Use of Volcanic Mulch to Rehabilitate Saline-Sodic Soils

M. Tejedor,* C. C. Jiménez, and F. Díaz

ABSTRACT

Natural soil salinization and sodication processes that restrict or prevent crop growth are commonplace in arid regions. In saline-sodic soils of arid parts of the Canarian archipelago, where annual rainfall is <150 mm, a traditional agriculture system has been developed using basaltic tephra mulch. This system has enabled dry crop farming to take place even under the most adverse of natural conditions. The present work compares the salinity-sodicity in the cultivated layer of soils that were covered with 10 to 15 cm of tephra mulch as recently as 20 yr ago with that of adjacent unmulched soils. These soils have never been irrigated. Results show significant differences in electrical conductivity (EC) and exchangeable Na percentage (ESP). The natural, unmulched soils are extremely saline-sodic (EC_{se} 43 dSm^{-1}, ESP 44), whereas the mulched soils are neither saline nor sodic (EC_{se} 1.5 dSm^{-1}, ESP 9). The reduction in salinity and sodicity in the mulched soils was related to the change in soil moisture regime caused by the mulch covering, which increases infiltration and reduces evaporation and upward movement of Na^+ and other salts. Probably, additional water from dew could also contribute. The greater dilution of soil solution through increased soil water content, increased Na^+ leaching and the dissolution of calcium salts may account for the desalinization and desodication. These results were confirmed through monitoring of a soil from the moment it was originally covered with tephra. They also revealed salt leaching process is a short-term. Tephra mulching can, therefore, be a highly efficient technique for the recovery of saline-sodic soils under dry farming conditions.

In arid regions, water scarcity contributes to natural salinization and sodication processes that limit soil productivity, resulting in soil degradation and contributing to desertification. Human activity can speed up such processes, but, by the same token, can also help reduce their effects and even rehabilitate affected soils. Examples of the latter include traditional farming systems using soil water conservation, which also constitute a means of reducing soil salinity and sodicity. One such case is the use of rock fragments as mulch, which has been shown to affect soil moisture properties (Modaihsh et al., 1985; Groenevelt et al., 1989; Nachtergaele et al., 1998; Tejedor et al., 2002). However, very little information is available on the influence of this technique in desalinization of soils of arid regions under non-irrigated farming conditions (Vargas et al., 1993, Tejedor et al., 1999a,b). Research has indicated that, under irrigated conditions, soil salinity can be reduced under mulch (Mendizabal and Verdejo 1961, 1962; Pérez de los Cobos, 1959). However, the possible effect of mulch on desodication has remained unaddressed.

In the eastern islands of the Canarian archipelago, situated in the intertropical region and characterized by extremely dry conditions, particularly on the island of Fuerteventura, soils are extremely saline and sodic and soil water content throughout the year is well below the wilting point. The island covers 1660 km^2 and is located between 28°45′ and 28°02′ N lat., some 115 km off the west coast of Africa (Fig. 1). Annual rainfall is <150 mm, falling mostly during the winter months; average annual temperature is about 18 to 20°C, with a year-round daily average of 8 h of sunshine; potential evapotranspiration is around 1800 mm with frequent strong winds. Frequently, there are invasions of Saharian dust, made up essentially of quartz, calcite, kaolinite, and illite. Approximately 89% of rainfall is lost through evapotranspiration (ETP), 8% infiltrates, and 3% is lost through runoff (Torres, 1995). In the natural systems of the island, ETP corresponds mainly to evaporation, considering the scarce vegetation. Although there are many wells, the water extracted tends to contain large amounts of NaCl and is saline (EC between 2-12 dSm^{-1}). Hence, the water used for human consumption on the island comes chiefly from desalinization of seawater.

