Soil Physical Properties and Moisture Content Affected by Site Preparation in the Afforestation of a Semiarid Rangeland

José Ignacio Querejeta,* Antonio Roldán, Juan Albaladejo, and Víctor Castillo

ABSTRACT

Revegetation of arid regions is primarily water-limited. To test the impact of several afforestation site preparation methods on the physical properties and the moisture content of the soil, a factorial experiment was conducted in a degraded semiarid rangeland of southeastern Spain. The land preparation treatments evaluated were terracing (mechanical or manual) and organic amendment (with or without urban solid refuse, USR). Terracing negatively affected some of the physical characteristics of the surface soil, such as the proportion of stable aggregates (21–33% decrease). Mechanical terracing increased soil water storage up to 40% more than manual terracing. The addition of USR counteracted many of the negative effects of terracing on soil physical properties and significantly increased soil moisture, particularly in the mechanical terraces (up to 40% increase compared with the nonamended treatment). The beneficial effects of the organic amendment on soil water content in the mechanical terraces persisted 4 yr after the single addition of the USR. The combination of mechanical terracing and USR addition significantly enhanced soil water availability, which is the most likely factor for the enhanced plant survival and growth seen in this study.

REVEGETATION is the most effective means for controlling soil degradation and for reclaiming abandoned agricultural lands in Mediterranean semiarid areas. The low availability of soil moisture due to scarce and irregular precipitation and frequent drought is a major obstacle to the successful revegetation of these areas (Albaladejo, 1990). Afforestation methodologies under semiarid environmental conditions usually include site preparation techniques aimed at enhancing water storage in the soil profile to improve the survival and growth of the planted species (Dent and Murtland, 1990). Mechanical terracing of slopes using bulldozers has been the most widely used land preparation method during recent decades in semiarid southeast Spain. Terracing greatly reduces runoff and enhances infiltration, thus promoting water conservation (Serrada, 1990). However, terracing can also negatively affect the fertility, structure, and biological characteristics of the soil (Finkel, 1986; Barber and Romero, 1994; Williams et al., 1995). Manual terracing, which produces less soil disturbance, is an alternative to conventional mechanical terracing.

Organic amendments could correct some of these negative effects of terracing on soils. Organic materials rich in easily decomposable C compounds, such as USR from sanitary landfills, can increase fertility and improve the physical and biological properties of degraded soils (El-Tayeb, 1989; Díaz et al., 1994; Roldán et al., 1994). Terracing and USR addition might therefore be a more successful site preparation combination for revegetation of degraded semiarid areas.

To evaluate the effect of different land preparation treatments (terracing and organic amendment) on soil properties and on plant performance, an experiment was established in 1992 in a degraded semiarid range of southeastern Spain. Growth, survival, and mycorrhizal status of the planted species (Alepo pine, *Pinus halepensis* Mill.) have been discussed elsewhere (Roldán et al., 1996a,b; Querejeta et al., 1998). Our study focused on the influence that terracing and USR addition had on the physical properties (bulk density, penetration resistance, sorptivity, saturated hydraulic conductivity, and aggregate stability) and water content of the soil.

MATERIALS AND METHODS

Field Site Description

The study was conducted in the El Aguilucho experimental area (37° 53′ N and 1° 15′ W, 180 m above sea level) in the foothills of the Carrascoy Range in Murcia Province (southeast Spain). The predominant soils are Haplocalcids and Petrocalcids (Soil Survey Staff, 1996) with a sandy loam texture (Table 1). The climate is semiarid Mediterranean, with extremely hot and dry summers. The average annual precipitation is 306 mm, occurring mostly in autumn and spring. The mean annual temperature is 17.6°C, and potential evapotranspiration reaches 903 mm yr^{-1}. The topography of the area is shaped by deep, wide gullies running from the Carrascoy Range in a south–north direction. The plant cover is sparse and degraded due to intensive grazing and ancient logging. The vegetation is dominated by slow-growing shrubs, with some patches of *P. halepensis*. The most common plant species are rosemary (*Rosmarinus officinalis* L.), *Anthyllis cytisoides* L., thyme (*Thymus* spp.), sun rose (*Helianthemum* spp.), and *Fumana* spp.

Experimental Design and Layout

The experiment was a two by two split-plot factorial design laid in five blocks (Snedecor and Cochran, 1989). Two terracing methods, mechanical terracing and manual terracing, were tested with and without organic amendment (USR). Each block included two whole plots (mechanical or manual terracing) subdivided into two subplots (with and without organic amendment).

The experimental area of 120 by 35 m was established on a homogeneous hillside (25% slope) facing east. Five blocks located at different levels of the hillside (from top to bottom) were considered. Each block was divided across the slope into two sections of 60 m and mechanical and manual terracing were randomly assigned to them. Mechanical terracing was carried out in June 1992. Terraces 4 m wide and 60 m long with a 3% reverse slope were excavated by a bulldozer. Mechanical terracing displaced the surface horizons of the soil profile,

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Abbreviations: TDR, time domain reflectometry; USR, urban solid refuse.

Table 1. Characteristics of the unaltered surface soil (0–5 cm) in the experimental area. Measurements were made prior to the application of the land preparation treatments.†

Organic matter, %	2.6 (0.5)
Coarse sand, %	40.9 (6.1)
Fine sand, %	24.1 (4.2)
Silt, %	30.4 (4.7)
Clay, %	4.6 (2.1)
Bulk density, Mg m^{-3}	1.45 (0.12)
Volumetric water content at matric potential −50 kPa, %	24.6 (4.9)
Volumetric water content at matric potential −1500 kPa, %	10.9 (2.1)
Saturated hydraulic conductivity, cm h^{-1}	19 (9.6)
Aggregate stability, %	71.6 (11.2)

† Values are means of five samples, each collected in one of the five blocks. Standard deviations are shown in parenthesis.

creating an uphill wall of 0.5 to 0.7 m. The thick subsoil lime crust existing in these terraces was broken by deep plowing along the planting line to a depth of 40 cm, using a single-tine subsoiler mounted at the rear of the bulldozer. Manual terracing was carried out in October 1992 and produced terraces 0.5 m wide and 60 m long with strips of natural vegetation between adjacent terraces. Both the manual terracing and the planting hole digging were done by ordinary handhoes. Each of the five blocks included one mechanical terrace and one manual terrace located next to each other at the same level of the hillslope.

Each whole plot (mechanical or manual terracing) was split across the slope into two subplots, one with and one without USR. The USR was a solid fresh material, neither composted nor ground but allowed to mature naturally for 15 d. The USR was supplied by the Murcia Municipal Treatment Plant. Selected chemical properties as determined by standard methods (Page et al., 1982) are shown in Table 2. At the beginning of the experiment in October 1992, the refuse was applied in a single addition at a rate of 10 kg m^{-2} applied area. This application rate is sufficient to improve the physical, chemical, and biological characteristics of the soil, while higher rates can give rise to the appearance of phytotoxicity or salinity problems (Díaz, 1992). In the mechanical terraces, USR was incorporated by rotovator tilling into the top 30 cm of the soil across the whole terraced area, while in the manual terraces it was incorporated within the planting holes only, using handhoes.

