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Soil water availability improved by site preparation in a *Pinus halepensis* afforestation under semiarid climate

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Abstract

An afforestation experiment with the drought resistant species *Pinus halepensis* Miller was conducted in a degraded semiarid rangeland of southeastern Spain to evaluate the influence of site preparation on soil moisture and seedling performance. Three different land preparation treatments were tested: manual terracing, mechanical terracing and mechanical terracing with organic amendment addition. Mechanical terracing (+/− organic amendment) always included subsoiling. Soil moisture to a depth of 1 m was monitored by the neutron scattering method during a 28-month-period. The study revealed significant differences among land treatments with respect to soil moisture content and water uptake by the seedlings. Mechanical terracing increased soil water storage up to 40% more effectively than manual terracing. Analysis of moisture depletion rates at different soil depths indicated that seedling access to the water stored into the deeper layers of the profile was constrained by high soil penetration resistance in the manual terraces. As a result of limited water availability, seedling survival after the dry summers of 1994 and 1995 was only 62% in this treatment (98% in the mechanical terraces). The addition of urban solid refuse (USR) further increased the water reserve in the mechanically terraced soils (up to 40%), due to enhanced water infiltration and diminished evaporation from the soil surface. Early root penetration to the deeper and wetter layers of the profile also contributed to increased water availability for the seedlings in the mechanical terraces+USR. Two years after planting, only the seedlings in this treatment were able to deplete homogeneously the moisture stored into the soil profile to a depth of 1 m. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Terracing; Organic amendment; Subsoiling; Soil water content.

1. Introduction

Dryland environments are by definition characterized by limited water availability and periods of pronounced moisture stress. Scarcity of water as a resource not only results from low annual precipitation and high potential evapotranspiration, but also from large temporal variability and unpredictability of rainfall events (Boer, 1999).

Soil attributes may reinforce or compensate temporal variation in precipitation by their effect on the partitioning of water in runoff, storage and evaporation. Dryland soils are often poorly developed, shallow, excessively stony, and poor in organic matter (Klemmedson, 1989). These characteristics tend to limit the moisture storage capacity of the soil profile.

According to several authors, the biological potential of the soil in semiarid environments can be described in terms of site water balance (Noy-Meir,

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1973; Fischer and Turner, 1978; Woodward, 1987). Primary production depends on plant available moisture, and more specifically on the importance of transpiration relative to other losses in the soil water budget. High vegetation densities can only be found in sites where soil properties allow a high proportion of the local rainfall to be retained as plant available soil moisture.

Land degradation in semiarid environments usually involves a worsening of soil physical–chemical properties and a shift in the relative importance of the local water balance components; runoff and evaporation losses tend to increase, while moisture storage in the soil profile decreases (Albaladejo, 1990; Boer, 1999). Plant cover elimination or deterioration is nearly always the origin of land degradation (Francis and Thornes, 1990), so revegetation is the best management practice for the control and eventual reversal of this process. Successful revegetation of degraded semiarid areas often requires the prior improvement of the local water budget through site preparation techniques such as contour terracing. The main objective of hillslope terracing is to increase water availability by reducing runoff losses and increasing the potential infiltration capacity of the soil (Serrada, 1990). Mechanical terracing has been the most widely used afforestation land preparation method in Spain during the last decades, and it always includes subsoiling as a standard practice. Manual terracing is an alternative technique that causes a comparatively minor disturbance in the plant cover and the soil profile.

The incorporation of certain organic amendments can exert a positive effect on the local water balance of the soil. Materials rich in carbon compounds easily decomposible by soil microorganisms can raise fertility levels, stimulate soil aggregate formation and stabilization, decrease bulk density, enhance hydraulic permeability and increase water holding capacity (Khaleel et al., 1981; Glaub and Gouleke, 1989; Díaz et al., 1994). These improvements can be particularly useful in terraced slopes, where the structure and the nutrient concentration of the soil are negatively affected by land preparation works. The combination of terracing and organic amendment addition might, therefore, represent a useful site preparation method in areas where the scarcity of moisture conditions revegetation success.

In order to evaluate the effectiveness of several site preparation techniques, an afforestation experiment with the drought resistant species *Pinus halepensis* Miller was established in 1992 in a degraded semiarid range of southeastern Spain. The results obtained relative to growth, survival and mycorrhizal status of the pine seedlings have been presented and discussed in previous articles (Roldan et al., 1996a,b; Querejeta et al., 1998). This paper concentrates on the role that terracing and USR addition played on water availability and on soil moisture depletion rates during the early stages of seedling development.

2. Materials and methods

2.1. Field site description

The study was conducted in El Aguilucho experimental area (coordinates 37°53′N and 1°15′W, 180 m above sea level) on 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 semi-arid 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 per year. The topography of the area is shaped

Table 1
Characteristics of the unaltered surface soil (0–10 cm) in the experimental area

Organic matter (%)	2.6
Total N (g kg^{-1})	1.1
Available P (mg kg^{-1})	16
Exchangeable K (cmol kg^{-1})	0.3
Coarse sand (%)	40.9
Fine sand (%)	24.1
Silt (%)	30.4
Clay (%)	4.6
Bulk density (g cm^{-3})	1.45
Volumetric water content at matric potential −50 kPa (%)	24.6
Volumetric water content at matric potential −1500 kPa (%)	10.9
Saturated hydraulic conductivity (cm h^{-1})	19
Aggregate stability (%)	71.6

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 *Pinus halepensis*; the most common plant species are *Rosmarinus officinalis* L., *Anthyllis cytisoides* L., *Thymus* sp., *Helianthemum* sp. and *Fumana* sp.