Although there are some plutonic and sedimentary formations on the island, basaltic volcanic materials predominate, with varying ages ranging from lower Miocene to Holocene (Abdel Monem et al., 1971). Most of the soils are Aridisols, particularly Petrocalcids and Haplocalcids, and to a lesser extent Paleargids, Natrargids, and Haplargids (Soil Survey Staff, 1999). There are also areas of Torripsamments, Torrifluvents, and Torriorthents (Soil Survey Staff, 1999). Despite these conditions, which should rule out any possibility of dryland farming, local farmers have, nonetheless, managed to develop a form of cropping that has not only rehabilitated the soils but also permitted production of several crops. The practice hinges on the use of a layer of tephra on the surface of the soil, acting as mulch. Non-irrigated crops commonly grown using the system include onion (*Allium cepa*), melon (*Cucumis melo*), watermelon (*Citrullus lanatus*), corn (*Zea mays*), potato (*Solanum tuberosum*), and—in bygone times—henequen (*Agave fourcroydes*) to produce fiber. The system has permitted annual cropping under average precipitation. In years with especially low precipitation, yields have been reduced.

The objectives of this study were to determine the differences between mulched and unmulched sites in salinity and sodicity, and to determine the rates of change of these parameters and possible mechanisms for these differences.

MATERIALS AND METHODS

Field plots

Seven sites were selected for this work (Fig. 1) none of which relied on water harvesting. At each site, one plot was

Dep. Edafología y Geología, Universidad de la Laguna, Tenerife, Spain. Received 8 July 2002. *Corresponding author (martesa@ull.es).

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677 S. Segoe Rd., Madison, WI 53711 USA

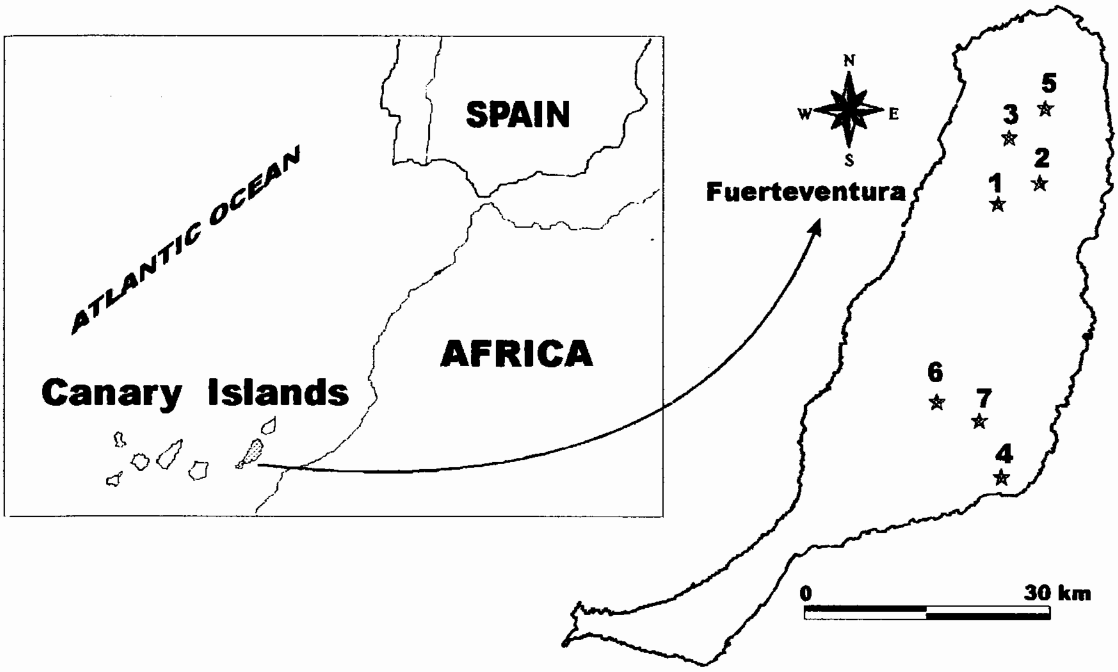

Fig. 1. View of the study area.