The Aleppo pine seedlings used in the experiment were not genetically improved for drought resistance or superior growth. Seed from El Valle nursery (Murcia) was sown in 300-mL plastic bags in a 3:1 soil/peat mixture. The seedlings were grown in this nursery for 1 yr without any fertilization. During November 1992, the 1-yr-old containerized seedlings were planted manually 70 cm apart from each other in a single row per terrace. The experiment was conducted under strictly natural conditions, with no irrigation or weeding.

Table 2. Selected chemical properties of the urban solid refuse used in the experiment.

Ash, g kg^{-1}	406
pH (1:10 aqueous extract)	6.8
Electrical conductivity (1:10), dS m^{-1}	4.4
Total organic C, g kg^{-1}	253
Extractable C, g kg^{-1}	48.1
C (fulvic acids), g kg^{-1}	31.7
C (humic acids), g kg^{-1}	16.4
C (carbohydrates), g kg^{-1}	49.5
Total N, g kg^{-1}	11.9
NO_3–N, g kg^{-1}	8.7
NH_4–N, g kg^{-1}	2.8
Total P, g kg^{-1}	5.5
Total K, g kg^{-1}	7.1
Assimilable K, g kg^{-1}	5.9
Polyphenols, g kg^{-1}	1.5
Cu, mg kg^{-1}	244
Ni, mg kg^{-1}	113
Zn, mg kg^{-1}	430
Cd, mg kg^{-1}	5
Cr, mg kg^{-1}	61
Pb, mg kg^{-1}	395

Sampling and Laboratory Procedures

Soil Physical Properties

Four years after the application of the land treatments, 50 soil cores were carefully excavated using steel cylindrical rings 5 cm in both diameter and height. In the manual terraces, all the soil cores were collected from the planting holes of the pines. Bulk density, water holding capacity, and saturated hydraulic conductivity were measured for each soil core. Soil bulk density was calculated from the oven-dried mass (105°C, 24 h) and known volume. Soil water holding capacity was determined using the sand box method (pF values 0, 0.4, 1, 1.5, and 2) and the Richards pressure membrane method (pF 2.7 and 4.2) as described by Martinez (1992). The saturated hydraulic conductivity of the soil was determined in the laboratory, using a constant head permeameter (Kessler and Oosterban, 1980).

Soil sorptivity was calculated from data obtained in the field by means of a single ring infiltrometer 30 cm in both diameter and height. Ten infiltration runs per treatment combination were conducted, maintaining a constant head of water 5 cm high inside the ring by manual topping up. All the infiltration runs were made during a dry period (soil moisture 5–8%), and one pine seedling was always included in the infiltration surface. Sorptivity values were obtained from cumulative infiltration data using the Philip's infiltration model (Sutikto and Chikamori, 1993). According to Clothier and White (1981), during the early stages of infiltration when the effect of gravity is insignificant, sorptivity can be calculated using the equation $S = I/t^{1/2}$, where I represents the cumulative water infiltrated into the soil at time t, S is the sorptivity, and t represents the time elapsed since the beginning of the infiltration run. A time of 5 min was chosen for sorptivity calculations.

Soil aggregate stability was determined following the procedure described by Díaz et al. (1994), which measures the percentage of soil aggregates between 0.2 and 4 mm that remain stable after being subjected to a simulated rainfall with an energy of 270 J m^{-2}.

Soil penetration resistance to a depth of 60 cm was measured using a cone penetrometer at five spots per treatment combination. The penetrometer probe was pressed into the soil at a steady rate against a proving ring that enabled the required pressure to be measured (Marshall and Holmes, 1988). The maximum pressure required to penetrate the soil to a depth of 60 cm was recorded at each sampling spot.

Soil Water Content

Three different gauging methods were used to measure soil water content: gravimetry, time domain reflectometry (TDR), and neutron scattering.

Soil water content in the 0- to 20-cm layer was measured gravimetrically (105°C, 24 h) every 15 d between April 1993 and May 1995. Soil samples were collected with a hand-driven probe (3-cm diam.) in 10 randomly selected spots per treatment combination. Each soil sample was split into two subsamples, corresponding with 0 to 10 cm and 10 to 20 cm deep.

In October 1993, 24 aluminum tubes for neutron probe access were installed to a depth of 60 to 90 cm, depending on

Table 3. Mean squares from analysis of variance of the soil physical properties, soil moisture content, and seedling height as affected by soil treatments. Differences in soil water content with time were tested with repeated-measures fully factorial multivariate analysis of variance.

		Mean squares							
	df	Organic matter	Bulk density	Penetration resistance	Sorptivity	Saturated hydraulic conductivity	Soil water content (1st yr)	Soil water content (2nd yr)	Pine seedling height (4 yr after planting)
Whole plots									
Blocks, B	4	0.008	0.002	140.3	2.80	356.4	271.6†	264.7†	4 564.8**
Terracing, T	1	0.171	0.008	38 822.1**	40.27**	6 811.7†	489.0**	52.8	76 799.3**
B × T	4	0.011	0.001	1 369.9	3.43	360.1	74.7	8.4	2 474.9**
Subplots									
Refuse, R	1	3.224**	0.176**	1 026.4	39.98**	52 316.2**	488.4**	221.6†	116 215.6**
R × B	4	0.048	0.001	527.5	2.16	294.9	18.2	19.3	604.5
R × T	1	1.017†	0.072**	601.1	23.93**	4 945.5†	304.4†	34.7	30 483.3**
R × T × B	4	0.054	0.003	872.6	1.36	336.2	83.1	62.6	798.8

** Significant at the 0.01 level of probability.
† Significant at the 0.1 level of probability.

the rock content of the soil profile. Soil water content at 30, 40, 50, 60, and 70 cm deep was monitored for 2 yr by means of an americium-berilium Troxler 4300 neutron probe (Troxler Electronic Laboratories, Research Triangle Park, NC). Measurements were made weekly during the first year, and with variable frequency (depending on rainfall event distribution) during the second year. The calibration of the neutron probe was accomplished using three lysimeters filled with soil from the experimental area that had been obtained during land preparation. Volumetric soil water content in each lysimeter was estimated from gravimetric and bulk density data. A linear fit model between neutron probe readings and volumetric soil water content data was developed following the recommendations of Greacen (1981). Differences in bulk density between the soil in the lysimeters and the soil in the experimental plots were considered in the calculations to transform neutron probe readings into volumetric water content (Greacen, 1981).

In order to obtain the water depletion rates of each treatment combination, surface (0–30 cm) soil water content was measured by TDR during November 1996. Twenty sampling spots per treatment combination were randomly selected for the vertical insertion of 10 pairs of parallel stainless steel rods 15 cm long and 10 pairs 30 cm long (2 terracing × 2 organic amendment × 2 depths × 10 samples/depth = 80 sampling points for the whole experiment). All TDR measurements were made within a 17-d interval between two rainfall events, with a frequency of 2 to 3 d. A Tektronix 1502B reflectometer (Tektronix, Beaverton, OR) and a 50-Ω coaxial transmission line with alligator clamp connections to the probes were used for the measurements. Soil water content values were calculated with the Topp equation (Topp and Davis, 1985; Zegelin et al., 1992).