2.2. Experimental design and layout

Three different site preparation methods were tested: manual terracing, mechanical terracing and mechanical terracing with organic amendment. The experiment was a randomized complete block design laid off in five blocks.

The experimental area of 120 m×35 m was established on a homogeneous hillslope (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 with subsoiling was carried out in June 1992; terraces 4 m wide and 60 m long were excavated by a bulldozer. The thick subsoil lime crust existing in these terraces was broken by deep plowing along the planting line, using a single tooth subsoiler mounted at the rear of the bulldozer. Manual terracing created terraces 0.5 m wide and 60 m long with strips of natural vegetation between adjacent terraces. Both the manual terracing and the subsequent pitting of the planting holes were done by ordinary handhoes. Unlike mechanical terracing, manual terracing did not include subsoiling.

Each block included one mechanical terrace and one manual terrace located next to each other at the same level of the hillslope. Each mechanical terrace was further split across the slope into two sections, one with and one without organic amendment addition. The organic amendment used was urban solid refuse (USR). The USR was a solid fresh material, neither composted nor ground but allowed to mature naturally for 15 days. The refuse was supplied by the Murcia Municipal Treatment Plant; analytical characteristics of the USR determined by standard methods (Page et al., 1982) are shown in Table 2. The refuse was applied in a single addition at the beginning of the experiment in October 1992. The application rate used was 10 kg m^{-2}. Previous studies had demonstrated that this application rate is sufficient to improve the physical–chemical and biological characteristics of the soil, while higher rates may give rise to the appearance of phytotoxicity or salinity problems (Díaz, 1992). The USR was incorporated into the top 30 cm of the soil of the mechanical terraces by rotovator tilling.

Table 2
Analytical characteristics 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
N (NO_3^{-2}) (g kg^{-1})	8.7
N (NH_4^+) (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

During November 1992, *Pinus halepensis* seedlings were planted manually in a single row per terrace with a stocking rate of 1800 pines ha^{-1}.

The experiment was conducted under strictly natural conditions, without any watering or weeding treatments.

2.3. Sampling and laboratory procedures

In order to determine soil organic matter and nutrient contents, 20 soil samples were taken from the 0–20 cm layer in each land treatment. Total organic C and total N were assessed by pre-treatment with HCl to eliminate carbonates, followed by combustion at 1020°C and determination in an automatic C and N analyzer. Available P was extracted with sodium bicarbonate (Olsen et al., 1954) and determined by colorimetry according to Murphy and Riley (1962).

Ammonium acetate-extractable K was determined by flame photometry (Schollemberger and Simon, 1954).

Fifteen cores of unaltered soil per land treatment were taken using steel cylindrical rings 5 cm in diameter to estimate bulk density, water holding capacity and saturated hydraulic conductivity. Soil water holding capacity was determined using the Richard's pressure membrane method (Martínez Fernández, 1992). Saturated hydraulic conductivity was determined using a constant head permeameter (Kessler and Oosterbaan, 1980). Bulk density was calculated after determination of the stove dried mass (105°, 24 h) of these soil cores of known volume.

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

The infiltration capacity of the soil was measured in the field by means of a single ring infiltrometer 30 cm in both diameter and height. Ten infiltration runs were carried out in each of the land treatments. All of them 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 the infiltration data using the Philip's infiltration model (Sutikto and Chikamori, 1993).

Soil penetration resistance to a depth of 60 cm was measured using a Stiboka penetrograph.

The moisture content of the soil profile was assessed by the neutron scattering method. In October 1993, 24 aluminium access tubes for neutron probe were installed to a depth of 60–90 cm, depending on the rock content of the soil profile. Soil moisture at 30, 40, 50, 60, and 70 cm deep was monitored for 2 years by means of an Americium–Berilium neutron probe (Troxler, Research Triangle, NC, USA). At 60 and 70 cm depths, measurements were made in the mechanical terraces only, because the high penetration resistance and high rock content of the soil in the manual terraces impeded the installation of the access tubes to these depths. The calibration of the neutron probe was accomplished using three lysimeters filled with soil from the experimental area that had been obtained during the land preparation works. Volumetric soil moisture in each lysimeter was estimated from gravimetric and bulk density data. A linear fit model between neutron probe readings and volumetric soil moisture was developed following the recommendations of Greacen (1981). When transforming neutron probe readings into volumetric moisture values, differences in soil bulk density between the lysimeters and the different layers of the soil profile in each land treatment were taken into account.

Root density in the rhizosphere of the seedlings between 0 and 20 cm deep was assessed during October 1996. Fifteen unaltered soil samples of 300 ml of volume were taken from the planting holes of the pines in each land treatment. All the pine roots in each soil sample were carefully separated in the laboratory, and their dry weight (105°, 5 h) was determined.

2.4. *Statistical analysis*

Soil physical–chemical data were subjected to analysis of variance, and comparisons among treatment means were made using Tukey's multiple range test. Effects of treatments on measured variables were tested for significance at the 0.05 level of confidence. Soil moisture record series corresponding to the different soil treatments were compared using the Wilcoxon signed rank test. Soil moisture depletion rates were compared both among treatments and within treatments by analysis of covariance.

3. Results and discussion

3.1. *Soil water content*

The results obtained by means of the neutron probe method showed that mechanical terracing controlled runoff, favored infiltration and increased the soil water reserve more effectively than manual terracing. Fig. 1 shows the evolution of the total amount of water stored within the surface 70 cm of the soil profile in the different land treatments. Soil water content in the mechanical terraces was always higher than in the manual terraces (Wilcoxon signed rank test, $P<0.001$).

