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Rehabilitation of saline soils by means of volcanic material coverings

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Summary

The scarcity of water in arid regions promotes natural soil salinization processes, which limit soil productivity, cause degradation and contribute to desertification. Human activity can speed up these processes although it can also help reduce their effects and even rehabilitate affected soils. A number of traditional soil water conservation systems used in farming are also techniques for reducing soil salinity. Examples include systems that involve the use of volcanic materials as mulch, a practice known as 'arenados' that has been common for decades in the Canary Islands. The present work examines short-term changes in the salinity of two saline soils, one with clay texture and the other with loamy texture, both of which were covered artificially with a 12-cm layer of basaltic pyroclasts. Monitoring over a period of 4 years, during which rainfall averaged 130 mm for the clay soil and 120 mm for the loam, revealed a decrease of approximately 76% and 86%, respectively, in the salinity of the top 40 cm of the profile in the two soils. The decreased salinity of the rooting zone, which is associated with an improved moisture regime in the covered soils has given rise to a form of dryland farming with acceptable yields in a soil environment which is otherwise poorly suited to agriculture.

Introduction

Salinization is considered to be one of the seven routes to desertification (Kassas, 1987) as well as one of the most important land degradation processes (Thomas & Middleton, 1993). Salt accumulation in soils hinders the growth of most crops and saline soils are associated with poor fertility (Tanji, 1990). In many arid and semiarid regions of the world this process is among the primary causes of poor productivity in farming and, in most cases, current irrigation methods and cultivation practices contribute little to rehabilitation (Qadir *et al*., 2000).

In Lanzarote and Fuerteventura, the easternmost of the Canary Islands (Spain), the extreme climatic conditions, with very little rainfall ($\approx$ 150 mm year^{-1}) and great evaporative demand ($\approx$ 1800 mm year^{-1}), the poor physical conditions of the soils, which severely restrict water penetration and movement, and the influence of the sea (a permanent source of cyclic salt), mean that salinity limits the growth of the majority of crops. Under these extremely adverse farming conditions, covering the soils with volcanic materials has led to the development of a dryland farming system that produces acceptable yields (Díaz, 2004).

The use of rock fragments as mulch to improve soil moisture has been widely reported in the literature (Groenevelt *et al*., 1989; Nachtergaele *et al*., 1998; Tejedor *et al*., 2002), although relatively little information has been published about the influence of such techniques on soil salinity (Tejedor *et al*., 2003a). Similarly, rock mulching tends to be overlooked in reviews and descriptions of the methods used to rehabilitate saline soils (FAO, 1988; Szabolcs, 1989; Qadir *et al*., 2000, 2001). Only Chhabra (1996) proposes mulching as a technique and examines its influence on evaporation and, consequently, on restricting the upward movement of salt to the surface.

Although very few works address the role of rock mulch in soil desalinization, several examine its use in dryland farming (Tejedor *et al*., 2003a). In irrigated soils, Pérez de los Cobos (1959), Mendizábal & Verdejo (1962) and Rueda & Rueda (1965) noted that the mulches used in southern Spain (systems based on the placing of a layer of beach sand (0.5–2 mm in diameter) approximately 10 cm thick on the soil) helped reduce soil salinity and allowed crops to grow in areas where the high electrical conductivity had made the soils unsuitable for farming. Although the authors did not provide data, they noted that covered soils irrigated with relatively saline water showed a gradual decrease in salinity from year to year. They attributed the effect to less evaporation, which prevents the salts from rising to the root zone, and also to leaching of the salts further down the profile. They also reported that in many of the covered soils a concentration of salts was found

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Table 1 Average pH, organic matter and $\mathrm{CaCO_3}$ contents and particle-size distributions at different depths

