

Impact of straw and rock-fragment mulches on soil moisture and early growth of holm oaks in a semiarid area



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ARTICLE INFO

Article history:

Received 16 November 2016

Received in revised form 11 January 2017

Accepted 14 January 2017

Available online xxxx

Keywords:

Quercus ilex

Dendrometer

Saplings

Water infiltration

Soil moisture sensors

Caliche

Cumulative growth

ABSTRACT

Planted seedlings and saplings usually exhibit low survival and growth rates under dry Mediterranean environments, especially late-successional species such as *Quercus*. In this work, we studied the effects of straw and rock-fragment mulches on the establishment conditions of holm oak (*Quercus ilex* L. subsp. *ballota* (Def.) Samp.) in SE Spain. Soil moisture was characterized at 4 soil depths (10, 20, 40, and 70 cm) for 3 treatments applied over 1 × 1 m plantation beds (rock-fragment cover [caliche], straw mulch, and control) where holm oak saplings were outplanted. Digital dendrometers were used to characterize sapling-growth characteristics including: physiological stress, cumulative growth, and number of days of growth. The results showed that straw mulch favored water infiltration and soil-water storage at 20, 40, and 70 cm in depth. By contrast, the rock fragments improved soil moisture only at 10 and 20 cm in depth with respect to the control, decreasing the water storage in deeper soil layers. Despite the absence of significant total growth differences after 20 months of tree monitoring, both types of mulch lengthened the number of days of plant growth and shortened the number of days of physiological stress in our holm oak saplings. The application of straw mulch or a rock-fragment cover changed the spatial and temporal soil-moisture distribution pattern throughout the soil profile. Straw mulch would be recommended for seedlings or saplings with deeper initial root systems (i.e. containers >20 cm high), whereas caliche-type rock fragments could be more suitable for small seedlings with shallower initial root systems (i.e. containers <20 cm high), or species with superficial root systems, such as *Pinus* species or other conifers.

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1. Introduction

Areas with Mediterranean-type climate show a hot dry season (summer) and a wet cool season (winter). In dry and semiarid Mediterranean areas, artificially regenerated plantations are characterized by low survival and slow growth, apparently due to environmental factors (Pausas et al., 2004). Low amounts of rainfall, uneven spatial and temporal rain distribution, isolated and sometimes heavy storms, extreme temperatures, and high evapotranspiration rates represent the main abiotic limitations in these areas together with topography and land use (Larcher, 1995; Vallejo et al., 2012). Thus, it is vital to boost the soil-water holding capacity and mitigate evaporation losses.

Under these limiting conditions, it becomes critical for seedlings to grow new roots to a depth where water is sufficient to survive the first few summers (Padilla and Pugnaire, 2007; Villar-Salvador et al., 2012). Therefore, the ecological restoration of semiarid and dry degraded lands involving seedling or sapling plantations of woody species

should develop field techniques to maximize water availability for introduced species, especially during the first post-planting period (Cortina et al., 2011; Vallejo et al., 2012). Field techniques to improve seedling establishment commonly prioritize the increase in rootable soil volume, nutrient availability, precipitation runoff collection, and water conservation, while controlling competition with existing vegetation (Chirino et al., 2009; Cortina et al., 2011).

Mulch to conserve soil moisture is commonly used in semiarid regions, as well as subhumid and humid regions, mainly due to its positive effect on soil temperature and infiltration, and its reduction of soil evaporation by breaking the capillarity (Russel, 1939; Ji and Unger, 2001; Jordán et al., 2010; Ma and Li, 2011; Cerdà et al., 2016; Keesstra et al., 2016). Mulch has been widely used as a post-planting treatment in agriculture, forestry systems, and environmental restoration to improve seedling establishment (Navarro et al., 2010; García-Moreno et al., 2013). In general, mulching the soil surface with straw, plastic, rock fragments, forest debris, etc., can improve the soil conditions, such as moisture, temperature, and available nutrients (Truax and Gagnon, 1993; Devine et al., 2007; Katra et al., 2008; Laliberté et al., 2008; Guo et al., 2010). It also improves the soil physical properties, such as bulk

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density, porosity, and aggregate stability (Jordán et al., 2010; Jordán et al., 2011), while increasing infiltration and decreasing runoff rates, as well as reducing soil-moisture loss from evaporation (Díaz et al., 2005). However, the effects depend on the thickness of the mulch and the fraction of soil surface covered (Allen et al., 2008). Some authors have pointed out that mulches are effective for post-planting preservation and conservation of soil water (Jiménez et al., 2007; Valdecantos et al., 2009).