Mechanical terracing displaced the top layer of the soil profile (rich in nutrients, organic matter and microbiological activity) and mixed up its different horizons, thus, worsening most of the physical–chemical properties of the substrate. The mechanical terraces without USR showed the lowest levels of fertility, organic matter content and aggregate stability

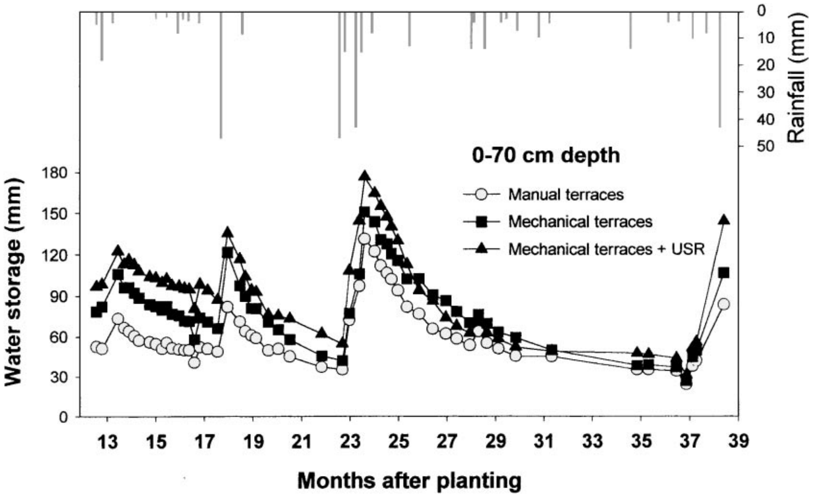

Fig. 1. Temporal evolution of soil water storage within the 0–70 cm soil layer in the different land treatments tested. Measurements were made by the neutron probe method during a 28-month-period.

of all the treatments (Table 3). However, terrain-driven concentration of surface water in the mechanically terraced hillslope significantly increased the recharge of the deep soil layers and the total water store in the profile (Fig. 1). Moreover, subsoiling effectively decreased the penetration resistance of the soil in the mechanical terraces (Table 3).

Manual terracing also changed the physical properties of the soil, but less intensely, since it only involved a few cm of the surface soil and did not include subsoiling. Therefore, the concentrations of nutrients and organic matter or the percentage of stables aggregates did not decrease as sharply as in the mechanical terraces (Table 3). Manual terracing did not enhance deep soil recharge, and consequently did not improve the moisture content of the profile (Fig. 1). This site preparation method did not decrease soil penetration resistance either (Table 3).

The addition of USR not only increased fertility, but also ameliorated the physical properties of the mechanically terraced soil (Table 3). Organic matter content and nutrient concentrations were significantly

Table 3
Physical–chemical properties of the soil in the three land treatments evaluated[a]

	Manual terraces	Mechanical terraces	Mechanical terraces+USR
Organic matter (%)	1.68 b	1.03 a	2.28 c
Total N (g kg^{-1})	0.77 b	0.50 a	1.46 c
Available P (mg g^{-1})	5.1 b	2.0 a	45.9 c
Exchangeable K (cmol kg^{-1})	0.23 b	0.14 a	0.70 c
Bulk density (g cm^{-3})	1.45 a	1.55 a	1.22 b
Penetration resistance (N cm^{-2})	342 b	154 a	182 a
Sorptivity (cm min$^{-1/2}$)	0.74 a	1.24 b	6.50 c
Saturated hydraulic conductivity (cm h^{-1})	23.2 a	28.3 a	157.6 b
Volumetric water content at matric potential −50 kPa (%)	21.1 a	24.8 a	28.7 b
Volumetric water content at matric potential −1500 kPa (%)	9 a	8.6 a	10.5 b
Aggregate stability (%)	66.3 ab	55.8 a	70.4 b

[a] Each value is mean of at least 10 replicates. Values in rows followed by the same letter do not differ significantly ($P<0.05$) as determined by Tukey's test.

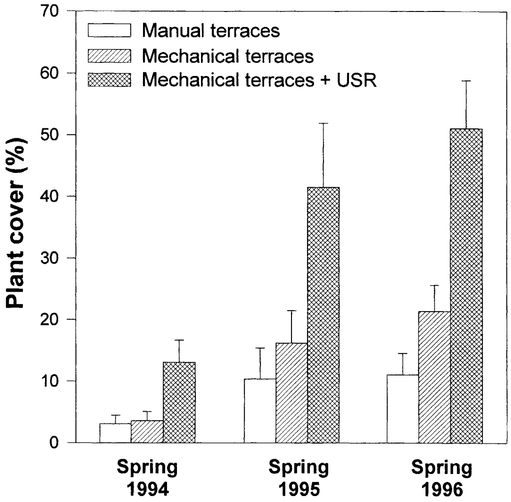

Fig. 2. Temporal evolution of plant cover (including spontaneous recolonizing vegetation) in the different land treatments. Each value is mean of eight replicates. Bars represent the standard error of the mean.

higher in the mechanical terraces+USR than in the rest of the treatments. The percentage of stable aggregates, the water holding capacity and the hydraulic permeability of the soil also increased after the addition of USR, which enhanced water infiltration and conservation into the profile (Fig. 1). As a result, soil water content in the mechanical terraces+USR was greater than in the rest of the treatments during most of the study period (Wilcoxon signed rank test, $P<0.05$), which favored the recolonization of the terraced slope by spontaneous vegetation (Fig. 2).