covered with tephra mulch and another adjacent one was left uncovered. The plots were chosen because they were representative of the different variants of the agricultural production system on the island, with regard to soil texture, tephra grain size, and cropping and cultural history. Textures ranged from clayey to sandy-loam (Table 1); tephra grain size varied from 2 to 4 and 8 to 16 mm (Fig. 2). In terms of the use made of the mulched soils, Sites 1, 3, and 5 were used for growing henequen until the 1990s, when this crop was abandoned on the island; Sites 6 and 7 were covered initially, with a view to farming, but a change of ownership of the land meant that none took place; Sites 2 and 4 were used for crop production at the time of the study, mainly onions and corn. As has already been mentioned, no cultivation is possible in the unmulched soils. The soils, Petrocalcids (Sites 1, 2, 6, and 7), Haplocalcids (Sites 3 and 4), and Torripsamments (Site 5), have been covered with a 10- to 15-cm thick layer of basaltic tephra from 20 to 53 yr. Soils were sampled at the beginning of November 2000, a particularly dry year (Table 2). At each of the seven sites, eight samples were taken at random from the cultivated layer (0–30 cm) of both the mulched and adjacent non-mulched soils and analyzed for selected physical and chemical properties. For purposes of statistical validity, means of the eight samples analyzed per plot treatment (mulched vs. non-mulched) are presented.

In addition, an experiment was designed to study the rate of the processes induced by the mulch cover. An area of site 5 (100 m^2) was covered with 12 cm layer of the 2- to 4-mm grain-sized predominant basaltic tephra on July 2001, within the dry period (2.2 mm in the preceding 5 mo). The first soil sampling was made at this starting point. Two more samplings were made, one on April 2002 (end of wet period) and the other on October 2002 (end of the dry period). The accumulated precipitation between sampling dates was 109.7 and 0 mm, respectively. Soil samples were taken to the 40-cm depth and subdivided into 10-cm increments. Gravimetric soil moisture content and EC of the 1:1 extracts were determined.

Table 1. Selected physicochemical properties of the soils.

Site identification	pH (H_2O)	pH 48 h	pHse†	$CaCO_3$	Gypsum	Clay	Silt	Fine sand	Coarse sand	Texture class
Mulched soil				g kg^{-1}						
1	9.2	8.6	8.0	139	0	443	358	126	74	Clay
2	9.5	8.6	8.3	39	0	266	528	171	35	Silt loam
3	9.5	8.7	8.1	278	0.2	369	396	175	60	Clay loam
4	9.0	8.6	7.9	139	0	243	445	158	153	Loam
5	9.0	8.7	7.5	93	0	111	64	426	398	Loamy sand
6	9.3	8.6	8.3	77	0	260	401	214	126	Loam
7	9.0	8.6	7.9	33	0	258	358	266	117	Loam
Mean	9.2	8.6	8.0	114	0	279	364	219	138	
Unmulched soil										
1	8.4	8.4	7.0	223	0.4	405	405	131	59	Silty clay
2	8.5	8.4	7.2	28	0.5	288	563	136	12	Silty clay loam
3	8.4	8.3	7.0	268	0.5	334	429	162	74	Clay loam
4	8.5	8.5	7.4	203	0.7	262	422	162	154	Loam
5	8.5	8.4	7.1	107	0.5	166	136	366	332	Sandy loam
6	8.7	8.5	7.3	83	0	239	444	226	91	Loam
7	8.7	8.5	7.3	38	0.1	262	370	265	102	Loam
Mean	8.5	8.4	7.2	136	0.4	279	396	207	118	

† pHse = pH of the saturation extract.

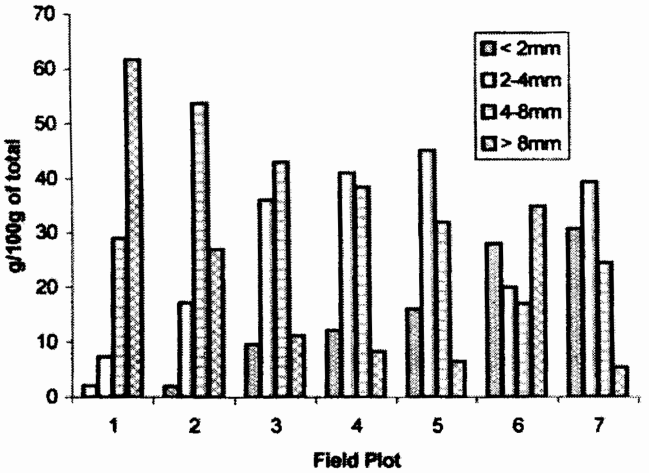

Fig. 2. Grain-size distribution of the tephra used for mulching.

