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Influence of the thickness and grain size of tephra mulch on soil water evaporation

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Abstract

On the island of Lanzarote (Canary Islands, Spain), under extremely arid conditions – including annual rainfall of below 150 mm – a system for dry farming has evolved based on the use of volcanic mulch. This paper presents the results of the laboratory experiments conducted to assess the influence of two parameters of the mulch – thickness and grain size – on soil water evaporation. A soil typical of the zone, a silty clay Haplocambids, was chosen for the experiment. The mulch cover consisted of medium-grain basaltic tephra in layers 2, 5 and 10 cm thick. A 5 cm thick layer was also studied for fine, medium and coarse basaltic tephra. The soil was saturated and drained until the water content accounted for approximately 50% of weight and it was then subjected to evaporation for 31 days. The evaporation rate was maintained at between 9.1 and 11.5 mm per day, in keeping with an arid climate. The accumulated evaporation in the covered soils, irrespective of the mulch thickness and grain size, was significantly lower than in the uncovered soil. The reduction in accumulated evaporation varied with the mulch thickness: 10 cm of mulch produced a 92% reduction, 5 cm a 83% reduction and 2 cm a reduction of 52%. The 5 and 10 cm coverings provided adequate soil insulation, unlike the 2 cm thickness, which was less effective as a barrier preventing loss through evaporation. All grain sizes reduced evaporation by 81–85%.

Keywords: Evaporation losses; Dry farming; Volcanic mulch; Arid regions; Canary Islands; Traditional farming

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1. Introduction

In arid regions with very little rainfall, evaporation causes major soil water loss, which restrict farming of annual crops. Despite this circumstance, throughout history man has developed farming practices aimed at reducing the amount of water lost. One such practice is the use of mulch, which can consist of a variety of materials. Inorganic mulch includes sand and rock fragments (Modaihsh et al., 1985; Groenevelt et al., 1989; Kemper et al., 1994; van Wesemael et al., 1996; Nachtergaele et al., 1998; Mellouli et al., 2000).

On the volcanic island of Lanzarote (Canary Islands, Spain), one of the most arid parts of the European Union given its annual rainfall of less than 150 mm, the long-standing tradition of using basaltic tephra mulch has made a certain amount of dry farming possible. The abundance of volcanic pyroclasts, the proximity of quarries and the duration of the system (effective for 20–25 years, after which the covering has to be replaced) make for an economically feasible farming practice, which is currently used in approximately 7000 ha. In previous works we have demonstrated the importance of this traditional practice for soil water conservation (Tejedor et al., 2003a) and for the rehabilitation of saline-sodic soils (Tejedor et al., 2003b), and we have also discussed the modifications caused in the soil classification (Tejedor et al., 2002a). The objective of this paper is to investigate the influence of the thickness and grain size of the tephra mulch on soil water evaporation. Three grain sizes (fine, medium and coarse) and three thickness of medium-grain tephra (2, 5 and 10 cm) were used for the laboratory experiment.

2. Materials and methods

The soil used in the study was 46% clay, 43% silt and 11% sand. It was taken in the area where the mulch is habitually used. The tephra was typical of that used in the traditional farming method. Of the parameters given in the literature for characterising the grain size of materials of this type (Folk, 1966; Prothero and Schwab, 1996; Bures, 1997) we used the median particle size (D_{50} or Φ_{50}) to differentiate the three types of tephra: fine ($1\ \text{mm} \leq D_{50} < 2\ \text{mm}$), medium ($2\ \text{mm} \leq D_{50} < 4\ \text{mm}$) and coarse ($D_{50} \geq 4\ \text{mm}$). The median particle size – the mesh size allowing 50% of the particles to pass through – reflects the most abundant grain size in the sample (Corey and Kemper, 1968). The grain size dispersion (σ) is calculated as $\sigma = ((\Phi_{84} - \Phi_{16})/4) + ((\Phi_{95} - \Phi_{5})/6.6)$, where Φ_{84}, Φ_{16}, Φ_{95} and Φ_{5} correspond, respectively, to the grain diameter below which small particles represent 84, 16, 95 and 5%. The soil surfaces were covered separately with tephra mulch as follows: (a) 5 cm of tephra of fine, medium and coarse grain and (b) 2, 5 and 10 cm of medium-grain tephra.