3.2. Moisture depletion rates

As shown by the neutron probe moisture record (Fig. 1), soil moisture depletion rates were clearly affected by land treatments. In order to study this aspect with more detail, three sections of the record (corresponding to the three periods of maximum water recharge of the soil profile, with their respective subsequent drying periods) were selected and analyzed. Data from weeks 55–70, 77–98 and 103–120 of the moisture record were used for this purpose. Drying curves adjusted to the experimental data were obtained by means of the following negative exponential model:

$$\mathrm{VWC} = \mathrm{VWC}_{\mathrm{init}}\,\mathrm{e}^{-kt}$$

where $\mathrm{VWC}_{\mathrm{init}}$ is the volumetric water content of the soil at the moment of maximum recharge after the rain, t the time elapsed since the moment of maximum recharge (in days), and k represents a soil water depletion rate (in per days) (Ting and Chang, 1985).

The fit of the drying curves thus obtained to the experimental data was quite good (70–99%) in all cases. The soil moisture depletion rates corresponding to the different land preparation treatments were compared by covariance analysis in order to detect any significant difference among them (results are shown in Figs. 3, 5 and 6). Within each treatment, water depletion rates at different soil depths were also compared by analysis of covariance (results are shown in Table 4).

3.2.1. First period

This period comprised the last part of the autumn of 1993 (1 year after seedling planting) and the winter of 1994. The rainfall of 27 mm were recorded during November, 0 mm during December, 2.5 mm during January, 12.5 mm during February, and 3.5 mm during the part of March considered.

Soil moisture depletion rates in the different land treatments were compared by analysis of covariance at each soil depth (Fig. 3). The moisture depletion rate in the topsoil of the mechanical terraces+USR was significantly lower than in the rest of the treatments. Taking into account that, by then, the seedlings were already greater and the spontaneous vegetation was more abundant in this land treatment than in the others (Figs. 2 and 4), this result may seem paradoxical. The moisture depletion rate would have been expected to increase due to greater plant transpiration in the mechanical terraces+USR. According to Marshall and Holmes (1988), land preparation methods that create a surface layer of loose soil favor moisture conservation, because the transfer of liquid water by capillarity from deeper horizons through this layer is sharply decreased. This reduction in the movement of water from the underlying soil to the surface puts a strong constraint on soil evaporation losses. In the mechanical terraces+USR, the organic amendment incorporation by means of rotovator tilling created a very loose and porous surface soil layer, thus, enhancing moisture conservation. Additionally, the higher density of the plant cover in this treatment must have diminished direct solar radiation on the soil surface

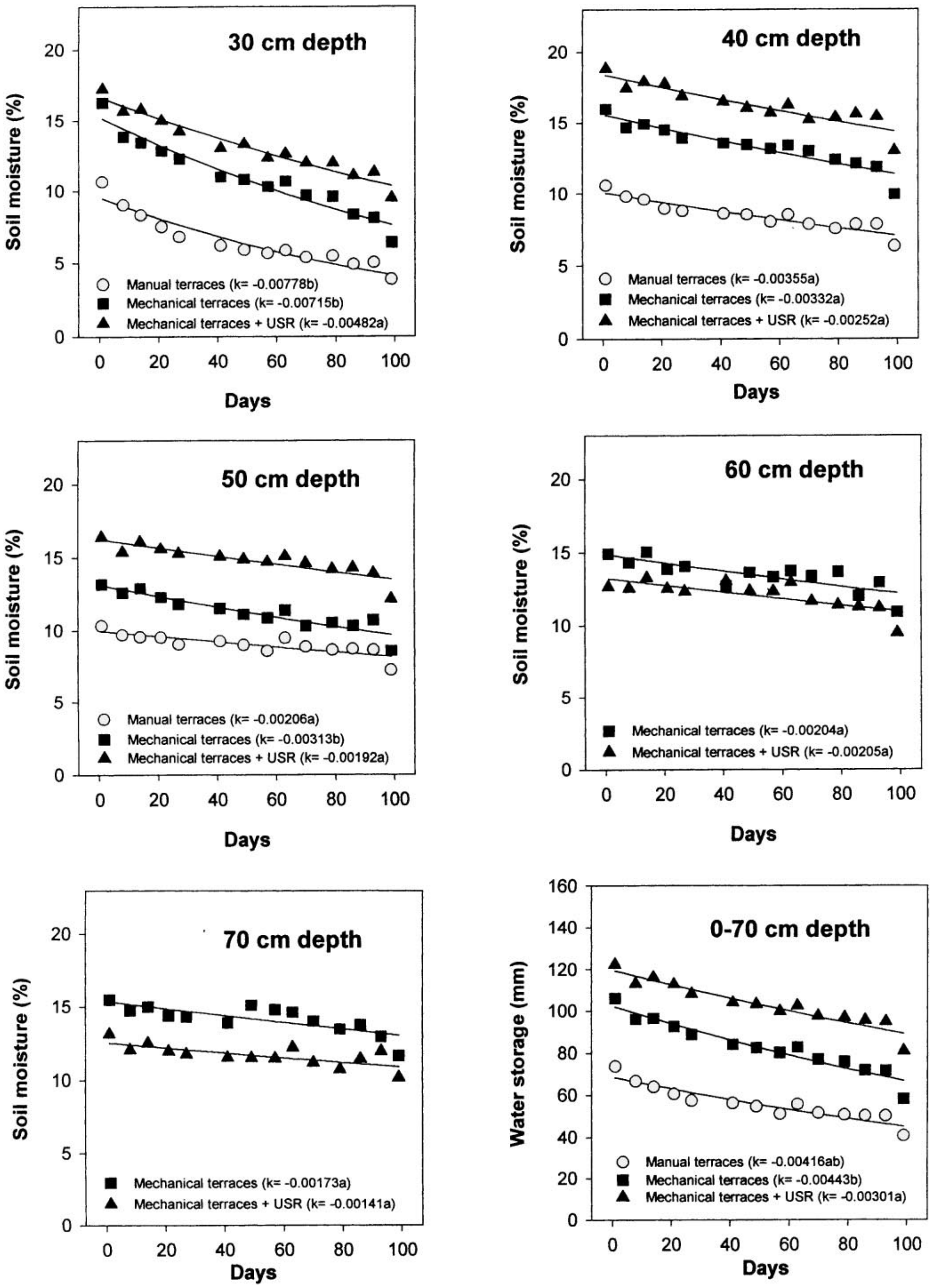

Fig. 3. Moisture depletion curves at five depths in the different land treatments. A graph showing the depletion curves of the total water store within the 0–70 cm layer of the profile is also included. Values of *k* represent moisture depletion rates. At each soil depth, *k* values in the different land treatments were compared using a covariance test. Values of *k* in the same graph sharing a letter do not differ significantly according to covariance test. Data correspond to the period December 1993–March 1994.