Depth			OM	$\mathrm{CaCO_3}$	Clay	Silt	Sand	
/cm	pH $_{1:2.5}$	pH s[a]	/g kg^{-1}					Texture class
Clay soil								
0–3	9.2	8.0	1.6	56.2	422	513	65	Silty clay
3–10	9.0	7.9	2.7	53.9	487	490	24	Silty clay
10–20	8.4	7.5	2.8	76.5	525	457	17	Silty clay
20–30	8.2	7.3	3.9	69.1	530	428	43	Silty clay
30–40	8.2	7.3	3.2	105.4	432	544	24	Silty clay
40–50	8.3	7.3	1.6	200.1	469	378	153	Clay
50–60	8.3	7.4	1.4	151.4	633	304	64	Clay
60–70	8.3	7.4	1.3	96.9	475	491	34	Silty clay
70–80	8.3	7.3	1.1	101.5	535	430	36	Silty clay
80–90	8.3	7.4	1.5	119.7	594	336	71	Clay
90–100	8.3	7.5	1.8	153.3	602	317	81	Clay
Loamy soil								
0–3	9.5	8.4	5.3	248.4	330	270	400	Clay loam
3–10	8.2	6.9	6.2	163.9	286	356	357	Clay loam
10–20	8.1	6.8	5.5	198.2	231	152	616	Sandy clay loam
20–30	8.4	7.2	5.1	79.3	259	129	613	Sandy clay loam
30–40	8.4	7.3	6.9	228.5	412	221	367	Clay
40–50	8.5	7.4	7.4	261.2	351	239	409	Clay loam
50–60	8.7	7.4	8.4	289.1	300	256	445	Clay loam
60–70	8.8	7.4	7.0	154.2	260	341	399	Loam
70–80	8.9	7.7	5.2	199.0	239	307	453	Loam
80–90	8.9	7.6	5.6	143.0	231	240	530	Sandy clay loam
90–100	8.5	7.3	5.4	110.7	276	254	470	Sandy clay loam

[a] pHs = pH in saturation extract.

Table 2 Initial composition of the soil solutions and ESP[a]

Depth	ECs[b]	$\mathrm{Ca^{2+}}$	$\mathrm{Mg^{2+}}$	$\mathrm{K^+}$	$\mathrm{Na^+}$	$\mathrm{HCO_3^-}$	$\mathrm{Cl^-}$	$\mathrm{SO_4^{2-}}$		ESP
/cm	/dS m^{-1}	/soluble ions/mmol l^{-1}							SAR[c]	/%
Clay soil										
0–3	0.7	1.1	0.6	0.8	2.4	2.3	2.7	0.7	1.9	1.5
3–10	7.9	2.9	1.3	0.1	62.9	2.5	78.7	1.7	30.9	30.7
10–20	39.3	19.5	12.2	2.6	341.2	1.4	464.3	4.4	60.6	46.9
20–30	42.2	43.0	35.8	2.9	309.6	1.3	466.5	11.0	34.9	33.4
30–40	50.6	42.2	44.5	2.9	333.3	1.2	571.2	9.1	35.8	34.0
40–50	49.4	44.9	56.7	3.0	376.8	1.1	614.2	8.5	37.4	35.0
50–60	46.3	34.1	42.6	3.5	400.9	1.0	543.2	6.9	45.8	39.9
60–70	43.3	29.6	42.5	1.9	335.6	1.2	513.7	8.8	39.5	36.3
70–80	42.2	28	42.3	2.4	378.9	1.2	497.8	8.0	45.2	39.5
80–90	43.1	22.1	34.5	2.5	393.5	1.2	474.0	7.1	52.4	43.2
90–100	41.9	25.7	40.3	2.7	349.5	1.2	495.8	7.1	43.0	38.4
Loamy soil										
0–3	2.3	0.4	0.1	0.9	19.9	6.4	14.6	2.1	28.1	28.7
3–10	54.5	55.3	17.4	10.1	416.7	1.4	612.0	21.1	48.9	41.5
10–20	83.7	100.1	35.2	14.9	760.3	1.3	878.2	39.1	65.4	48.8
20–30	63.9	44.0	21.6	11.4	640.3	1.6	718.5	29.7	79.1	53.6
30–40	68.6	45.0	24.2	11.9	690.1	1.4	760.0	31.5	83.0	54.8
40–50	66.3	43.5	21.2	12.3	680.2	1.7	723.0	38.5	84.6	55.3
50–60	55.3	30.6	16.1	9.5	576.2	1.9	613.4	37.7	84.3	55.2
60–70	50.2	23.7	13.1	8.0	520.3	1.9	527.9	17.3	85.9	55.6
70–80	49.3	19.8	11.0	8.1	506.4	2.5	531.3	19.0	91.2	57.1
80–90	48.0	19.3	10.9	7.6	526.5	1.9	524.7	25.8	95.9	58.4
90–100	52.7	31.1	13.6	7.9	537.7	1.7	558.8	44.7	80.5	54.0

[a] ESP = exchangeable sodium percentage; [b] ECs = electrical conductivity of the saturation extract; [c] SAR = sodium adsorption ratio.

between 0.8 and 1 m depth, although no details were given with regard to the evolution of this layer.