In order to simulate evaporation, we used metacrylate columns with heights of 30 cm (uncovered soil) and 32, 35 and 40 cm (for 2, 5 and 10 cm mulched soil, respectively). The columns were 8.4 cm inner diameter, provided with a drainage system. The soil was air-dried, 5 mm-sieved and placed in the columns, with a bulk density of 1.1 mg m^{-3}. It was saturated by capillary rise for 2 days and excess water was drained off for a further 2 days. The columns were covered with plastic to prevent loss. The weight of each was recorded (water content accounted for approximately 50% of the weight). Column bases were sealed, the plastic removed and the surface was covered with the different mulches. Columns of uncovered soil were used as controls and others containing only water were installed also. The water columns were filled daily to the same level. Three replications were carried out in each case. The columns were placed randomly on a round table in such a way that all the tops were at the same height and exposed to the same radiation. The energy required for evaporation was supplied by a 1500 W heat lamp placed at a height of 1.2 m above the central axis of the table. Room temperature and relative humidity were monitored using five temperature sensors and five hygrometers. Two fans allowed air to circulate and the temperature and humidity were kept at 35 ± 2 °C and 45–50%, respectively throughout the experiment. Water loss in the columns was determined by daily weighing on 31 consecutive days. Results were analysed statistically using the SPSS for Windows package, version 10.0.6 (SPSS Inc., 1999). Differences were considered statistically significant at $p < 0.05$. Water content at the beginning and end of the experiment was determined gravimetrically.

3. Results and discussion

The dominant particle size in the fine-grain mulch was 0.5–1 mm (27%), compared to 2–4 mm (36%) for the medium and 4–8 mm (47%) for the coarse mulch (Table 1). Porosity is high in all three cases, although given the material's scorious nature the crucial parameter is pore size (Fig. 1). Macro and mesopores were abundant (>40%) in the coarse tephra, whereas in the fine and medium tephra micropores were by far the most common (>80%). The coarse tephra was more homogeneous in terms of particle size distribution. All three types have very low water retention capacity (5% at 100 cm tension in a water column). The coarse tephra reaches equilibrium more rapidly than the medium and fine tephra. The soil infiltration rate is better (60–125 mm h^{-1} in the covered soil compared to 5–20 mm h^{-1} in the bare soil). The chemical composition of the tephra is characteristic of basaltic materials, with no significant difference between the three: 43% SiO_2, 11.6% Al_2O_3, 12.7% Fe_2O_3, 0.18% MnO, 14.1% MgO, 10.1% CaO, 3.3% Na_2O, 1.4% K_2O, 2.7% TiO_2, 0.84% P_2O_5.

The evaporation rate of the water-only columns – taken to be the potential evaporation – ranged between 9.1 and 11.5 mm per day, with an average of 10 mm per day, in line with daily losses in arid climate (Modaihsh et al., 1985; Mellouli et al., 2000).

Soil water loss by evaporation under constant external conditions occurs essentially in two phases (Black et al., 1969; Hillel, 1971). In the first, when the soil moisture is still high,

Table 1
Characteristics of the selected tephra mulch

	Grain size distribution (mm)						D_{50}	σ	Pt (%)	B.D. (mg m^{-3})
	<0.5	0.5–1	1–2	2–4	4–8	>8				
Fine tephra	21.0	26.7	22.4	19.9	9.2	0.7	1.1	1.41	58.1	1.11
Medium tephra	8.4	9.6	19.5	36.1	22.0	4.6	2.6	1.34	63.0	0.98
Coarse tephra	2.1	1.0	5.3	29.1	47.4	15.3	4.8	0.84	71.3	0.76

D_{50}: median particle size; σ: grain size dispersion; Pt: total porosity; B.D.: bulk density.

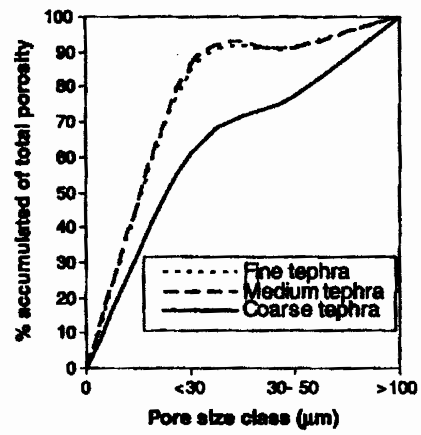

Fig. 1. Accumulated pore-size distribution of the studied tephra.

the losses occur at high and relatively constant evaporation rates. During this stage, the water rises to the surface via capillary movements controlled by atmospheric evaporative demand. In the second, which commences when soil moisture begins to fall, losses by evaporation occur at decreasing rates. With gradual loss of pore water, a progressive change takes place from liquid to vapour flow, which is much slower. Unlike the first phase, this second one is limited by the amount of water in the soil. The tephra mulch breaks up capillary diffusion, forcing the water transport upwards to the atmosphere to occur in the vapour phase.