Table 4
Soil moisture depletion rates at different depths in the profile[a]

Depth (cm)	December 1993–March 1994			April 1994–September 1994			October 1994–February 1995		
	Manual terraces	Mechanical terraces	Mechanical terraces+USR	Manual terraces	Mechanical terraces	Mechanical terraces+USR	Manual terraces	Mechanical terraces	Mechanical terraces+USR
30	−7.78c	−7.15 c	−4.82 c	−13.00 c	−13.10 d	−9.87 c	−10.12 c	−8.72 d	−10.67 b
40	−3.55b	−3.32 b	−2.52 b	−3.63 b	−5.49 c	−4.86 b	−6.46 b	−4.02 b	−7.70 a
50	−2.01a	−3.13 b	−1.92 ab	−2.06 a	−3.69 b	−3.17 a	−5.76 a	−4.86 c	−8.05 a
60	–	−2.04 a	−2.05 ab	–	−1.36 a	−3.23 a	–	−3.57 a	−8.25 a
70	–	−1.73 a	−1.41 a	–	−0.90 a	−3.41 a	–	−4.50 bc	−7.72 a

[a] Original data (in per days) were multiplied by 1000 to reduce the number of decimals. Within each land treatment, values of k at different soil depths were compared by analysis of covariance. Values in the same column sharing letter do not differ significantly ($p<0.05$) according to covariance analysis.

and probably contributed to reducing soil evaporation losses.

The moisture depletion rates at different depths within each land treatment were also compared by covariance analysis, in order to understand from what soil horizons the seedlings were extracting more water at any particular stage of their growth (Table 4). The highest topsoil moisture depletion rate was recorded in the manual terraces, but rates decreased sharply with depth in this treatment. This suggests a preferential absorption by the seedlings of the moisture stored in the surface soil layers, as well as a water extraction increasingly difficult with depth.

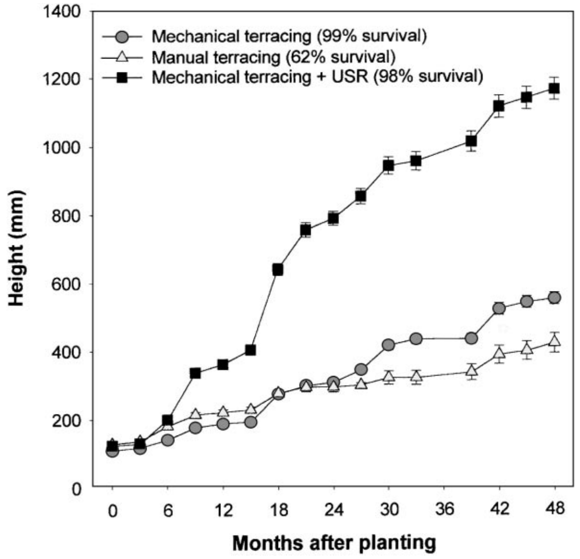

Fig. 4. Survival and growth of the *Pinus halepensis* seedlings during a 4-year-period in the different land treatments. Each height value is mean of at least 75 replicates. Bars represent the standard error of the mean.

The low soil moisture depletion rates measured at 60 and 70 cm deep showed that seedling access to the subsoil water was still limited in both the mechanical terraces with and without USR.

3.2.2. Second period

This includes the spring and the summer of 1994. The amount of rainfall recorded in the experimental area was 44 mm during April, 8.5 mm during May, 1 mm during June and 0 mm during July, August and the part of September considered. This was a very dry period, and water depletion rates were consequently high (Fig. 5).

The moisture stored within surface soil horizons was again depleted significantly more slowly in the mechanical terraces+USR than in the mechanical terraces without USR (the k values in the different land treatments can be compared by depth in Fig. 5). This difference was smaller than during the former period, however. On the contrary, water depletion rates at 60 and 70 cm deep were 200% higher in the mechanical terraces+USR than in the mechanical terraces without USR (Fig. 5), while there were no differences during the previous period. This result suggests that, in the mechanical terraces+USR, the seedlings' roots had already reached the deepest layers of the profile, and were able to uptake the water stored there.

When comparing the drying curves obtained at different depths in each soil treatment (Table 4), the sharp decrease of the water depletion rates with depth in the manual terraces stands out again. At 30 cm