Soil water depletion rate constants were calculated from the TDR drying curves, adjusting the experimental data to a negative exponential model $VWC = VWC_0[\exp(-kt)]$, where VWC_0 is the initial volumetric water content of the soil at the moment of maximum recharge after the rain, t is the time elapsed since the rainfall (in days), and k is the soil water depletion rate constant in $days^{-1}$ (Ting and Chang, 1985).

RESULTS AND DISCUSSION

Soil Physical Properties

Surface soil bulk density significantly decreased after the addition of USR, although this effect was greater in the mechanical terraces than in the manual terraces (Tables 3 and 4). The highest bulk density value was recorded in the mechanical terraces without USR, probably because the low organic matter content of the soil and the use of heavy machinery favored the compaction of the surface layer of the ground.

Soil penetration resistance to a depth of 60 cm was measured along the planting lines in the mechanical terraces and in the planting holes in the manual terraces. Subsoiling was much more effective than planting hole digging to reduce the penetration resistance of the soil, with values 50% lower in the mechanical terraces than in the manual ones (Tables 3 and 4).

Soil aggregate stability in the different treatment combinations was monitored during the early stages of the experiment. Initially, a drop in aggregate stability was observed for all treatments (Tables 1 and 4). Although differences among combinations were not significant at

Table 4. Physical properties of the soil in the four land treatment combinations evaluated. Except when otherwise indicated, samples were taken 4 yr after land treatment application (January 1997).†

	Manual terraces	Manual terraces + USR‡	Mechanical terraces	Mechanical terraces + USR‡
Organic matter, %	1.68 (0.21)a§	2.02 (0.35)ab	1.03 (0.11)a	2.28 (0.41)b
Bulk density, g cm^{-3}	1.45 (0.14)a	1.40 (0.17)ab	1.55 (0.12)a	1.22 (0.19)b
Penetration resistance, N cm^{-2}	342 (57)b	356 (89)b	154 (39)a	182 (46)a
Sorptivity, cm $min^{-1/2}$	0.74 (0.31)a	1.50 (0.68)b	1.24 (0.29)b	6.50 (2.03)c
Saturated hydraulic conductivity, cm h^{-1}	23.2 (13.8)a	91.7 (48.7)ab	28.3 (12.1)a	157.6 (60.5)b
Aggregate stability, %				
Mar. 1993	57.1 (11.6)a	60.9 (14.4)a	48.1 (7.9)a	62.2 (15.1)a
July 1993	61.2 (10.3)a	63.5 (13.0)a	56.7 (11.4)a	61.3 (17.2)a
July 1994	66.3 (8.1)ab	68.1 (9.5)b	54.9 (6.2)a	65.8 (10.7)ab
Dec. 1995	–	–	55.8 (5.9)a	70.4 (7.1)b

† Each value is a mean of at least 10 replicates. Standard deviation of the means are shown in parenthesis.
‡ USR is urban solid refuse.
§ Values in rows followed by the same letter do not differ significantly ($P < 0.05$) as determined by Duncan's test.

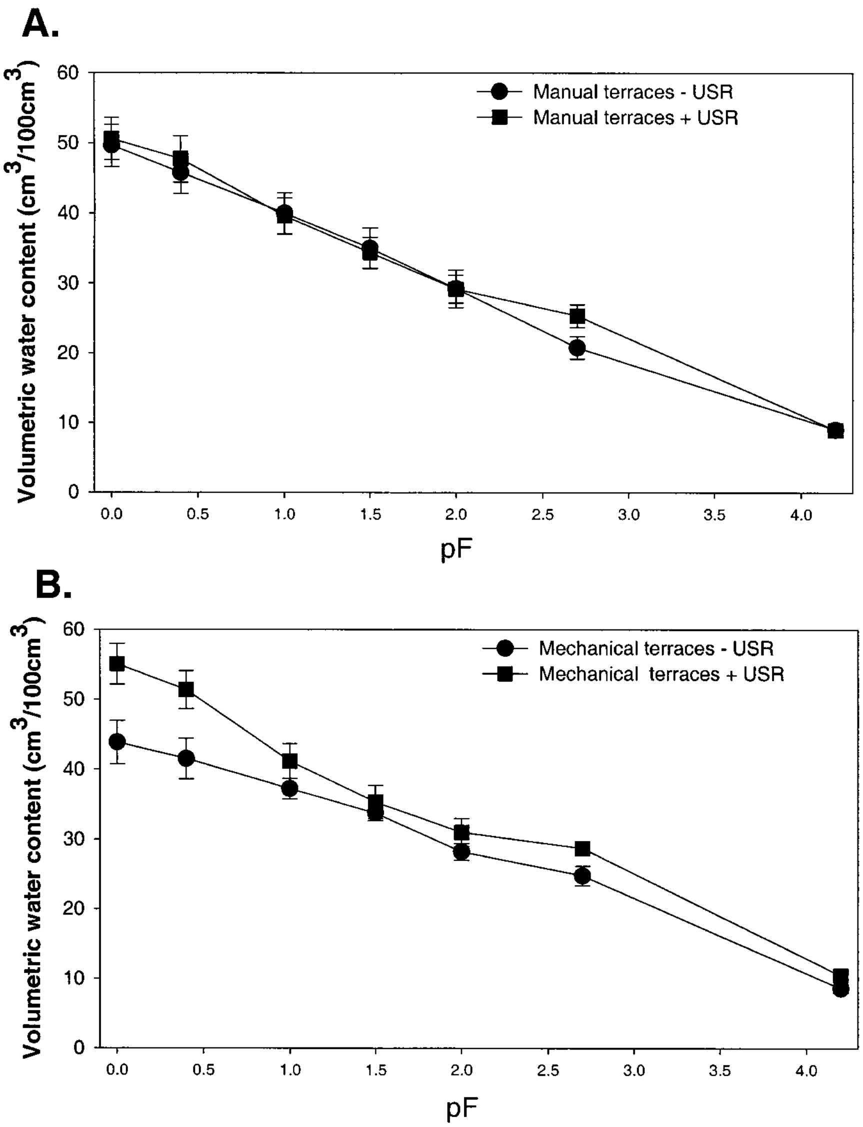

Fig. 1. Water release characteristics of the surface soil horizon (0–5 cm) in the different land treatments. Soils were sampled in January 1997. Each volumetric water content value is the mean of at least 10 replicates. The term pF means the logarithm to the base 10 of the matric suction expressed in cm. (A) Manual terraces. (B) Mechanical terraces. USR is urban solid refuse.

the beginning, mechanical terracing seemed to decrease the percentage of stable aggregates of the surface soil to a greater extent than manual terracing. The lowest values were measured in the mechanical terraces without USR. The organic amendment tended to increase the stability level of aggregates in the terraced soils. Three years after the application of the land treatments (December 1995), a new survey was conducted to study the long-term effect of the organic amendment on soil aggregate stability. Only the mechanical terraces were sampled this time, in order to concentrate on how the USR influenced soil structure. The USR significantly ($P < 0.05$) increased the percentage of stable aggregates in the mechanically terraced soils (Table 4).