Tejedor *et al.* (2003a) reported that the salinity in the root zone of soils mulched with basaltic pyroclasts 20–50 years ago on the island of Fuerteventura was considerably less than in the unmulched adjacent soils. The reduction was such that in most cases the salt concentrations were no longer an impediment to crop growth. The aim of the present work is to determine the rate of salinity reduction in relation to rock mulching. To that end, we studied the evolution of the saline profile in soils with large concentrations of salt, as from the moment they were covered with basaltic pyroclasts.

Materials and methods

Two natural saline-sodic soils on the island of Fuerteventura, Canary Islands, Spain (28°45′04″ and 28°02′16″ north; 13°49′12″ and 14°30′24″ west) were selected for the study. The first (site 1) is situated 280 m above sea level on one of the island's central plains, with an annual rainfall of 212 mm year^{-1} (average of a 34-year series from a nearby meteorological station), although the average figure for the 4 years of the study was just 130 mm year^{-1}. The soil is deep (more than 1 m) and of clay texture. The second soil (site 2) is situated 80 m above sea level, in the north of the island, with an average annual rainfall of 100 mm year^{-1} (from a 34-year series) but 120 mm year^{-1} during the study period. This second soil, also over 1 m in depth, is of loamy texture. Both are classified as Haplosalids (Soil Survey Staff, 1999).

Samples were taken every 10-cm depth for soil characterization. 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 1:2.5 soil:water suspensions (Chapman & Pratt, 1961) and in saturation extracts (US Salinity Laboratory Staff, 1954). Carbonate content was determined by volumetric calcimeter (Allison & Moodie, 1965). Electrical conductivity (ECs), soluble cations and soluble anions were determined in the saturation extracts (USDA-NRCS, 1996). The EC was also measured in 1:1 extracts (EC 1:1) (US Salinity Laboratory Staff, 1954). The determination of $\mathrm{Cl^-}$ and $\mathrm{SO_4^{2-}}$ ions was performed by anion chromatography, $\mathrm{HCO_3^-}$ by potentiometric titration with HCl, $\mathrm{Ca^{2+}}$ and $\mathrm{Mg^{2+}}$ by atomic absorption spectrophotometry and $\mathrm{K^+}$ and $\mathrm{Na^+}$ by flame emission spectrophotometry. The exchangeable sodium percentage (ESP) was estimated indirectly from values of the sodium adsorption ratio (SAR) by means of the appropriate equation (US Salinity Laboratory Staff, 1954). Particle-size distribution (particles < 2 mm) was determined by the hydrometer method after samples were dispersed in sodium hexametaphosphate solution and shaken on a horizontal reciprocating shaker for 12 hours (Day, 1965).