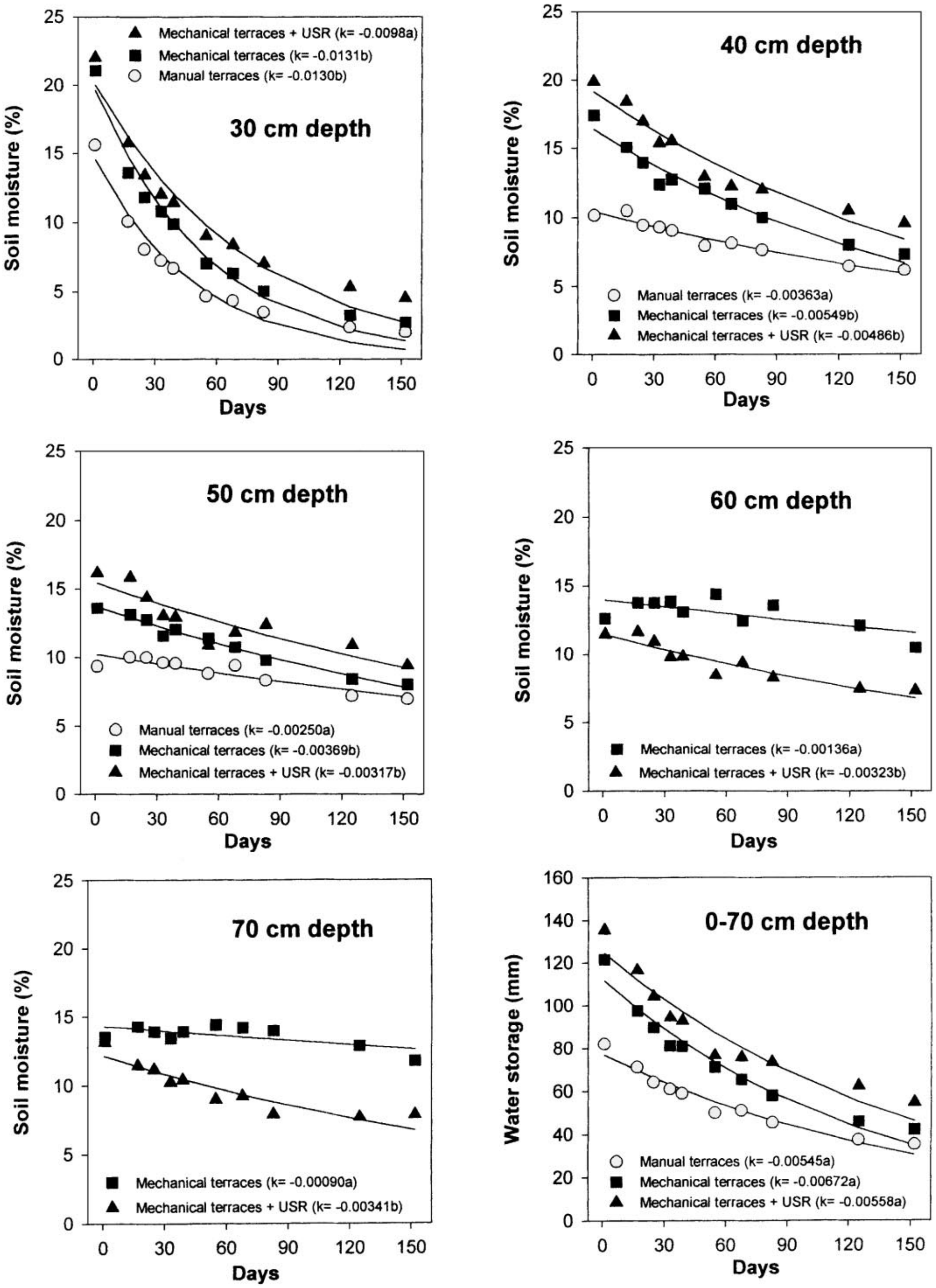

Fig. 5. Moisture depletion curves at five depths in the different land treatments. A graph showing the depletion curves of the total water store within the 0–70 cm layer of the profile is also included. Values of *k* represent moisture depletion rates. At each soil depth, *k* in the different land treatments were compared using a covariance test. Values of *k* in the same graph, sharing a letter do not differ significantly according to covariance test. Data correspond to the period April 1994–September 1994.

deep, water depletion rates were very similar in the manual terraces and in the mechanical terraces+USR, but at 40 and 50 cm deep they were significantly greater in the second treatment. The low rates obtained at 40 and 50 cm deep show that it was difficult for the seedlings in the manual terraces to extract water from the soil even at these shallow depths, theoretically easy to reach by their sinker roots. It was precisely during this period (summer 1994) that a high seedling mortality occurred in the manual terraces.

3.2.3. Third period

This includes the autumn of 1994 and the winter of 1995. The early autumn was relatively rainy, and the maximum soil water recharge of the whole record was achieved during this period. The total amount of rainfall recorded during the part of September considered was 61 and 58 mm in October, 8 mm during November, 13 mm in December and 0 mm during January and February.

This time, surface soil depletion rates were significantly higher in the mechanical terraces+USR than in the mechanical terraces without USR (as shown by the k values in Fig. 6), the reverse of what had been observed before. This seems quite logical, since differences between these two treatments with respect to standing plant biomass were already very large by then (Figs. 2 and 4). Water depletion rates at 60 and 70 cm deep were also 100% higher in the mechanical terraces+USR than in the mechanical terraces without USR (Fig. 6). The high moisture depletion rate of the subsoil in the mechanical terraces+USR showed that, 2 years after planting, the saplings were already able to use the water stored in the profile quite homogeneously, at least to a depth of 1 m. (Table 4).

The comparison of the soil moisture depletion rates from different horizons in the manual terraces again showed a sharp contrast between the curves from 30 and 50 cm deep (Table 4). As shown in Fig. 6, water depletion rate at 30 cm deep was similar to that in the mechanical terraces+USR, but at 50 cm it was significantly lower.

3.3. Soil water consumption by the seedlings

The analysis of the soil moisture depletion rates showed that the water stored in the manual terraces' planting holes was exhausted more rapidly than the water stored in the surface soil of the mechanical terraces. This disparity between manual and mechanical terraces was probably due to differences in soil water consumption patterns by the *Pinus halepensis* seedlings.