Saturated hydraulic conductivity was highest in the mechanical terraces with USR (between 72 and 580% higher than in the other treatment combinations, Table 4). The mean value in the manual terraces with USR was also 256% greater than in the treatments without organic amendment. Sorptivity values in the mechanical terraces with USR were 334 to 780% higher than in the other treatment combinations (Table 4). The lowest sorptivity values were recorded in the manual terraces without USR. Therefore, both mechanical terracing and USR addition significantly increased soil permeability (Table 3). Significant USR × terracing interactions showed a synergistic positive effect of mechanical terracing and USR on saturated hydraulic conductivity and sorptivity.

The water holding capacity of the surface soil (0–5 cm) was greater in the mechanical terraces with USR than in the rest of the treatment combinations (Fig. 1). The addition of USR increased the soil water holding capacity in the mechanical terraces to a greater extent than in the manual ones. In the mechanical terraces, land preparation activity displaced the top soil layer, which could hold more water due to its higher organic matter content, so the USR addition was particularly

Table 5. Descriptive statistics of the surface soil water content as determined by the gravimetric method.

	Manual terraces		Manual terraces + USR‡		Mechanical terraces		Mechanical terraces + USR‡	
depth (cm)	0–10	10–20	0–10	10–20	0–10	10–20	0–10	10–20
Mean value, %	5.04	6.06	5.47	6.75	5.10	6.69	7.45	9.28
Standard deviation	4.16	3.81	4.63	4.54	4.39	4.23	5.55	5.22
Minimum value	0.43	1.03	0.12	0.55	0.07	0.32	0.27	0.51
Maximum value	18.02	16.02	19.53	21.26	22.12	21.9	30.25	28.25

† Data were taken during the period April 1993 to May 1995. Measurements were made biweekly on 10 replicates per treatment combination (2 replicates per block).
‡ USR is urban solid refuse.

beneficial there (significant USR × terracing interaction for organic matter, Table 3; organic matter mean values, Table 4).

These data support the assumption that organic amendments can increase both the water holding capacity and the amount of water available for plants (matric potential range between pF 2 and 4.2) in the soil (Epstein et al., 1976). There has been some controversy in this respect, however, since several authors (Gupta et al., 1977; Khaleel et al., 1981) reported that the increase in water holding capacity after the organic amendment shows a similar magnitude along the whole moisture characteristic curve. This would mean that the amount of water available for plants does not really change after the amendment. Our data showed that, at least in the mechanical terraces, the addition of USR slightly increased the amount of water held by the soil between pF 2 and 4.2 (Fig. 1), thus increasing water availability for plants. Although this increment was modest, it should not be underrated, since water is the main limiting factor for the biological productivity of soils in semiarid environments. Moreover, plant species adapted to arid environments are probably able to take up soil moisture below the matric potential limit (pF 4.2) commonly considered as permanent wilting point (Marshall and Holmes, 1988).

We conclude that the addition of USR not only increased fertility levels (Querejeta et al., 1998) and reactivated the soil microbiota (Roldán et al., 1996b; Garcia et al., 1998), but also improved the physical properties of the terraced soils. This improvement was greater in the mechanical terraces than in the manual terraces, in part due to the different USR incorporation techniques used. Alternatively, the significantly greater availability of water in the mechanical terraces with USR (Table 5) favored the proliferation of soil microbial populations and the recolonization of the terraced slope by spontaneous vegetation (Fig. 2). Soil microorganisms can excrete cementing polysacharides and can act as binding agents of mineral particles, thus enhancing aggregation and improving soil structure (Roldán et al., 1994). In our experiment, the proliferation of microorganisms after the addition of the USR (Roldán et al., 1996b) improved the infiltration and the water holding capacities of the terraced soil, which in turn facilitated plant establishment and growth. The accumulation of litter and the production of root exudates in the plant rizosphere further stimulated the development of the soil microbiota, to the advantage of the soil structure (García et al., 1998). Due to the greater availability of water in the mechanical terraces, the addition of USR triggered a positive feedback process during which the physical properties of the soil improved through time. In the manual terraces, the incorporation of USR also improved physical properties, but this beneficial effect was limited to the small volume of soil inside the planting holes of the pine. Moreover, the ineffectiveness of

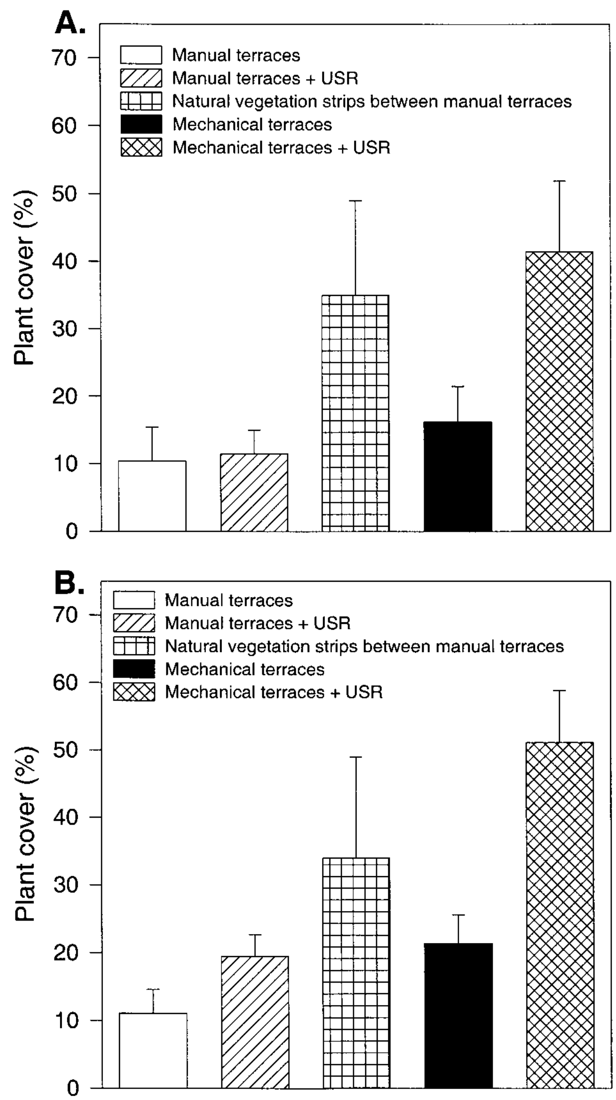

Fig. 2. Percentages of plant cover (including spontaneous recolonizing vegetation) in the different treatment combinations during April. Each value is the mean of eight replicates. Bars represent the standard error of the mean. (A) Spring 1995. (B) Spring 1996. USR is urban solid refuse.