Laboratory

Determination of grain-size distribution of the tephra was performed by mechanical sieving. Bulk soil samples were allowed to air-dry and were then ground to pass a 2-mm mesh sieve for laboratory analysis. Soil pH was measured in a 1:2.5 soil/water suspension (Chapman and Pratt, 1961) and in the saturation extract. Carbonate content was determined by volumetric calcimeter according to Allison and Moodie (1965, p. 1389–1392). Electrical conductivity (EC_{se}), soluble cations, and soluble anions were measured in the saturation extracts and 1:1 extracts (USDA-NRCS, 1996). The analytical determination of Cl and SO_4 was performed by anion chromatography, HCO_3 ion by potentiometric titration with HCl, Ca and Mg by atomic absorption spectrophotometry and K and Na by flame emission spectrophotometry. The cation-exchange capacity was determined after Bower et al. (1952). Exchangeable Na and K were extracted with a buffered neutral 1 *M* NH_4OAc solution, and Ca and Mg by 1 *M* NaOAc (pH 8.2) solution to avoid the carbonate dissolution and overestimation of these cations. Cation concentrations were determined as above. Exchangeable Na percentage was estimated by direct determination of exchangeable Na and cation-exchange capacity and indirectly from SAR values using the appropriate equation in the U.S. Salinity Laboratory Staff (U.S. Salinity Laboratory Staff, 1954). Gypsum content was estimated by precipitation with acetone (U.S. Salinity Laboratory Staff, 1954). Particle-size analysis (particles <2mm) was determined after samples were dispersed in sodium hexametaphosphate solution and shaken on a horizontal reciprocating shaker for 12 h using the hydrometer method (Day, 1965). The Mann-Whitney U test was used for statistical comparisons (Canavos, 2001). The SPSS package version 10.0.6 (SPSS Inc., 1999) was used.

RESULTS AND DISCUSSION

Mulch and Soil Characteristics

In all cases, the materials used as mulch were basaltic pyroclasts with variable grain size ranging from 2 to 4 mm (Plot 7) to over 8 mm in diameter (Plot 1). However, the dominant grain size for all plots was 2 to 8 mm (Fig. 2).

The study plots presented a range in texture, from clayey in Plot 1 to loamy sand in Plot 5 (Table 1). Overall, loamy textures predominated. Additionally, at each study plot the mulched and unmulched soils had similar textures. All soils contained calcium carbonate and were base saturated. The mulched and unmulched soils were alkaline in reaction (Table 1). In unmulched soils, which were saline and calcareous, equilibrium pH was reached quickly, but in mulched soils, which were only calcareous, it took 48 h to reach equilibrium pH. When 48-h equilibration was used, no significant differences were observed in the pH values between the mulched and unmulched soils (Table 1). However, the soils differ considerably in EC and ESP values, depending on whether they were mulched or unmulched.

Electrical conductivity of the saturation extract was low in the mulched soils, with an average of 1.5 dS m^{-1}, although most were <1 dS m^{-1} (Table 3). In all cases, the EC_{se} of the mulched soils was below the 4 dS m^{-1} value used to differentiate saline soils (U.S. Salinity Laboratory Staff, 1954). Conversely, in the adjacent unmulched soils, EC_{se} values exceeded this, with an average of 43.3 dS m^{-1}. It should be noted that the spatial variation of the EC_{se} in the mulched soils was small compared with that of the unmulched soils (Standard Deviation for mulched soils = 0.70; for unmulched soils = 24.3). The Mann-Whitney U test applied to the EC_{se} obtained in the mulched and unmulched soils in each of the studied plots showed significant differences at the 0.01 probability level.