Deep rooting becomes increasingly important for the water uptake of pines as the surface soil dries out (Talsma and Gardner, 1986). Deep roots are a long hydraulic path with relatively low conductivity, and therefore only supply a significant proportion of the total water uptake of plants when the surface soil is dry (Oren and Sheriff, 1995). Normally, most of the water and nutrient absorption of pines is accomplished by the roots in the surface 30–40 cm of the profile (Roberts, 1976; Nambiar, 1990). However, it is precisely during the early stages of seedling development when deep rooting becomes more necessary in case of exhaustion of the topsoil moisture (Sands and Nambiar, 1984; Mitchell and Correll, 1987). In semiarid environments, water extraction from deep in the profile represents the only way to maintain the supply during the frequent drought periods. Wetting of deep soil horizons requires greater amounts of precipitation, and hence occurs less frequently. However, once wet they likely remain so for a longer time. In our case, a large part of the experimental period was characterized by extremely dry conditions. The total amount of rainfall in El Aguilucho area between January 1994 and December 1995 was 320 mm, of which only 103 mm corresponded to the year 1995. Under such harsh climatic conditions, deep rooting was crucial for seedling survival and growth.

Mechanical terracing most likely favored the deep rooting habit typical of pines (Stone and Kalisz, 1991; Pallardy et al., 1995), since subsoiling decreased soil resistance to root penetration into the profile. As a result, the volume of soil explored by roots in search of moisture probably grew larger, thus increasing the effective reserve of water available for the seedlings. Moreover, sinker roots may have enhanced water infiltration into the deeper horizons of the soil profile (as suggested by the high sorptivity values found in the rhizosphere of the seedlings in the mechanical terraces, Table 3). Water stored in deep soil horizons is better protected from direct evaporation (Sands and Mulligan, 1990).

The results of the sampling of roots carried out in October 1996 within the rhizosphere of the pines may

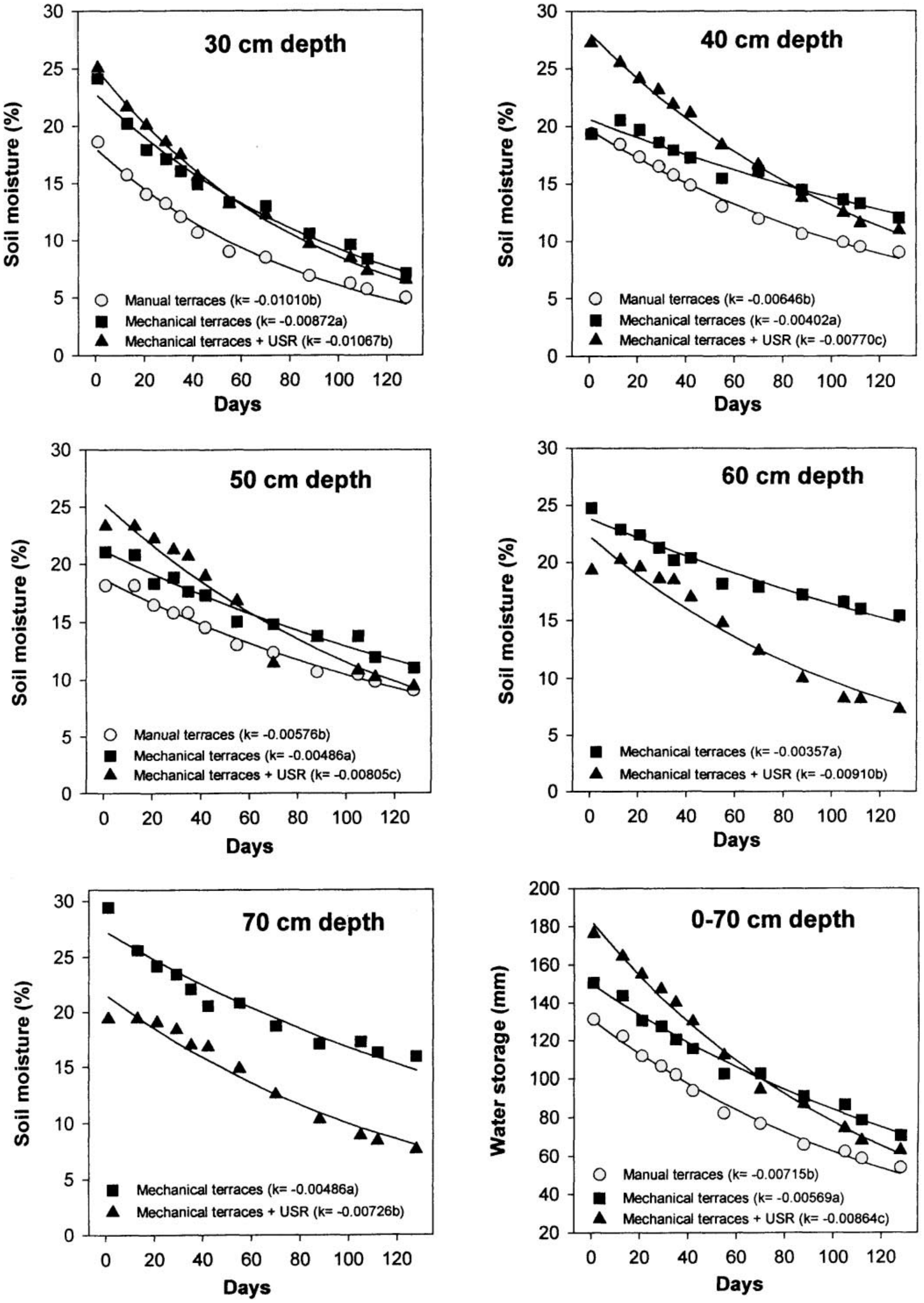

Fig. 6. Moisture depletion curves at five depths in the different land treatments. A graph showing the depletion curves of the total water store within the 0–70 cm layer of the profile is also included. Values of k represent moisture depletion rates. Values of k at each soil depth in the different land treatments were compared using a covariance test. Values of k in the same graph sharing a letter do not differ significantly according to covariance test. Data correspond to the period October 1994–February 1995.