Figs. 2 and 3, which show the daily evaporation rates for the different layer thickness and grain size study conditions, clearly illustrate the physical principles described. In the unmulched soil, evaporation remained at the constant rate of drying (phase 1) for the first 6

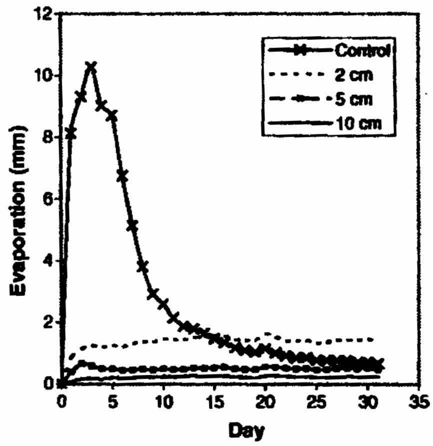

Fig. 2. Effect of different thickness of medium tephra mulch on daily evaporation.

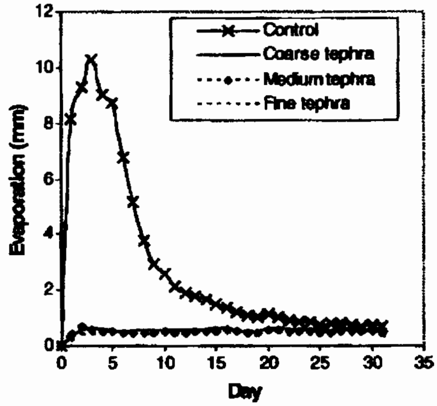

Fig. 3. Effect of different grain size of tephra mulch (5 cm thick) on daily evaporation.

days of the experiment, after which the second phase – decreasing evaporation rate – commenced. The mulched soils, irrespective of layer thickness and grain size, presented a constant rate of drying throughout the experiment. The longer first phase means that by the end of the study period the evaporation rates of the mulched soils are similar to those of the uncovered soil, although the accumulated evaporation differs markedly (Figs. 4 and 5). The accumulated evaporation in the covered soils, regardless of the mulch thickness and grain size, is significantly lower than in the bare soil. Hence, although daily evaporation rates may be lower in the bare soils during phase two of drying, the initial water losses in phase one are greater. This result concurs with the findings of other authors (Groenevelt et al., 1989; Kamar, 1994; van Wesemael et al., 1996) who also noted reduced evaporation loss in gravel-mulched soils. With the basaltic tephra mulch used here, the reduction was found to

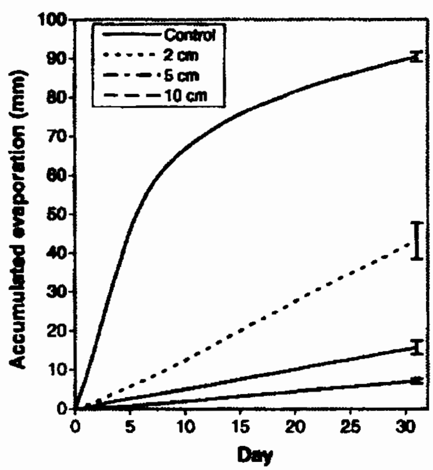

Fig. 4. Effect of different thickness of medium tephra mulch on cumulative evaporation.

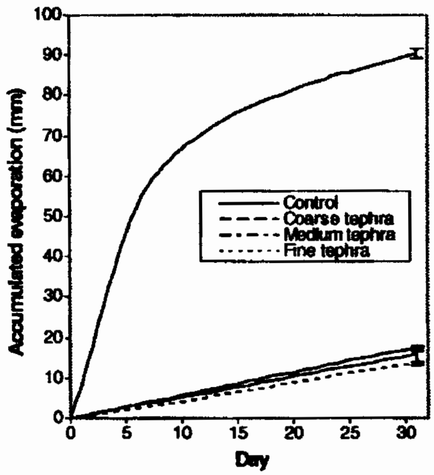

Fig. 5. Effect of different grain size of tephra mulch (5 cm thick) on cumulative evaporation.

be greater, probably due to its physical characteristics (among others, low water retention capacity, high hydraulic conductivity in wet conditions and very low in dry conditions). Mellouli et al. (2000) found, however, that a layer of 5 cm of rock fragments proved ineffective in reducing evaporation after 46 days of experiment (a mere 1.9% reduction compared to the control).