In Mediterranean environments, different mulches (e.g. slash, black polyethylene, compost) have been tested as post-planting techniques in beds around oak seedlings to enhance survival and growth of the seedlings (Navarro-Cerrillo et al., 2005; Larchevêque et al., 2006; Valdecantos et al., 2009; Ceacero et al., 2012). The effects of rock fragments and plastic mulch on soil-water conservation have been systematically studied in dry-area crops as well as in forestry (Devine et al., 2007; Katra et al., 2008; Laliberté et al., 2008; Guo et al., 2010; Bakker et al., 2012; Valdecantos et al., 2014), but these studies have not documented how different mulching techniques affect to the soil-water content and its temporal dynamics (Jiménez et al., 2007; Jiménez et al., 2016).

Another way to improve survival and growth of containerized stock planted under dry conditions is to increase plant size. In fact, some studies claim that bigger or taller containers than conventional sizes (200–350 cm³, 15–20 cm deep) increase efficiency in the field performance of Mediterranean species (Oliet et al., 2012). However, very few outplanting studies have been done using the ‘target plant concept’ (sensu Pinto et al., 2012) to restore Mediterranean environments with holm oak and other oak saplings grown in non-conventional volumes of containers (but see Tsakalimi et al., 2005; González-Rodríguez et al., 2011; Jiménez et al., 2014). Although out of our goals, the higher prize per plant versus higher probability of survival and growth, together with the fact to obtain an adult and productive tree in less time should be tested in the near future. In any case, all progress of knowledge about restoration of oak woodlands and savannas (dehesas) in Mediterranean areas should be a priority for the environmental management, since they constitute biodiversity-rich habitats, priority ecoregions for global conservation, as well as protected ecosystems under the Pan-European network “Natura 2000” (Sánchez-González et al., 2015).

The aim of this study was to evaluate the impact of mulch treatments on soil moisture and early growth of holm oaks in a semi-arid environment. Specifically, we analyzed the effectiveness of rock-fragment and straw mulch over the planting beds with respect to water content through the soil profile and analyzed the early field response of holm oak saplings cultivated in non-conventional container sizes.

2. Material and methods

2.1. Study area

The experiment was conducted in the Dehesas de Becerra (Guadix-Baza Basin, Granada), in the SE Iberian Peninsula (37°25′11″N and 3°05′16″W) at 1032 m a.s.l. The climate is semiarid Mediterranean, with cold winters and hot, dry summers. According to the classification of Rivas-Martínez and Loidi (1999), the area is in the xeric-oceanic bioclimate, mesomediterranean thermotype, and semiarid ombrotpe. Precipitation and air-temperature data have been recorded every 30 min in the nearby weather station since 1998 (Cortijo Becerra, 37°25′58″N, 3°06′05″W; 972 m a.s.l.; THIES model DL-15). Precipitation patterns show high inter-annual variability, with an annual mean of 320 mm. Data collected during the study period (March 2010 to November 2012) exhibited this variability with means of 480.0 mm (1 Oct. 2009–30 Sept. 2010), 465.6, and 162.8 mm for following hydrological years, respectively. The minimum and maximum mean monthly temperatures are −2 °C in January and 33 °C in July. In winter, the

temperature can drop to as low as −19 °C (January 2005) and in summer can reach 40 °C (August 2012).

The study area was a flat, tilled agricultural zone with scattered holm oaks from the end of the 19th century until 1993, when plowing ceased. Prior to this, it was a communal land with an alpha-grass steppe mixed with open holm oak woodlands (“dehesa” in Spanish). It was used by the local population to feed livestock, hunt, and gather firewood (Camarero and Campos, 1991; Huntsinger et al., 2004; Olea et al., 2004; Paniza Cabrera, 2015). Currently, it has a tree density of 10 trees per hectare. The soil is classified as a Petric Calcisol (IUSS Working Group, 2006) with a sandy clay loam texture (54.5% sand, 19% silt, and 22.7% clay), and is very homogeneous throughout the assay area. The main characteristics for the post-tilled (1993), undisturbed soil in the first 30 cm of profile are the following: 38.2% CaCO₃ content, 38.4% gravel content, 0.88 g·cm³ average bulk density, 8.4 pH, and electrical conductivity assumed to be <1 dS m^{−1}.