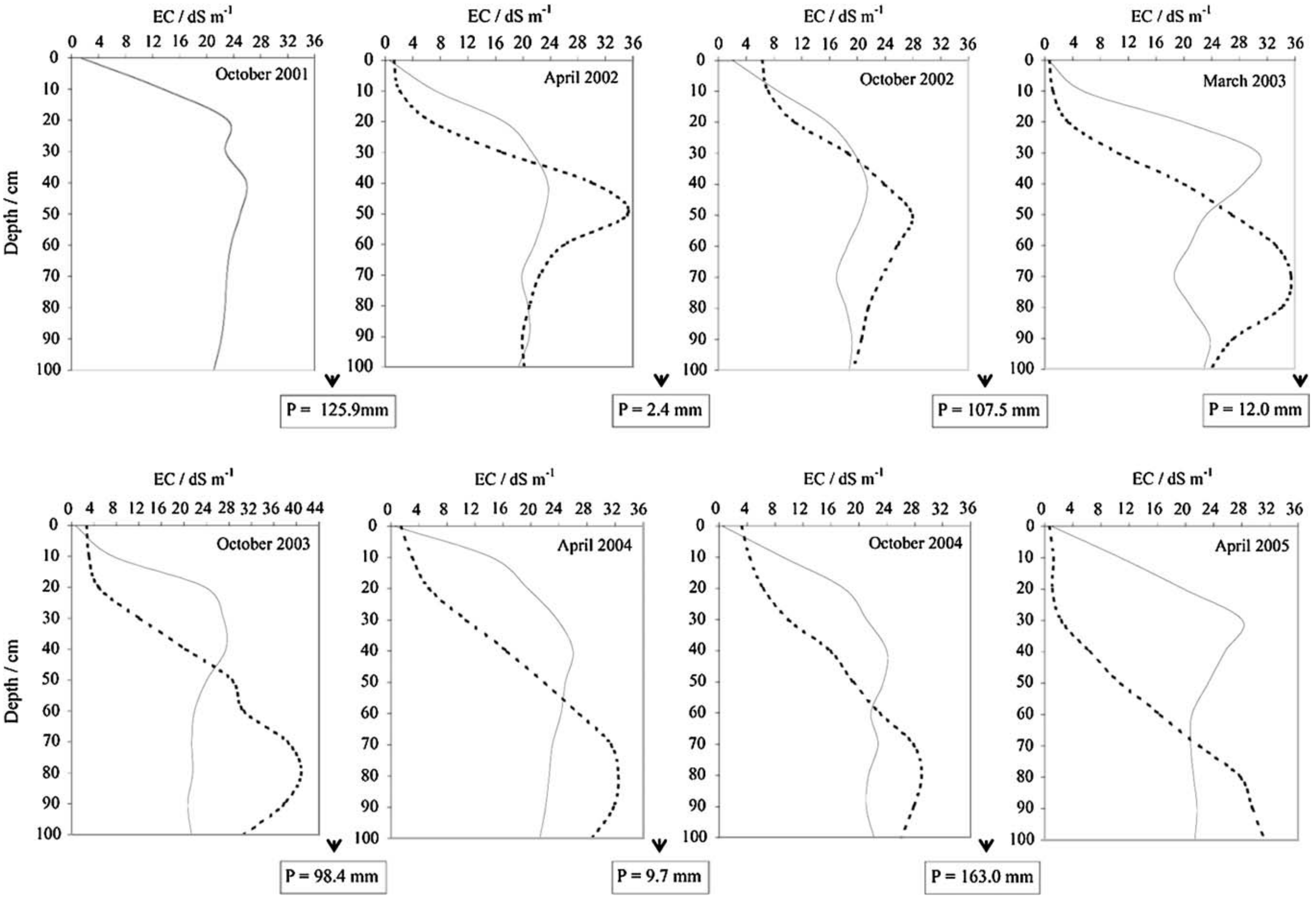

Figure 1 Clay soil. Evolution of salinity (EC in 1:1 extracts) in the mulched and unmulched profiles during the monitoring period. P = cumulative precipitation between consecutive sampling periods. —, unmulched soil; -----, mulched soil.

At each of the two sites the soil of a 100-m^2 plot was covered in the summer of 2001 with a layer of approximately 12 cm of coarse-grain basaltic pyroclasts (median particle size, D_{50}, was 6.4 mm; predominant grain size was 2–8 mm) and a similar-sized adjacent plot was left uncovered. The grain size of the volcanic material used as the covering was determined by sieving with a mechanical shaker. We monitored the evolution of salinity by means of the EC of 1:1 extracts.

An initial set of samples was taken prior to covering the soil (May 2001 in the loamy soil and October 2001 in the clay soil) and seven further sets of samples were taken subsequently, four after wet periods (April 2002, April 2003, April 2004 and April 2005) and three after dry periods (October 2002, October 2003 and October 2004). On each date, samples were taken every 10 cm to 1-m depth from 10 profiles (five in the mulched soil and five in the unmulched soil).

For each sample and depth, we tested the significance of the differences between the electrical conductivity data for both the mulched and the unmulched soils. For groups of values that were normally distributed (Kolmogorov-Smirnov test), we applied a *t*-test for independent samples. For those not fitting a normal distribution, the Mann–Whitney U non-parametric test was used. Differences were considered statistically significant at $P < 0.05$.

Rainfall between the samplings was recorded at meteorological stations close to the sites and part of the network of stations of the Department of Water Services (Servicio Hidráulico, Las Palmas de Gran Canaria).

Results and discussion

Tables 1 and 2 set out the initial physical and chemical properties of the soil profiles at the two sites. The organic matter content is greater at site 2, although in all cases it is below 10 mg kg^{-1} throughout the profile. Such values are typical of arid region soils, which have sparse vegetation cover and little biological activity. Both soils contain calcium carbonate and an alkaline reaction is present at virtually all depths. The textures of the first soil are silty clay and clay, with an average clay content > 50%. The second has more loamy textures, with a predominance of clay loam and sandy clay loam. In contrast to site 1, the average clay content in the profile is < 30%.