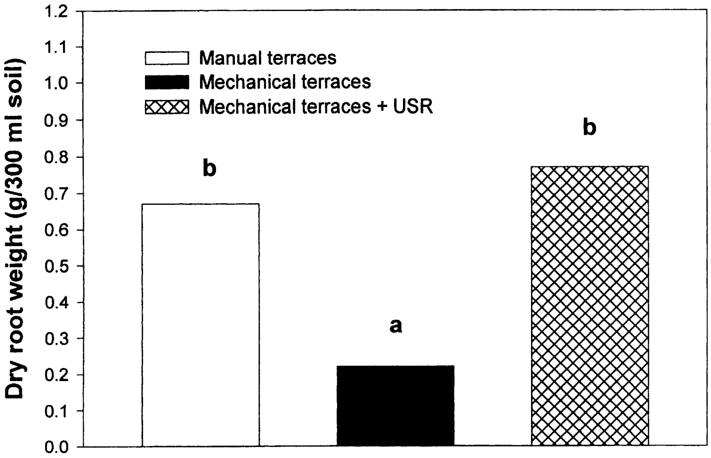

Fig. 7. Density of *Pinus halepensis* roots within the 0–20 cm soil layer in the different land treatments. Columns sharing a letter do not differ significantly according to Duncan's test.

help to explain the observed differences in moisture depletion rates between manual and mechanical terraces (Fig. 7). The distribution of roots into the soil profile is normally a function of the average depth of the wetting front. Plants in arid environments often show root distributions that enable them to maximize transpiration (Boer, 1999). Although seedlings in the mechanical terraces without USR were significantly larger (Fig. 4) than those in the manual terraces by the time of the root sampling, pine root density in the topsoil of the manual terraces was three times higher than in the topsoil of the mechanical terraces. Root densities in the mechanical terraces+USR and in the manual terraces were similar despite huge differences in seedling development. Therefore, the density of pine roots in the topsoil of the manual terraces was disproportionately large in relation to the size of the seedlings, which suggests that root extension beyond the limits of the planting holes was constrained by the high penetration resistance of the soil. The high moisture depletion rate measured in the topsoil of the manual terraces agreed well with the high density of roots found there. The sharp decrease of moisture depletion rates with depth was probably due to the difficult access by the seedling roots to the water stored below the bottom of the planting holes. All these data seem to indicate that seedlings in the manual terraces were very dependent on the moisture content of the surface soil. This could explain the high seedling mortality observed in this land treatment during the intense drought of the summers of 1994 and 1995, as well as the poor development of the pines that survived (Fig. 4). Therefore, the experimental data indicated that the low availability of water and the high soil penetration resistance in the manual terraces strongly limited the survival and growth of *Pinus halepensis* seedlings in this semiarid environment.

On the contrary, the greater water and nutrient content and the favorable physical properties of the soil in the mechanical terraces+USR allowed the seedlings to grow rapidly. Subsoiling most likely favored the early development of sinker roots, as suggested by the high moisture depletion rates of the deep horizons of the soil in this treatment. Early access to the water stored deep in the profile provided the seedlings in the mechanical terraces+USR with an additional advantage that further enhanced their growth. The high concentration of nutrients in the mechanical terraces+USR (Table 3) probably contributed to improve the water relations of the pines during dry periods. Fertilization with N and P can enhance root hydraulic conductivity and can improve the adjustment of the stomatal control of water losses (Nambiar, 1990; Oren and Sheriff, 1995). A high availability of K in the soil can also increase plant resistance to drought (Chamshama and Hall, 1987). Hillerdal-Hagströmer et al. (1982) and Squire et al.

(1987) demonstrated that fertilization treatments can increase water use efficiency in several species of pines.

4. Conclusion

Manual terracing did not enhance soil water storage substantially, and consequently, did not increase moisture availability for the introduced plants. Moreover, the high penetration resistance of the soil in this treatment probably constrained the extension of the pine seedlings' root systems, thus, increasing their vulnerability to surface soil moisture exhaustion. Moisture depletion rates in the manual terraces decreased sharply with depth, which indicated that root access to the lower and wetter layers of the profile was limited. High seedling mortality during the dry summers of 1994 and 1995 supported this hypothesis.

Mechanical terracing with subsoiling increased soil water storage much more effectively than manual terracing. The analysis of soil moisture depletion rates showed that subsoiling allowed the seedlings in the mechanical terraces to extend their roots into the deeper layers of the profile, thus, favoring their access to an increased and more durable store of water. As a result, virtually all the pines in the mechanical terraces survived during the extreme drought of the years 1994 and 1995.

The combination of mechanical terracing, subsoiling and USR addition greatly enhanced soil water infiltration and conservation, which significantly increased moisture availability for plants in this semiarid environment. The fast growth of the pine seedlings and the proliferation of spontaneous vegetation could be to a great extent explained by the improvement in the local water budget attained by this site preparation technique. Early root extension to deeper and wetter soil compartments enabled the seedlings in this treatment to lengthen their growing periods even under severe drought conditions.

Climatic changes expected from the enhanced greenhouse effect might result in drier conditions over many of the present semiarid areas of the world. This would further hinder the applicability of conventional afforestation methods in sites where water is the main limiting factor for plant establishment. In this context, the combination of mechanical terracing and USR addition appears as an interesting alternative for the revegetation of degraded drylands.

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