2.2. Experimental design, soil moisture, and growth monitoring

In February 2010, 9 planting holes with 3-m spacing were dug by an excavator (bucket dimensions of 50 × 80 cm). In March 2010, 6- to 7-year-old holm oak saplings (*Quercus ilex* L. subsp. *ballota* (Samp.) Desf.) in 24 l pots (32 cm deep and 35 cm in diameter) were planted with ECH₂O® soil moisture sensors (20 × 3.2 cm, Decagon Devices®, Pullman, WA, USA) installed at 10, 20, 40, and 70 cm depths in each planting hole ($n = 36$). The sensors were placed horizontally and slightly inclined into the disturbed soil, simulating the planting conditions. Volumetric soil-moisture data (m³ m^{−3}; hereafter, θ) were recorded with HOBO® dataloggers (U12 of 4 external channels, Meteo-U12-006), every 30 min from March 2010 to November 2012 (988 days). Wilting point (measured at 1500 KPa, hereafter WP) and field capacity (at 33 KPa, hereafter FC) were measured in soil samples taken at 0–30 and 30–70 cm, but the average (WP = 10.2%, FC = 14.2%) was used since very similar values were found at both soil depths, likely due to the homogenization of the soil horizons by the soil preparation treatment for planting. WP and FC were measured at the laboratory, by means of the Richards's pressure chamber (Richards, 1965).

Sapling growth between May 2011 and November 2012 was also monitored by measuring changes in the stem circumference variation (SCV), using digital circumference DC2 dendrometers (range 15 mm; accuracy $\pm 2 \mu\text{m}$, Ecomatik®, Munich, Germany). These SCVs correspond to diurnal circumference variations composed of diurnal rhythms of water storage depletion and replenishment (Kozłowski and Winget, 1964; Offenthaler et al., 2001; Deslauriers et al., 2007) and seasonal tree growth (Deslauriers et al., 2003; Bouriaud et al., 2005). Dendrometers were installed on the nine saplings (3 per mulch treatment plus control) at 60 cm above the soil level. SCV was recorded every 30 min and stored in dataloggers (HOBO® U12). The following SCV-derived indexes were calculated (according to Fernández and Cuevas, 2010): daily maximum stem circumference (MXSC), and cumulative growth ($\text{CG} = \sum_{\text{DOY}}^{\text{DOY}} \text{DG}$; for N days), where DG = daily growth ($\text{DG} = \text{MXSC}_{\text{DOY}+1} - \text{MXSC}_{\text{DOY}}$), and DOY = day of year.

Focusing on daily growth data over the growing seasons, we monitored the growing periods (those starting when at least two days show positive daily growth within three consecutive days; GP) and the decreasing growth periods (those starting when at least two days show zero or negative growth within three consecutive days, indicating water stress processes; DP). In our study period, GPs were detected mainly in spring 2011 and 2012, and fall 2012, while DPs corresponded with summer drought of 2011 and 2012. The number of days of growth and the decrease were counted within these periods to be analyzed.

2.3. Mulching treatments

Three treatments were considered in this experiment: straw mulch (here-in-after, straw; $n = 3$), rock-fragment mulch (rock fragments;

$n = 3$), and control (TC; $n = 3$). These were randomly assigned to the 9 planting beds. For the straw mulch, a 15–20 cm thick straw cover was spread over a 1×1 m area. The rock-fragment mulch covered a 1×1 m area and were exclusively rocks coming originally from the soil petric horizon (caliche or calcrete). The rock fragments ('stone' size sensu U.S. classification) were laid on the soil surface in a single layer, and they were collected on site (piled on soil surface through decades of plowing). Three planting beds were untreated and used as control. Irrigation commenced immediately and was repeated 3 times during the first growing season (April, June and August); saplings each received 50 l of water per event. To prevent damage from wild herbivores and livestock, all saplings were protected by wire mesh up to 1 m high.

2.4. Data analyses

Statistical analyses were made to establish the effects of the mulch treatments on soil-water-content data and how this changes over time. Repeated-measures analyses of variance (RM-ANOVAs) using a confidence level of 95% were performed on soil-water-content data. Comparative analyses were made among treatments at each depth and among depths within each respective mulch treatment. The between-subjects factors were the 'mulch treatment' and 'depth', and the within-subject factor was 'time'. In addition, a two-way factorial analysis was run to explore the effect of the factor 'mulching treatment' and 'period' (GP, and DP) on the number of days of growth and days of physiological stress (shrinking), respectively, of the planted holm oaks. Cumulative growth at the end of the study period was analyzed through one-way ANOVA ($n = 3$). Multiple-comparison testing was done using Tukey's mean separation test (assuming equal variances). Normality and homogeneity were checked by the Shapiro-Wilk and the Bartlett tests, respectively. Spearman correlation analysis was used to determine the degree of dependence between soil-water content and the variables of precipitation and air temperature. Data analysis was done with the statistical software package R (version 2.15.1; R Development Core Team, 2013), using library Rcmdr (Fox, 2005), and STATISTIX 8 (Analytical Software®, Tallahassee, Florida, USA). The α level for statistical significance was 0.05 in all cases.