As Table 2 shows, the EC of the saturated extracts was very great in both soils, with values in excess of 20 dS m^{-1} throughout the profiles, except in the top 3 cm where the EC was less than 4 dS m^{-1}, and in the 3–10 cm layer at site 1 (< 8 dS m^{-1}). The soils are therefore extremely saline and restrict the growth of most crops and of natural vegetation. The soil solution is dominated by sodium and chloride, which is evidence of the essentially marine origin of the salts. The soils are also sodic, with exchangeable sodium percentages well above 20%.

Figures 1 and 2 show the evolution of the salinity (EC 1:1) in the soils at the two sites from the time they were covered, as well as that of the unmulched adjacent soils. For each date, the average values for the EC (1:1) are given for the five profiles. Also given is the cumulative precipitation between sampling periods. The month of April marks the end of the wet period and October the end of the dry period.

The original soils had EC 1:1-values above 12 dS m^{-1} at all depths, except in the top 3 cm (1.4 dS m^{-1} in the clay soil and 4.1 dS m^{-1} in the loamy soil). With only very slight differences, the processes undergone after covering with the layer of pyroclasts were the same in the loamy soil and the clay soil, and very different to those in the adjacent unmulched soils.

Following the first rainfall (April 2002), the leaching of salts was already evident in the mulched soils (slightly more marked in the loamy soil), with the salts from the first 20–30 cm accumulating at 40–50 cm. The top 20 cm then had an EC of less than 7 dS m^{-1}. In the unmulched soils the salinity curve after this first period of rain was similar to the initial curve, with slight surface leaching. Significant differences ($P < 0.05$) were found between the mulched and unmulched soils at 10, 20 and 50 cm in the clay soil and at 10, 20 and 30 cm in the loamy soil. The samples taken later revealed that in the mulched soils the leaching became more pronounced with subsequent periods of rainfall.

Although in the mulched soils an upward movement of salt was seen in the samples taken after the dry period (October), the concentrations remained small in the top 20 cm and tended to be less than those in the unmulched soils. The upward rise was normally accompanied by a reduction in the salinity of deeper parts where the salts had accumulated. The salt profile of the unmulched soils showed very little change compared to that of the rainy periods, given the negligible water penetration and movement.