Comparing the results by mulch thickness, the differences in the amount of water evaporation at the end of the study period were statistically significant (Table 2). The reduction in accumulated evaporation was proportional to the mulch thickness. Based on similar initial water content, the greatest reduction was seen in the case of the soil under 10 cm of mulch (92%), followed by 5 cm (83%) and 2 cm (52%). The 2 cm layer, although showing less evaporation than the control soil, appeared to provide insufficient insulation, given the still considerable loss of water. The 5 cm layer was almost as effective as the

Table 2
Effects of the different treatments on water content and evaporation

	Control	Thickness of medium tephra mulch			Grain size of the 5 cm tephra mulch		
		2 cm	5 cm	10 cm	Fine	Medium	Coarse
Initial soil moisture (mm)	153.5	150.9	161.8	155.9	159.7	161.8	162.8
Final soil moisture (mm)	63.1	107.7	145.8	148.1	145.8	145.8	144.8
Final mulch moisture (mm)	0	0.1	0.3	0.7	0.3	0.3	0.6
E_{31} (mm)	90.4 a	43.1b	15.7 c	7.1 d	13.6 c	15.7 c	17.4 c
$\Delta E_{31}/E_{31}$control (%)	0	52.3	82.6	92.1	85.0	82.6	80.8
$d_{0.5}$ (days)	5	33	89	191	101	89	80

E_{31}: cumulative evaporation at the end of the experiment; $\Delta E_{31}/E_{31}$control: relative efficiency in E_{31} reduction compared to the control; $d_{0.5}$: time period when one-half amount of E_{31} is lost. Values followed by a different letters in the same row are significantly different ($p < 0.05$).

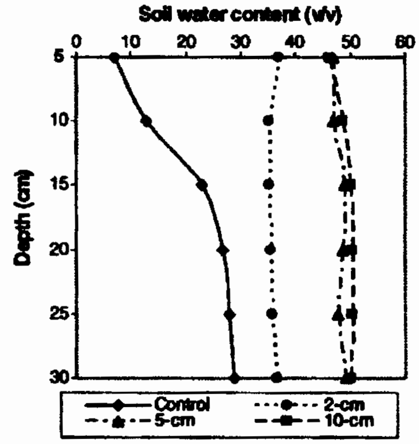

Fig. 6. Influence of mulch-thickness on soil moisture distribution profiles at the end of experiment.

10 cm covering, in contrast to field study results, where a more marked difference in soil water content was found between the two (Tejedor et al., 2002b). Comparing the results by grain size, the differences between the three (fine, medium and coarse) in terms of accumulated evaporation were not statistically significant (Table 2), although in all three cases the differences compared to the control soil were. That said, the fine tephra tended to be more effective, followed by medium and coarse. These results coincide with field observations, which evidenced a similar tendency as regards effectiveness for soil water conservation (Tejedor et al., 2003a), although more marked differences were found between the fine and medium grain sizes. Table 2 shows the water content at the beginning and at the end of the experiment, along with other, related parameters. Figs. 6 and 7 show

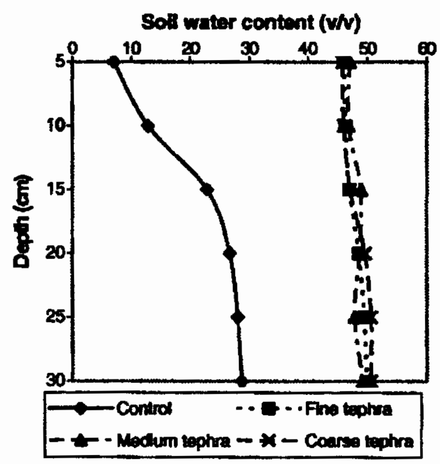

Fig. 7. Influence of mulch grain size on soil moisture distribution profiles at the end of the experiment.

the moisture distribution in the soil columns at the end of the experiment. Water content at all depths of the covered soils was higher than in the uncovered soils. In the former, water distribution in the profile was markedly uniform, whereas in the latter a sudden increase was seen at approximately 15 cm, as of which point the distribution was also homogenous. This circumstance is explained by the natural mulching effect exerted by the dry surface layer formed. The slower evaporation rate in the mulched soils compared to the control soil is also apparent in the time taken to lose half the accumulated evaporation in the latter, $d_{0.5}$ (Mellouli et al., 2000): 5 days in the uncovered soil compared to 191 days in the soil with 10 cm of tephra.

4. Conclusions

In arid conditions, covering soils with basaltic tephra reduces the amount of water lost through evaporation, the reduction being greater than with other inorganic mulch materials reported in the literature. More research on the nature of the basaltic tephra would be needed to fully understand its better suitability. The effectiveness of this reduction is directly linked to the thickness of the covering and is inversely related to grain size. These results coincide largely with normal practice among local farmers, who have a distinct preference for coverings of 7–12 cm of fine and medium grain tephra. The nature of our laboratory experiment, with more limited soil depth and surface, has resulted in less marked differences between the various treatments than those found under field conditions. The use of tephra mulch on the island of Lanzarote in extremely arid conditions has permitted the development of a form of dry farming, enabling onions, lentils, maize and sweet potato to be grown. This easily-managed technique could be transferred to other volcanic regions in the world possessing similar environmental conditions.

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