The dominant ions in the saturation extracts were Cl^- and Na^+, with lower concentrations in the mulched soils and higher concentrations in the unmulched soils (Table 3). It is worth noting that bicarbonate, although present in both types, was more common in the mulched soils and, in some instances, was more abundant than Cl^-. No soluble carbonates were found.

In both the mulched and unmulched soils, cation-exchange capacity values were similar (about 21 $cmol_c$ kg^{-1}) (Table 3) and reflect the predominantly illitic clay mineralogy (Torres, 1995). Exchangeable Mg and K values were similar in both soils. In contrast, exchange-

Table 2. Rainfall data (mm of rain) for the study area.

Period/Year	J	F	M	A	M	J	J	A	S	O	N	D	TOTAL
1971–2001	17.2	16.2	13.0	5.4	1.0	0.0	0.0	0.0	2.6	8.5	13.0	22.3	99.2
1999	27.5 N†	0.2 N	27.6 O‡	0.2 N	0.0 N	0.0 N	0.0 N	0.0 N	0.8 N	49.9 O	2.8 N	33.1 N	142.1 N
2000	16.8 N	6.6 N	0.0 N	3.2 N	1.4 N	0.0 N	0.0 N	0.0 N	2.5 N	1.3 N	3.8 N	9.1 N	44.7 N
2001	0.6 N	0.0 N	0.2 N	1.0 N	0.0 N	0.0 N	0.4 O	0.0 N	0.0 N	0.6 N	57.2 O	4.1 N	64.1 N
Standard deviation	27.2	24.3	14.2	9.1	2.7	0.1	0.1	0.0	4.3	14.9	17.2	27.3	51.4

† N = Normal (type of month and year in accord with Soil Taxonomy [Soil Survey Staff, 1999]).
‡ O = Outlier.

Table 3. Exchange complex and soil solution properties.

Identification site	ECse†	Water solubles ions							Exchangeable complex					ESP§	ESPc#
		Ca	Mg	K	Na	HCO_3	Cl	SO_4	Ca	Mg	K	Na	CEC‡		
	$dS m^{-1}$	$mmol\ L^{-1}$							$cmol_c\ kg^{-1}$					%	
Mulched soil															
1	1.0	2.8	1.2	0.3	7.9	3.4	5.3	2.7	12.5	5.2	3.1	1.8	22.5	8.0	9.4
2	0.9	1.0	0.5	0.2	7.9	4.1	2.6	4.8	10.7	5.0	3.9	4.0	23.6	16.9	14.7
3	1.5	1.6	1.0	0.5	11.3	4.4	11.0	3.1	10.7	6.5	3.6	3.4	24.3	14.0	16.2
4	2.3	19.1	4.4	0.6	15.2	2.3	6.3	21.8	15.0	2.5	2.6	1.4	23.0	6.1	7.4
5	3.2	9.9	5.6	1.2	16.1	2.2	23.7	9.8	8.5	2.9	2.6	1.6	16.6	9.6	9.8
6	0.6	1.4	0.7	0.2	5.0	3.7	1.9	3.0	9.6	3.1	2.1	1.2	16.0	7.5	10.8
7	0.7	3.8	1.5	0.2	2.9	2.3	2.6	2.5	11.2	4.9	2.9	0.6	20.1	3.0	2.4
Unmulched soil															
1	39.0	169.4	153.2	2.5	250.4	1.3	441.5	32.6	5.5	5.9	2.1	9.6	21.0	45.7	28.5
2	42.6	223.2	72.0	3.3	303.1	2.4	356.8	30.8	9.6	5.6	3.5	9.6	26.9	35.7	31.8
3	70.1	218.0	229.1	9.3	519.7	1.5	701.4	56.2	5.5	6.6	4.1	19.0	27.3	69.6	41.6
4	29.2	156.8	70.7	5.5	165.8	1.6	341.7	44.4	7.4	2.7	3.1	6.8	21.6	32.1	23.8
5	94.5	431.3	257.5	15.1	849.2	1.3	1246.0	61.0	4.9	2.6	3.6	12.7	17.5	72.6	48.5
6	14.6	55.6	23.4	2.8	82.1	1.7	143.8	10.1	5.8	2.9	2.6	4.5	15.8	28.5	20.7
7	13.2	55.7	31.5	2.3	73.1	2.2	136.0	9.9	10.8	4.3	2.9	4.2	19.7	23.5	18.0