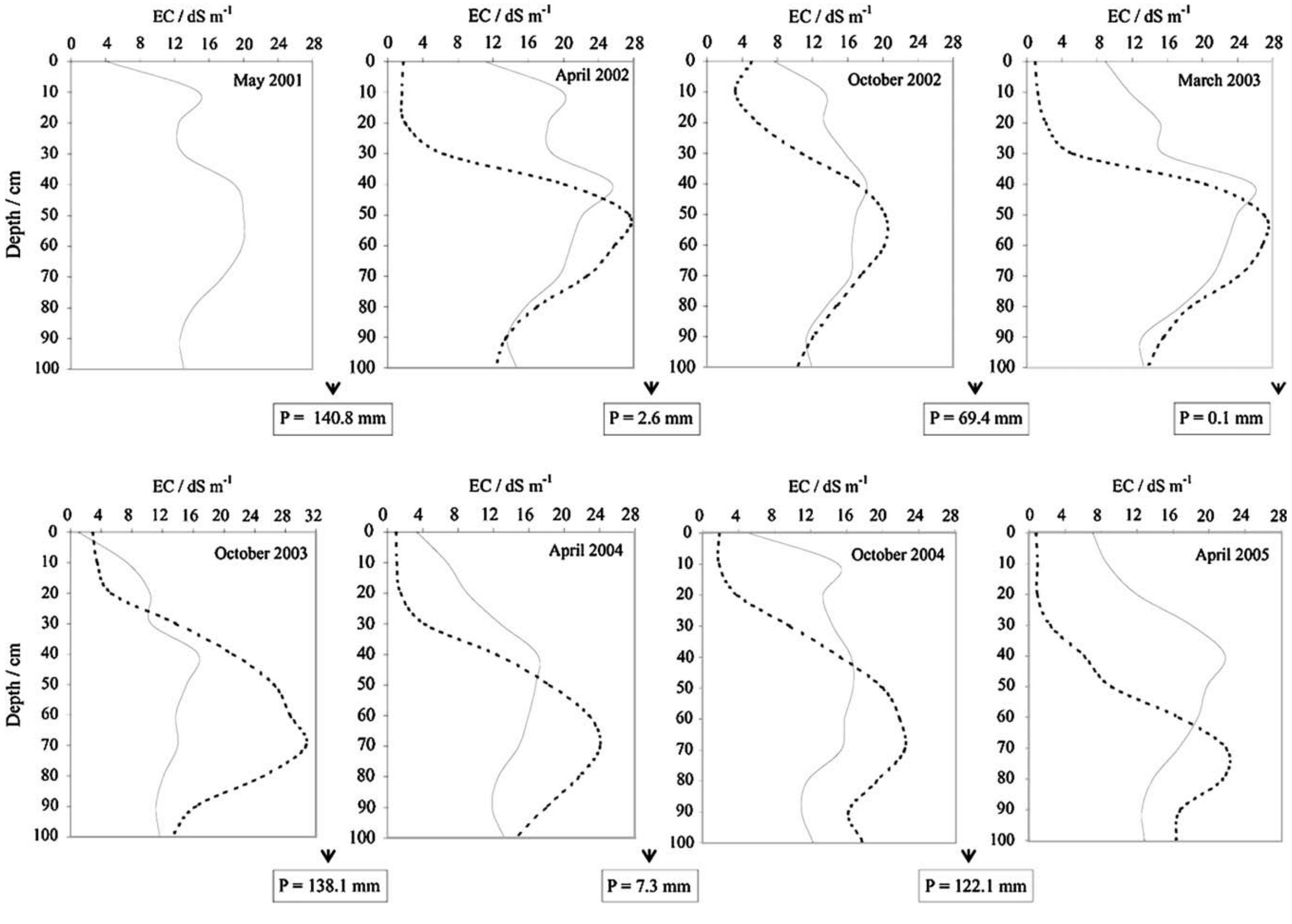

Figure 2 Loamy soil. Evolution of salinity (EC in 1:1 extracts) in the mulched and unmulched profiles during the monitoring period. P = cumulative precipitation between consecutive sampling periods. —, unmulched soil; -----, mulched soil.

Figures 3 and 4 show box plots to illustrate the variability of the salinity throughout the profile in the mulched soils and in the adjacent unmulched soils at the end of the trial (April 2005). In both soils, the EC in the top 30 cm of the mulched soils was <4 dS m^{-1}, a figure easily surpassed in the unmulched soils. In the clay soil, the differences between the mulched and unmulched soils were significant at depths of 10, 20, 30, 40 and 50 cm, and in the loamy soil at 20, 30, 40 and 50 cm. At the end of the experiment, there was a reduction of 76% (clay texture) and 86% (loamy texture) in the average salinity in the top 30 cm of the mulched soils, compared to the unmulched soils. The reduction of salinity in the top 40 cm in a short time (4 years) illustrates the effectiveness of basaltic pyroclast mulches in ameliorating saline soils, particularly when one bears in mind the little rainfall required to achieve this (a total of 519 mm and 480 mm, respectively, over the 4 years).

The experiment shows that, irrespective of the soil texture, the processes that take place in the mulched soils are the same. The salts undergo relatively rapid leaching, with subsequent accumulation of salts at depth. The salt accumulation zone after 4 years, although still within the first metre of the soil, has moved downwards considerably, compared to the first year (80 cm compared to 50 cm).

Figure 5 shows the evolution of the moisture of the clay soil during the experiment. Note how, following covering with the pyroclasts, the soil moisture content in the mulched soils is much greater than in the unmulched soil. Tejedor *et al.* (2002) have shown that this change can be so marked that a soil originally having an aridic soil moisture regime can become udic (Soil Survey Staff, 1999). The contribution of soil mulching to desalinization through moisture change is evident. Once covered with a layer of pyroclasts, we believe that saline soil benefits from increased infiltration of the little rain that falls. The infiltration capacity of the unmulched soils is, in contrast, very low due to the generalized formation of a surface sealing crust, which also favours runoff processes (Tejedor *et al.*, 2003b). Following wet periods, the concentration of soluble salts in the

