long transects. The Pp–Ic differences were extremely high for some variables such as SAR (almost ten times), indicating that the plants can create 'alkalinity islands'. The between-plants sites (Ip) showed slightly higher values compared with the control sites (Ic). As an example, OC changed between 8 and $6\,g\,kg^{-1}$. Although these differences were not statistically significant, they may indicate that a slight and diffuse nutrient enrichment process is taking place within the plantations compared with the surrounding rangeland areas. Similarly, the furrow patches (Pf) showed slightly higher values if compared with the Ip and Ic interpatches. The Pf to Ic differences were statistically significant for OC (100%) and Mg^{2+} (63%). This indicates that the furrows play a direct nutrient sink action by trapping the litter. Compared with the Pp patches, the soluble salts are accumulated to a much lower extent in furrows (Pf). Here, they are most likely washed during rainfall because of the water harvesting action of the furrows.

The comparison of the patch and interpatch samples according to each land management group (only interpatch in CR and GR; patch and interpatch in Y1, Y2 and M) showed the varying effects produced by the different plant age and productivity levels (Table IV). Only in the best developed plantations (Y2 group) the patch–interpatch comparison yielded big and significant differences for most variables including pH, which increased from 8·5 to 9·2. On the other hand, even the patches of the least developed plantations (Y1-P) showed significantly higher OC (63%) and EC (85%) compared with the control sites belonging to the GR group. If the M-P samples are considered (older senescing plants), the difference compared with GR was significant for more variables (OC, N, Mg^{2+}, K^{+} and SO_4^{2-}) but not for all soluble salts. The different effects observed in Y2 and M plantations may indicate that, while the increase in organic matter induced by the plant is a relatively stable feature, the increase in salts (particularly sodium and chloride) at the soil surface may be rather labile and dependent on continuous input by the plant litter. In fact, previous studies highlighted that soil salinity under *A. nummularia* canopy can show consistent interseasonal fluctuations (Sharma & Tongway, 1973; Cepeda-Pizarro *et al.*, 1992) and be linked to climate humidity. Further research would be needed to better understand this aspect, considering both biomass production and climate.

The statistical correlations (Table V) showed that all the variables that are strongly influenced by the plant action are also correlated with each other, including the NC index. This was expected because the NC values are mainly influenced by the amount of litter on the ground and by its degree of incorporation into the soil.

Forty years ago, Sharma (1973) first warned about the use of *A. nummularia* to restore degraded soils, highlighting the potential deleterious effects of the increased available sodium content on the topsoil structure and the possible toxic effects for the other plants species. The absolute alkalinity values of the studied soils are relatively low on average, considering that SAR values should be higher than 13 for the soils to be alkaline. However, the observed change rates are very high. If the best developed plants (Y2-P patches) are compared with the nearby interpatch areas (Y2-I), the difference is more than 450%, with maximum SAR values around 4·8. Such an increase, generated in a relatively short time (Y2 plants were 5–6 years old at the time when the assessment was conducted) should not be considered sustainable.

However, this species has been largely used to improve rangeland productivity in dryland regions, probably because this aspect has been overlooked. Much greater emphasis was given to biomass productivity, which can be very high in well-managed plantations, and can actually improve local livelihood conditions (Zucca *et al.*, 2015).

On the other hand, a range of alternative uses of this plant are under study. Its use was promoted as a viable option to support industrial livestock production on poorly productive soils (O'Sullivan, 2013); canopy and root system development models were designed to maximize its productivity in semi-arid and arid environments (Descheemaeker *et al.*, 2014); management strategies were proposed to extend the duration of its lifecycle in field conditions in order to favour the 'revegetation of inhospitable areas' (de Souza *et al.*, 2014). The plants' impact on soil salinity does not seem to be a major concern in these studies, in view of its fodder production and of its adaptability to soil aridity and salinity. Furthermore, the extraordinary capacity of *A. nummularia* to extract salts from the soil is raising scientific attention, as it is increasingly seen as an affective option for the remediation of saline soils (Hasanuzzaman *et al.*, 2014). These applications are often oriented to a relatively more intensive land use and are based on the assumption that most of the fresh plant biomass is to be removed from the field (e.g. by harvesting), thus taking away the extracted salts accumulated in the leaves. However, under extensive management conditions, abundant litter can accumulate in the field strongly affecting the top soil alkalinity, as shown by this study.

CONCLUSIONS

This study quantified the drastic changes induced by the *A. nummularia* plants on the topsoil properties. Compared with previous studies, the research was conducted on a bigger number of plantations belonging to different productivity and age types and was based on a greater number of samples. Although some important aspects deserve further investigation, such as the temporal salinity changes in relation to climatic humidity, some main conclusions can be drawn.

The plants were indeed able to create a 'fertility island' in term of topsoil enrichment with organic matter. Under the most productive plants OC contents was doubled in short time (5–6 years) compared with the surrounding soils, reaching values around 1·3% that constitute a considerable stock in view of the aridity of the study area. Considering the other positive effects described by previous studies, such as soil surface mulching produced by litter, the improved microclimate produced by shadowing, increased habitat availability for many animal species, and last but not least, the economic benefits generated for the local communities; the role of this plant in rangeland restoration must be given adequate consideration. However, the study demonstrated that the impact in terms of soil salinity and alkalinity can be much greater compared with the already worrying changes reported by previous studies. SAR (Sodium Adsorption Rate, an indicator of alkalinity) increased by up to ten times compared with the control sites creating real 'alkalinity islands'. Alternative strategies based on more intensive management of the plants and on the harvest of the salt-bearing green biomass could reduce the detrimental effects of the salinity increase and ensure a more effective exploitation of the plants' qualities.

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