† ECse = electrical conductivity of the saturation extract.
‡ CEC = cation exchange capacity.
§ ESP = exchangeable sodium percentage.
# ESPc = exchangeable sodium percentage calculated from SAR.

able Na and Ca differed significantly between the mulched and unmulched soils. In the non-mulched soils exchangeable Na was the dominant cation while exchangeable calcium predominated in the mulched soils (Table 3).

Since ESP is the most widely used sodicity criterion, and in view of the analytical problems usually encountered in its determination in soils rich in soluble salts, the SAR was used to estimate the calculated ESP (ESP_c) (Table 3). As with the EC_{se}, considerable differences in ESP between the mulched and unmulched soils were detected using both directly determined ESP and calculated ESP_c. In the mulched soils, the average ESP was 9.3, compared with 44.0 in the unmulched soils. In the former, ESP_c was slightly greater than when determined directly, although the values were very similar. By contrast, in the unmulched soils the difference was found to be much greater, with the value obtained by direct determination being considerably greater. Greater homogeneity of the soil under the mulch cover was indicated by less spatial variation in ESP compared with the unmulched soils (average SD for mulched soils = 3.3; average SD for unmulched soils = 23.4 or 9.6, depending on whether determined directly or calculated). When the Mann-Whitney U test was applied to the ESP values for the two types of soils at each of the study plots, differences between the mulched and unmulched soils were significant at the 0.01 probability level in most of the cases, and at the 0.05 probability level in the rest. The ESP values of the mulched soils were generally less than the 15%, threshold used to define sodic soils, whereas in the unmulched soils, the values were considerably >15%.

Generally, the tephra-covered soils did not contain gypsum, unlike the unmulched soils, where it was found in small quantities. The absence of the gypsum in the mulched soils may reflect increased dissolution. In addition, the Saharian dust accumulation was probably higher in the covered soils due to the trap dust effect (Goossens, 1995). This should have been reflect by a higher carbonate content in the mulched soils, but was not observed. This circumstance could be the result of dissolution of carbonate in the tephra layer were the pH should be lower than in the soil and act as a source of Ca^{2+} to displace Na^+.

Based on the EC_{se} and ESP, according to the accepted limits used for determining saline and/or sodic soils (U.S. Salinity Laboratory Staff, 1954), the tephra-covered soils were neither saline nor sodic. In contrast, the adjacent unmulched soils were markedly saline and sodic.

In the Fig. 3 and 4, the results of monitoring of the soil moisture content and EC of the short-term experiment are shown. Despite the short-time period elapsed, a difference in soil moisture content was also seen. The moisture was found to be higher in the mulched soil than in its uncovered neighbor. An inverse relationship appears between the evolution of the EC and moisture values.

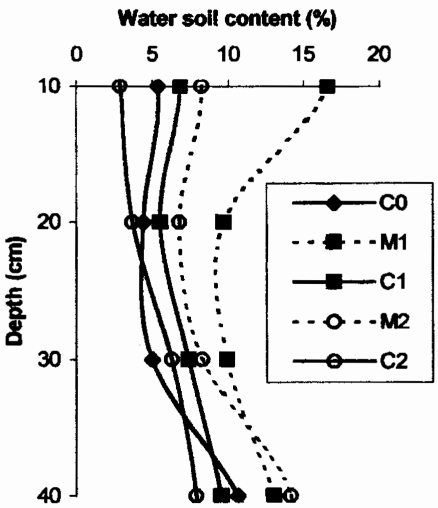

Fig. 3. Evolution of the soil water content in the short-term experiment. C0 = Starting point; M1 = Mulched soil after the wet period; C1 = Unmulched soil after the wet period; M2 = Mulched soil after the dry period; C2 = Unmulched soil after the dry period.