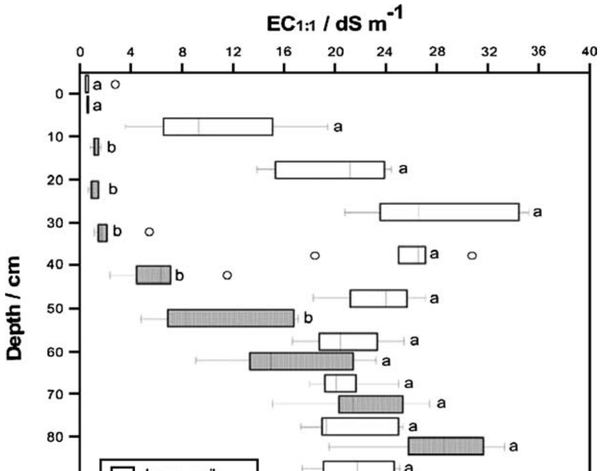

Figure 3 Clay soil. Variability of the EC$_{1:1}$ of mulched and unmulched soils after 4 years (April 2005). □, unmulched soil; ▨, mulched soil. The boxes indicate the interquartile range. The vertical line between two percentiles shows the median value. The whiskers to the sides of each box extend from the smallest to the largest of the values considered to be in the normal range. The two isolated circles represent non-typical values. Two different letters alongside boxes indicate significant differences ($P < 0.05$) and two letters the same indicate non-significant differences ($P > 0.05$).

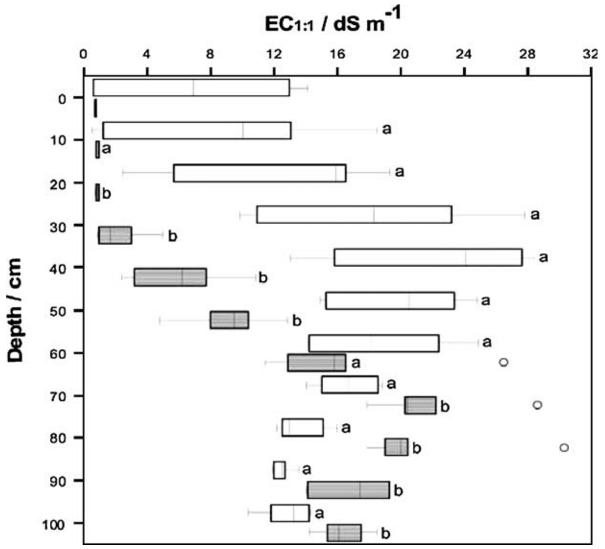

Figure 4 Loamy soil. Variability of the EC$_{1:1}$ of mulched and unmulched soils after 4 years (April 2005). □, unmulched soil; ▨, mulched soil (see Figure 3 caption for further details).

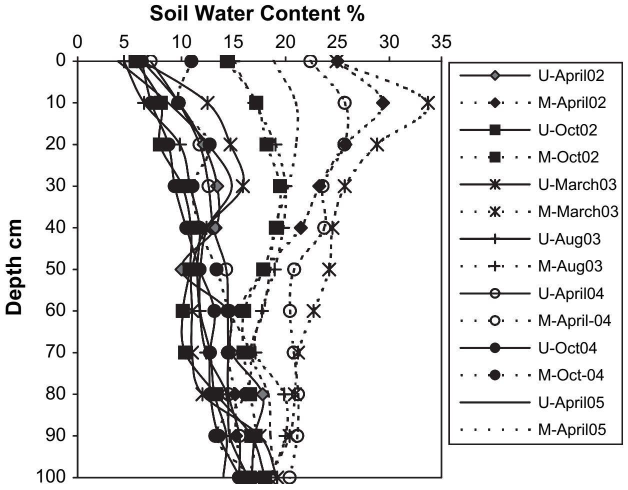

Figure 5 Clay soil. Evolution of soil water content in the mulched and unmulched profiles during the monitoring period. —, unmulched soil; -----, mulched soil.

mulched soils decreases gradually as a result of leaching, a situation which does not arise in the unmulched soils due to the aforementioned surface sealing. Electrical conductivity (1:1 extracts) is reduced and the soil loses much of its saline character. The salts accumulate further down the profile and, notwithstanding the evaporative demand, they do not rise again towards the surface due to the insulating effect of the mulch (Díaz *et al*., 2005).

Conclusions

Our experiment shows that the use of basaltic pyroclasts as mulch induces leaching of soluble salts beyond the root zone within very short periods of time. This finding coincides with the experience of local farmers, that a tephra mulch allows crops to be grown on salt-rich soils that would otherwise be unproductive, after just one or two periods of rainfall. The important and rapid reduction noted in the salinity is directly associated with the changes in the moisture regime that come about when the soils are covered with mulch consisting of basaltic pyroclasts.

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