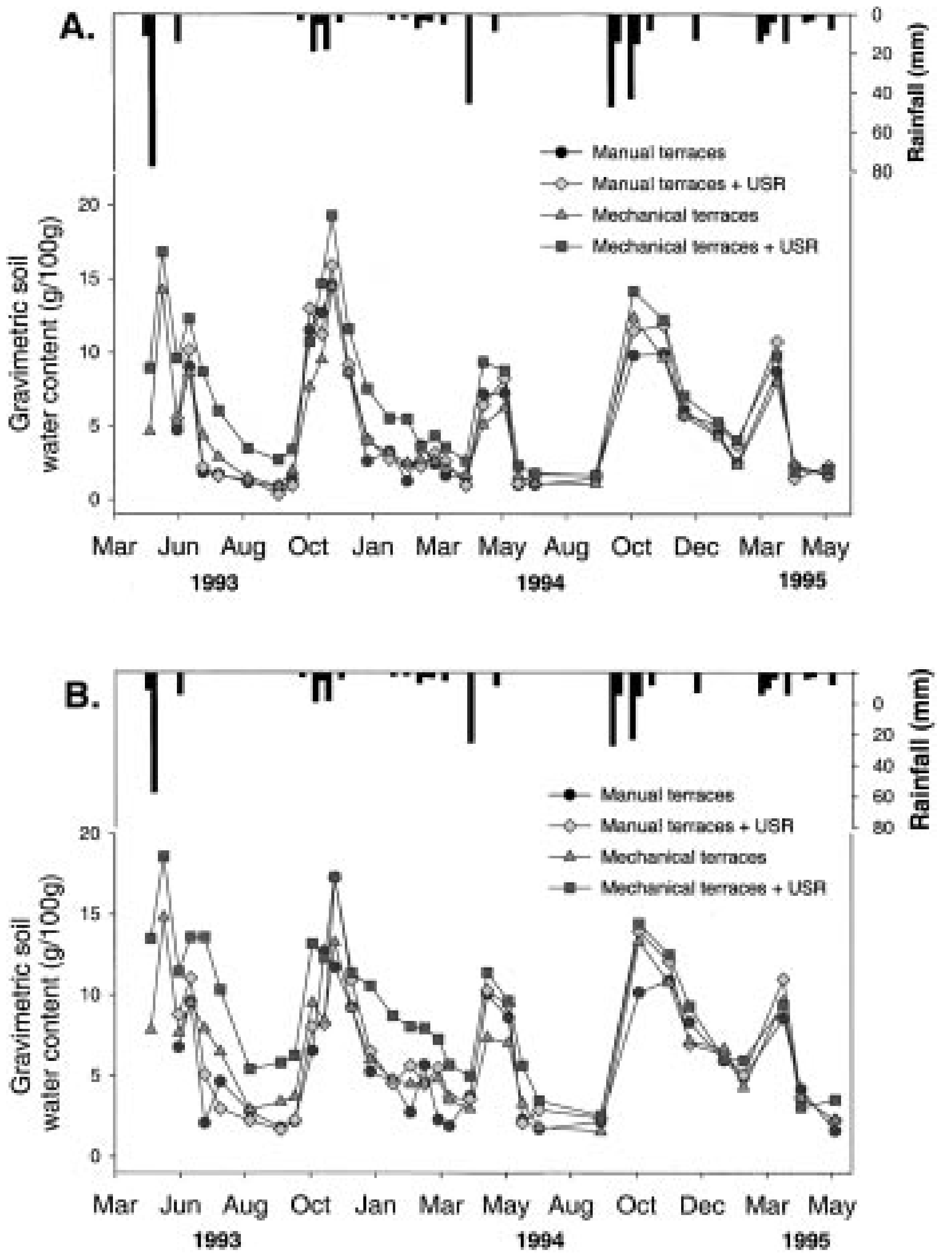

Fig. 3. Two-year evolution of gravimetric soil water content in the surface soil layer of the different treatment combinations. Each value is the mean of 10 replicates (two per replication block). (A) 0–10 cm depth. (B) 10–20 cm depth. USR is urban solid refuse.

the manual terraces at increasing water availability impeded the full development of those biological processes that fostered the effect of the USR amendment in the mechanically terraced soils.

Evolution of the Surface Soil Water Content

The water content of the 0- to 20-cm surface soil (Fig. 3) was significantly higher in the mechanical terraces with USR than in the rest of the treatment combinations (Wilcoxon signed rank test, $P < 0.001$). Both mechanical terracing and USR addition tended to increase soil water content (Table 3). The combination of mechanical terracing and USR had a synergistic positive effect on soil moisture during the first year of the gravimetric record (significant USR $\times$ terracing interaction, Table 3). Surface soil water content in the manual terraces with USR was also greater than in the manual terraces without organic amendment (Wilcoxon signed rank test, $P < 0.05$).

Table 5 shows the average soil water contents in the different treatment combinations during a period of 2 yr. The mean value in the 0- to 10-cm depth of the mechanical terraces + USR was 48% higher than in the manual terraces without USR, 46% higher than in the mechanical terraces without USR, and 36% higher than in the manual terraces with USR. In the 10- to 20-cm depth, differences were 53, 39, and 37%, respectively. Disparities in soil water content between mechanical terracing with USR and the rest of the treatments were greater during dry periods (73–106%) than during wet periods (23–50%). The manual terraces without organic amendment showed the lowest surface soil water content; in the manual terraces with USR, the average value was 8.5% higher at the 0- to 10-cm layer, and 11% higher at the 10- to 20-cm layer. However, this increment was smaller than in the mechanical terraces, probably due to the superior effectiveness of mechanical terracing in preventing runoff and in enhancing water infiltration into the soil.

Differences among treatment combinations tended to decrease about the end of the gravimetric record, perhaps due to the intense drought of 1994 and 1995 (total annual precipitation of 212 and 102.5 mm, respectively). Under such a severe drought, the water stored in the surface soil was most likely exhausted by plant consumption and direct evaporation in all the treatment combinations, irrespective of the initial differences among them. During the second year, only the USR factor showed a significant ($P = 0.061$) effect on soil water content (Table 3).

Moisture Depletion Rate

After a rainfall event of 56 mm in November 1996, the volumetric moisture content of the soil was measured during a 16-d period at two depths, 0 to 15 and 0 to 30 cm. Our primary goals were to obtain drying curves for each of the different treatment combinations and to check whether the positive effect of the USR on the water content of the surface soil still remained 4 yr after the amendment. Soil water content at the 0- to 15-cm depth was significantly greater in the mechanical terraces with USR than in the other treatment combinations (Fig. 4). The day after the rainfall event, when the soil was wettest, this difference was between 28 and 48%, and increased to 67 to 72% as the soil dried. In the manual terraces with USR, the values recorded 1 d after the rainfall event were 13.5% higher than in the manual terraces without amendment, but this difference decreased to 3% at the end of the drying period. The soil water content in the manual terraces without USR was always the lowest. In the 0- to 30-cm layer, the mechanical terraces with USR also showed the highest soil water content (Fig. 4); however, differences were smaller than those recorded at the 0- to 15-cm depth. No significant differences between manual terraces with and without USR were found at this depth. Therefore, TDR data confirmed that differences among treatment combinations still persisted 4 yr after the organic amendment, showing a pattern very similar to that obtained previously by the gravimetric method. It seems that the decrease in differences among treatment combinations observed during the end of 1994 and the beginning of 1995 with regards to soil water content was temporary and attributable to the intense drought of this period. Differences appeared again after the reestablishment of the normal rainfall regime.