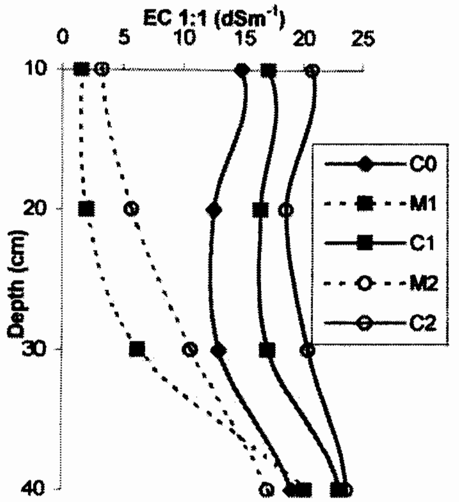

Fig. 4. Evolution of the soil salinity in the short-term experiment. C0 = Starting point; M1 = Mulched soil after the wet period; C1 = Unmulched soil after the wet period; M2 = Mulched soil after the dry period; C2 = Unmulched soil after the dry period.

It is clear that mulching of these previously unproductive soils has resulted in an increase in their suitability for cultivation.

DISCUSSION

In tephra-covered soils, the soil moisture regime was changed greatly. In the arid regions of the Canary Islands, it was demonstrated that non-mulched soils have an aridic regime, whereas adjacent tephra-mulched soils eventually develop a udic regime (Tejedor et al., 2002). This led us to the hypothesis that the reduction in the salinity and sodicity observed in this study was closely linked to the changes in moisture regime brought about by mulching.

Once covered with a layer of tephra mulch, infiltration of rainfall was improved. On the other hand, the environmental conditions (high air humidity and the important drop of night temperature, among others) led us to suspect that dew may be an important source of additional water. This issue is currently being investigated. Soil water loss through evaporation was reduced and thus the moisture regime converted to a more humid one, resulting in diminished upward movement of soil solution. Following the rare periods of rain, the concentration of soluble salts gradually decreased through leaching. Electrical conductivity was also reduced and the soil lost its saline character. Since some moisture was retained year-round (Tejedor et al., 2002), upward movement of soluble salts was limited during dry periods, and the accumulation of salts in the rooting zone avoided. This resulted in salinity levels that remained tolerable for most plants.

The decrease in Na^+ associated with the exchange complex was likely related to a combination of processes. These include the dilution of soil solution by increased soil water content, the ease with which Na^+ was leached under an udic soil moisture regime, and the dissolution of calcium salts. These processes all contribute to the displacement of exchangeable Na^+ by Ca^{2+}, which then became the dominant cation on the exchange complex. Consequently, ESP was reduced to a level that plants could tolerate, and the soil lost its sodic nature. The source of the Ca^{2+} is under investigation.

Clearly, the desalinization and desodication processes seemed to operate simultaneously. No relationship was found between the intensity of desalinization and/or desodication and mulch grain size, nor with the age of the systems. The most recent covering dated back only 20 yr; these processes certainly take place within shorter time periods, at least the salt leaching process, as suggested by the results obtained in the short-term experiment. When the arable layer of an initially highly saline soil was covered, leaching intensity increased during the rainy season and upward movement of salts in the subsequent dry period was more restricted in the surface layers. The processes whereby salts are washed and then move back up are cyclical and progressively cause the salts in the root zone to be eliminated from the mulched soils.

In conclusion, the use of tephra mulch in arid zones has been shown to be an excellent technique that enables remediation of unproductive saline-sodic soils. Over short time periods, mulched saline-sodic soils turn to non-saline, non-sodic soils without the use of irrigation. As a result, these soils can be utilized for dry farming. These findings coincide with the impressions of local farmers, whose experience tells them "in the case of a soil rich in salts, a covering of tephra can facilitate crop production after just one, or at most two, periods of rainfall."

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