Homogeneity of slopes of the drying curves was tested to check for time × treatment interactions, taking time as a covariate (Snedecor and Cochran, 1989). Values of

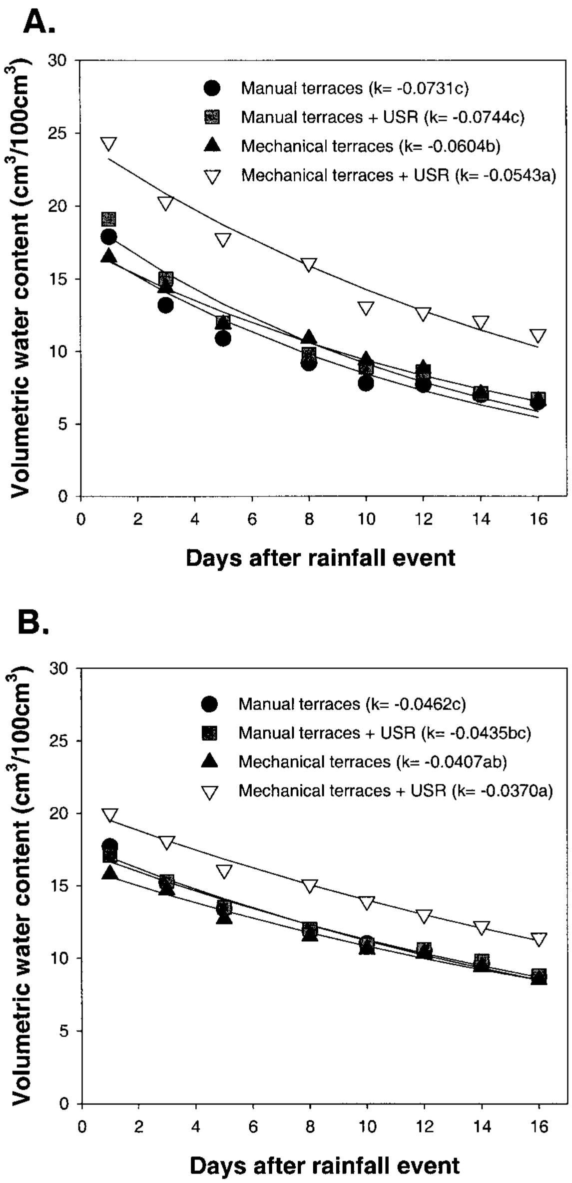

Fig. 4. Water depletion curves at two soil depths in the different land treatments after a rainfall event of 56 mm in November 1996. Measurements were made by time domain reflectometry. Each value is the mean of 10 replicates. Values of *k* (water depletion rate constants) followed by the same letter are not significantly different according to homogeneity of slopes test. (A) 0–15 cm depth. (B) 0–30 cm depth. USR is urban solid refuse.

K indicated that the moisture depletion rate of the surface soil was significantly lower in the mechanical terraces with USR than in the rest of the treatment combinations during the period following the rainfall (Fig. 4). This difference was greater in the 0- to 15-cm layer than in the 0- to 30-cm layer, suggesting that it was related to the organic amendment that had been incorporated into the surface soil. The plant cover in the mechanical terraces with USR was much denser than in the rest of the treatment combinations by the time TDR measurements were made (Fig. 2), so this result seems paradoxical, as soil moisture depletion rate was expected to increase due to greater plant evapotranspiration. According to Marshall and Holmes (1988), land prepara-

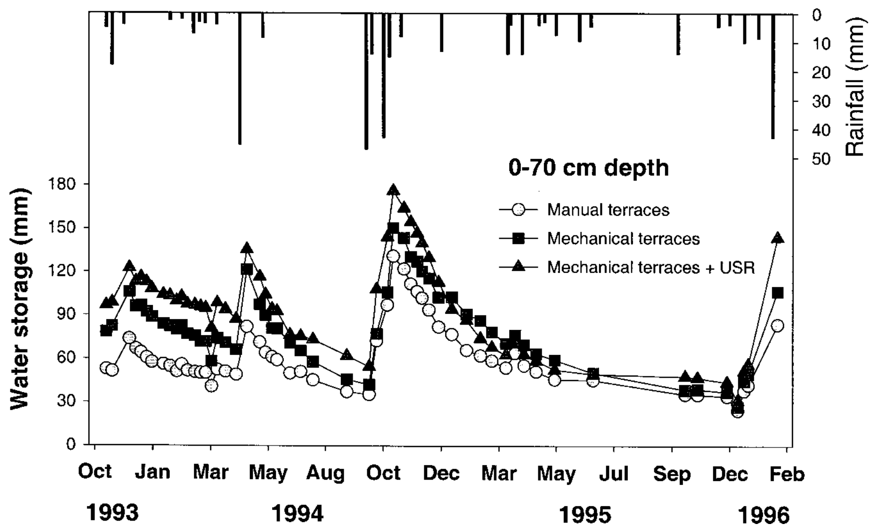

Fig. 5. Evolution of water storage into the 0- to 70-cm soil layer in the different treatment combinations. Each value is the mean of at least 6 replicates. Measurements were made by the neutron probe method during a 28-mo period. Values corresponding with the manual terraces with and without USR were grouped together due to the small number of replicates in these treatment combinations. USR is urban solid refuse.

tion methods that create a surface layer of loose soil favor moisture conservation in the soil profile. The transfer of liquid water by capillarity from deeper horizons through this superficial layer decreases sharply, resulting in diminished moisture loss by direct evaporation from the soil surface, since water stored in the deeper horizons can then be transferred through this superficial layer only in the form of vapor. In the mechanical terraces with USR, the organic amendment incorporation into the soil by means of rotovator tilling created a very loose and porous surface horizon, thus enhancing moisture conservation in the soil profile.

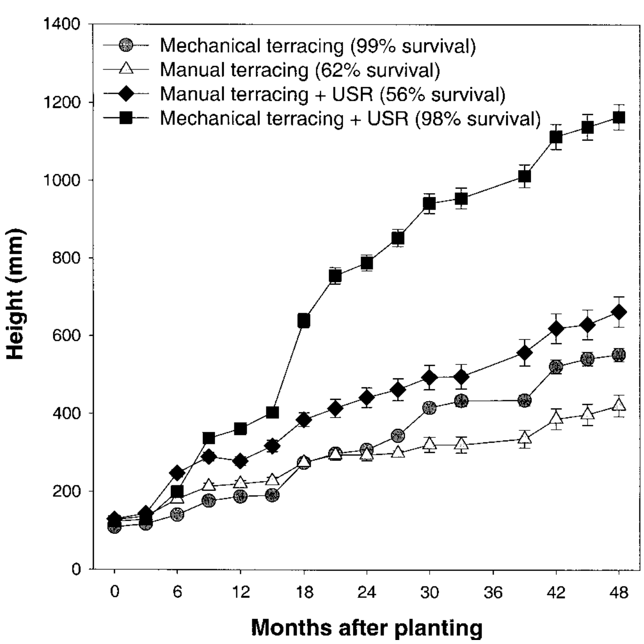

Fig. 6. Survival and growth of the *Pinus halepensis* seedlings during a 4-yr period in the different treatment combinations. Each height value is the mean of at least 75 seedlings. Bars represent the standard error of the mean. USR is urban solid refuse.

Water Storage in the Soil Profile

Water availability in the surface 70 cm of the soil profile in the mechanical terraces was always greater than in the manual terraces (Fig. 5; Wilcoxon signed rank test, $P < 0.001$). Neutron probe data confirmed that mechanical terracing controlled runoff, favored infiltration, and increased water storage in the soil profile more effectively than manual terracing. These positive effects of mechanical terracing occurred despite displacement of the top layer of the soil profile (the richest in organic matter and biological activity) and mixing of different horizons, thus degrading most physical properties.

Manual terracing also changed the physical properties of the soil, but less intensely since it involved only a few centimeters of the surface soil. This soil preparation method showed the important advantage of its low visual impact on the landscape: the topography of the slope hardly changed and strips of unaltered vegetation remained between manual terraces. However, this technique was not effective in preventing runoff water losses from the slope and consequently did not improve soil water availability. Manual terracing did not decrease soil penetration resistance and probably did not enhance deep rooting, which is essential for water uptake by plants during drought in semiarid environments (Talsma and Gardner, 1986). This explains the low survival percentage and the slow growth rate of the pine seedlings in the manual terraces as compared with the mechanical terraces (Fig. 6).

The positive effect of the USR amendment on soil moisture content was greatest in combination with mechanical terracing, which again revealed a synergistic interaction between these two land preparation methods. The beneficial effect of the USR addition on soil moisture was not limited to the top soil horizon directly affected by it. Since USR addition improved not only the water holding capacity but also the permeability of the surface soil, rain water in the mechanical terraces could infiltrate rapidly into the deepest horizons where it was better protected from direct evaporation (Marshall and Holmes, 1988). The total amount of water stored in the surface 70 cm of the soil profile in the mechanical terraces with USR (Fig. 5) was up to 35% higher than in the mechanical terraces without USR during wet intervals (January 1996), and up to 40% higher during dry periods (September 1994). As a result, the pine seedlings grew significantly faster in the mechanical terraces with USR than in the other treatment combinations (Fig. 6; significant terracing × USR interaction for seedling growth, Table 3), since water is the main limiting factor for plant development in semiarid environments.

The neutron probe data show that differences among treatment combinations in soil moisture tended to decrease through time (Fig. 5). This may be explained by the dissimilar development of the plant cover in the four treatment combinations. In the mechanical terraces with USR, where water availability was greatest during the early stages of the experiment, the subsequent greater development of the vegetation (Fig. 2 and 6) progressively depleted the surplus soil moisture that initially existed there. This trend was probably accentuated by the drought, since differences in soil water content among treatment combinations reappeared when significant rain occurred again at the end of the record (December 1995 and January 1996). As a matter of fact, it was precisely in January 1996 that differences in water storage between the mechanical terraces with USR and the rest of the treatment combinations reached a maximum (Fig. 5). Therefore, neutron probe data seem to confirm that the beneficial effect of USR addition on the water storage capacity of the soil profile in the mechanical terraces persisted through time.

CONCLUSIONS

Mechanical terracing with subsoiling enhanced water storage in the soil profile and decreased soil penetration resistance more effectively than manual terracing. The addition of USR not only offset to a great extent many of the negative effects of mechanical terracing on the physical properties of the soil, but also boosted the hydrological benefits of this site preparation method. The structure, permeability, and water holding capacity of the mechanically terraced soils substantially improved with the organic amendment, thus favoring water storage and moisture conservation into the soil profile. The beneficial effect of the USR addition on soil moisture in the mechanical terraces persisted and was not limited to the surface soil layer.

The combination of mechanical terracing with subsoiling and USR addition proved to be an effective site preparation method for the afforestation of a semiarid area. It can improve the survival and growth of *Pinus halepensis* and foster recolonization by spontaneous vegetation even under severe drought conditions. This combined technique could be particularly suitable for the afforestation of abandoned agricultural land, where the negative effects of mechanical terracing on the plant cover and on the physical and biological properties of the soil would be minimal.

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REFERENCES

Albaladejo, J. 1990. Impact of the degradation processes on soil quality in arid mediterranean environment. p. 193–215. *In* J.L. Rubio and J. Rickson (ed.) Strategies to combat desertification in Mediterranean Europe. Comision of the European Communities, Luxembourg.

Barber, R.G., and D. Romero. 1994. Effects of bulldozer and chain clearing on soil properties and crop yields. Soil Sci. Soc. Am. J. 58:1768–1775.

Clothier, B.E., and I. White. 1981. Measurements of sorptivity and soil water diffusivity in the field. Soil Sci. Soc. Am. J. 45:241–245.

Dent, D., and R. Murtland. 1990. Land evaluation for afforestation in a semi-arid environment: The montane plains of the central highland of North Yemen. Catena. 17:509–523.

Díaz, E. 1992. Efecto de la adición de residuos urbanos en la regeneración de suelos degradados como medio de control de la desertificación. Tesis doctoral. Universidad de Murcia, Spain.

Díaz, E., A. Roldán, A. Lax, and J. Albaladejo. 1994. Formation of stable aggregates in a degraded soil by amendment with urban refuse and peat. Geoderma 63:277–288.

El-Tayeb, O.M. 1989. Organic matter and soil microbiology in arid land rehabilitation. Special Issue. Arid Soil Res. Rehab.Vol. 3, no. 2. Taylor & Francis, Philadelphia, PA.

Epstein, E., J.M. Taylor and R.L. Chaney. 1976. Effects of sewage sludge and sludge compost applied to soil on some soil physical and chemical properties. J. Environ. Qual. 5:422–425.

Finkel, H.J. 1986. Engineering measures for soil and water conservation: Terracing and benching. p. 85–91. *In* H.J. Finkel (ed.) Semiarid soil and water conservation. CRC Press, Boca Raton, FL.

Garcia, C., T. Hernandez, J. Albaladejo, V. Castillo, and A. Roldán. 1998. Revegetation in semiarid zones: Influence of terracing and organic refuse on microbial activity. Soil Sci. Soc. Am. J. 62: 670–676.

Greacen, E.L. 1981. Soil water assessment by the neutron method. CSIRO, Collingwood, Australia.

Gupta, S.C., R.H. Dowdy, and W.E. Larson. 1977. Hydraulic and thermal properties of a sandy soil as influenced by incorporation of sewage sludge. Soil Sci. Soc. Am. J. 41:601–605.

Kessler, J., and R.J. Oosterbaan. 1980. Determining hydraulic conductivity of soils. p. 253–296. *In* Drainage principles and applications. Vol. III. ILRI, Wageningen, the Netherlands.

Khaleel, R., K.R. Redy, and M.R. Overcash. 1981. Changes in soil properties due to organic waste applications: A review. J. Environ. Qual. 10:133–141.

Marshall, T.J., and J.W. Holmes. 1988. Soil physics. Cambridge Univ. Press, Cambridge, UK.

Martínez, J. 1992. Variabilidad espacial de las propiedades físicas e hídricas de los suelos en medio semiárido Mediterráneo. Cuenca de la Rambla de Perea. Murcia. Tesis doctoral. Universidad de Murcia, Spain.

Page, A.L., R.H. Miller, and O.R. Keeny. 1982. Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Querejeta, I., A. Roldán, J. Albaladejo, and V. Castillo. 1998. The role of mycorrhizae, site preparation and organic amendment in the afforestation of a semiarid mediterranean site with *Pinus halepensis*. For. Sci. 44:203–211.

Roldán, A., F. García-Orenes, and J. Albaladejo. 1994. An incubation experiment to determine factors involving aggregation changes in an arid soil receiving urban refuse. Soil Biol. Biochem. 26: 1699–1707.

Roldán, A., I. Querejeta, J. Albaladejo, and V. Castillo. 1996a. Survival and growth of *Pinus halepensis* Miller seedlings in a semiarid environment after forest soil transfer, terracing and organic amendments. Ann. Sci. For. 53:1099–1112.

Roldán, A., I. Querejeta, J. Albaladejo, and V. Castillo. 1996b. Growth response of *Pinus halepensis* to inoculation with *Pisolithus arhizus* in a terraced rangeland amended with urban refuse. Plant Soil 179:35–43.

Serrada, R. 1990. Consideraciones sobre el impacto de la repoblación forestal en el suelo. Ecología 1:453–462.

Snedecor, G.W., and W.G. Cochran. 1989. Statistical methods. 8th ed. Iowa State Univ. Press, Ames.

Soil Survey Staff. 1996. Keys to soil taxonomy. 7th ed. Pocahontas Press, Blacksburg, VA.

Sutikto, T., and K. Chikamori. 1993. Evaluation of Philip's infiltration equation for cultivated upland terraces in Indonesia. J. Hydrol. 143:279–295.

Talsma, T., and E.A. Gardner. 1986. Soil water extraction by a mixed eucalypt forest during a drought period. Aust. J. Soil Res. 24:25–32.

Ting, J.C., and M. Chang. 1985. Soil moisture depletion under three southern pine plantations in East Texas. For. Ecol. Manage. 12:179–193.

Topp, C.G., and J.L. Davis. 1985. Measurement of soil water content using time-domain reflectometry (TDR): A field evaluation. Soil Sci. Soc. Am. J. 49:19–24.

Williams, A., J.L. Ternan, A. Elmes, M. González del Tánago, and R. Blanco. 1995. A field study of the influence of land management and soil properties on runoff and soil loss in Central Spain. Environ. Monit. Assess. 37:333–345.

Zegelin, S.J., I. White, and G.F. Russell. 1992. A critique of the time domain reflectometry technique for determining field soil-water content. p. 187–208. *In* G.D. Topp et al. (ed.) properties: Bringing theory into practice. SSSA Spec. Publ. 30. SSSA, Madison, WI.

Tillage and Saline Irrigation Effects on Water and Salt Distribution in a Sloping Field

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ABSTRACT

Application of saline water using moving irrigation systems (MIS) can affect the water and salt distribution in the field and the crop yield because of runoff formation. The objective of this study was to determine the effects of tillage and water application methods on the distributions of water content, salt concentration in soil, and corn (*Zea mays* L.) yield under irrigation with saline water by MIS. The experimental site was located in a forage corn field in the Negev, Israel. Three tillage treatments were studied: (i) conventional tillage (control); (ii) microbasin; and (iii) diked furrows (dike). The control and the microbasin plots were irrigated with sprinkler MIS, and the dike plots with flooding MIS. The studied parameters were measured in five sampling sites located 25 m apart along the slope. The average dry canopy yields of the whole slope in the control, dike, and microbasin treatments were 21.7, 25.3, and 30.6 Mg ha^{-1}, respectively, and their coefficient of variance (CV) values along the slope were 7.9, 5.7, and 3.5%, respectively. In the control treatment, soil water content increased from 0.12 kg kg^{-1} upslope to 0.19.0 kg kg^{-1} downslope. In contrast, no slope effect on soil water content was found in the microbasin and dike treatments. The electrical conductivity (EC) of the 0- to 0.3-m soil layer in the control treatment increased in the downslope direction from 2.0 to 4.0 dS m^{-1}. Conversely, in the microbasin and dike treatments, no consistent trend of the EC was observed with slope, and their average values were 3.4 and 7.0 dS m^{-1}, respectively. It was suggested that these yield differences were related to the differences in the distribution of the soil water content and the salt concentration in soil within the field.

Providing an optimal environment in the root zone in a cultivated field is an important goal of agricultural practices, essential for achieving a high crop yield. Soil tillage and irrigation methods could affect the water and salt regime in the root zone and their uniform distribution within the irrigated field, and all these could have significant effects on crop yield (Bielorai et al., 1978; Letey et al., 1984; Warrick and Gardner, 1983).

Moving irrigation systems have become increasingly popular in recent years (Anonymous, 1993). However, an MIS is designed to apply given amounts of water within relatively short periods; therefore, it is characterized by a relatively high instantaneous rate of water application (Gilley and Mielke, 1980). When the water application rate exceeds the soil infiltration rate, runoff will occur. For example, toward the outer end of a 53-ha center-pivot, Addink (1975) found runoff values as high as 65% of the applied water on a very fine sandy soil. Likewise, Beh-Hur (1994) found that under irrigation with MIS (average application rate of ≈100 mm h^{-1}), the runoff percentage of irrigation water from 3 by 5 m plots in cotton (*Gossypium hirsatum* L.), corn, and peanut (*Arachis hypogaea* L.) fields was ≈40% and in potato (*Solanum tuberosum* L.) field ≈60%.

According to the field characteristics (slope and soil surface roughness), the runoff may flow out of the field and/or accumulate in small depressions within the field. Runoff from a cultivated field is usually lost to crop production, and it accelerates soil erosion and fertilizer depletion. Local runoff within the field leads to nonuniform water distribution and reduces irrigation efficiency and crop yield significantly (Letey et al., 1984; Ben-Hur et al., 1995).

The runoff potential under irrigation with MIS is especially high in soils that are characterized by low permeability (Kincaid et al., 1969). Ben-Hur et al. (1989) indicated that seal formation at the soil surface during irrigation with sprinkler MIS is the main cause for the reduction of soil permeability in a semiarid region.

Soil tillage practices, such as microbasins (pitting) and dikes across the furrows, increase the surface storage capacity of the field, which in turn decreases runoff formation within the field. Morin et al. (1984) observed that these practices increased the surface storage in a

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Abbreviations: CV, coefficient of variance; EC, electrical conductivity; LEPAS, low-energy precision application socks; MIS, moving irrigation system; SAR, Na adsorption ratio.