Finally, we monitored the daily-averaged θ after a precipitation event in the late spring of 2011 and throughout the duration of a drying process (93 days). First focus day was May 3rd (d1), and next were May 20th (d18), June 3rd (d32), June 20th (d49), July 3rd (d62), and August 3rd (d93). Two-way factorial analyses were run to explore the effect of the factor "mulching treatment" and "soil depth" on daily-averaged θ . Data were plotted by θ , depth, and time to visualize trends. Additionally, ratios were calculated using the mean θ of each mulch treatment (rock fragments and straw) with regard to the control. Values > 1 indicated improved θ relative to the control.

3. Results

3.1. Differences of daily-averaged soil moisture between mulch treatments

Repeated-measures analysis on daily-averaged θ data ($n = 988$) revealed differences among the mulch treatments for 10, 20, 40, and 70 cm ($p < 0.001$, Table 1). The 'time' factor was also significant for all depths ($p < 0.001$), as well as the mulch $\times$ time interaction ($p < 0.001$). On average, straw mulch resulted in significantly lower θ values than did control at 10 cm; conversely, straw showed higher θ values than control at 20, 40, and 70 cm soil depths (Fig. 1). By contrast, rock fragments provided significantly greater θ than did control at 10 and 20 cm, whereas the θ values at 40 and 70 cm were significantly lower than control. Rock fragments showed higher θ at 10 cm in depth with regard to the straw mulch, while the straw mulch showed higher θ values at 40 and 70 cm.

Table 1

Repeated-measures analysis of variance results showing differences in daily-averaged soil water content at four soil depths (10, 20, 40, and 70 cm) due to mulch treatments (T), changes over time (T) and the interaction terms (T $\times$ T). Significant differences are indicated in bold ($p < 0.05$).

Depth		Treatment (T)	Period (T)	T $\times$ T
10	df	2	987	1488
	F	611.939	8.130	5.301
	p	<0.001	<0.001	<0.001
20	df	2	987	1488
	F	149.895	5.133	2.222
	p	<0.001	<0.001	<0.001
40	df	2	987	1488
	F	672.825	3.603	1.873
	p	<0.001	<0.001	<0.001
70	df	2	987	1488
	F	270.248	3.412	2.004
	p	<0.001	<0.001	<0.001

During the first summer after mulch application (2010), great fluctuations appeared in the daily-averaged θ for all treatments (Fig. 2), due to the irrigation events. The highest amounts of precipitation were registered in winter (2010–2011) and spring (2011), so that θ increased for all treatments and depths. At 10 cm, θ was higher for rock-fragment mulch. At 20 cm, the differences among treatments proved greater, with straw mulch registering the highest mean values ($> 20\%$ at 70 cm) and the rock fragments the lowest ($< 15\%$ at 40 cm). During the summer of 2011, the daily-averaged θ decreased for all treatments at the four depths studied. Overall, θ tended to increase with depth.

In general, the mean values of daily-averaged θ were higher than WP (10.2%) for all treatments and depths during winter 2010–2011 and spring 2011 (Fig. 2). Despite precipitation and increases in daily-averaged θ during the late autumn and winter 2011, soil moisture hardly reached the WP. From summer 2011 to autumn 2012, all daily-averaged θ values down to 40 cm were lower than WP, and only the straw and control treatments showed mean values above or near the WP at 70 cm depth.

3.2. Daily-averaged soil-moisture changes in the soil profile

The repeated-measures analysis revealed differences among depths within each treatment ($p < 0.001$, Table 2). The factor "time" was also significant in all cases ($p < 0.001$), but the depth $\times$ time interaction was not significant in any case ($p = 1$). For the control treatment, daily-averaged θ increased with depth, but values at 10 and 20 cm did not significantly differ (Fig. 1). In the rock-fragment treatment, daily-averaged θ was significantly different among depths; however, the lowest

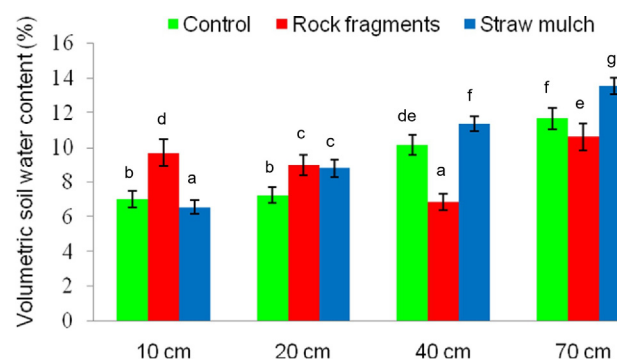


Fig. 1. Mean values ($\pm$ SE) of daily-averaged volumetric soil-water content (%) for control, rock-fragment, and straw-mulch treatments at 10, 20, 40, and 70 cm soil depths throughout the study period (March 2010 to November 2012). Different letters (RM-ANOVA results) indicate significant differences among mulch treatments and depths (Tukey's analysis, $p < 0.05$).

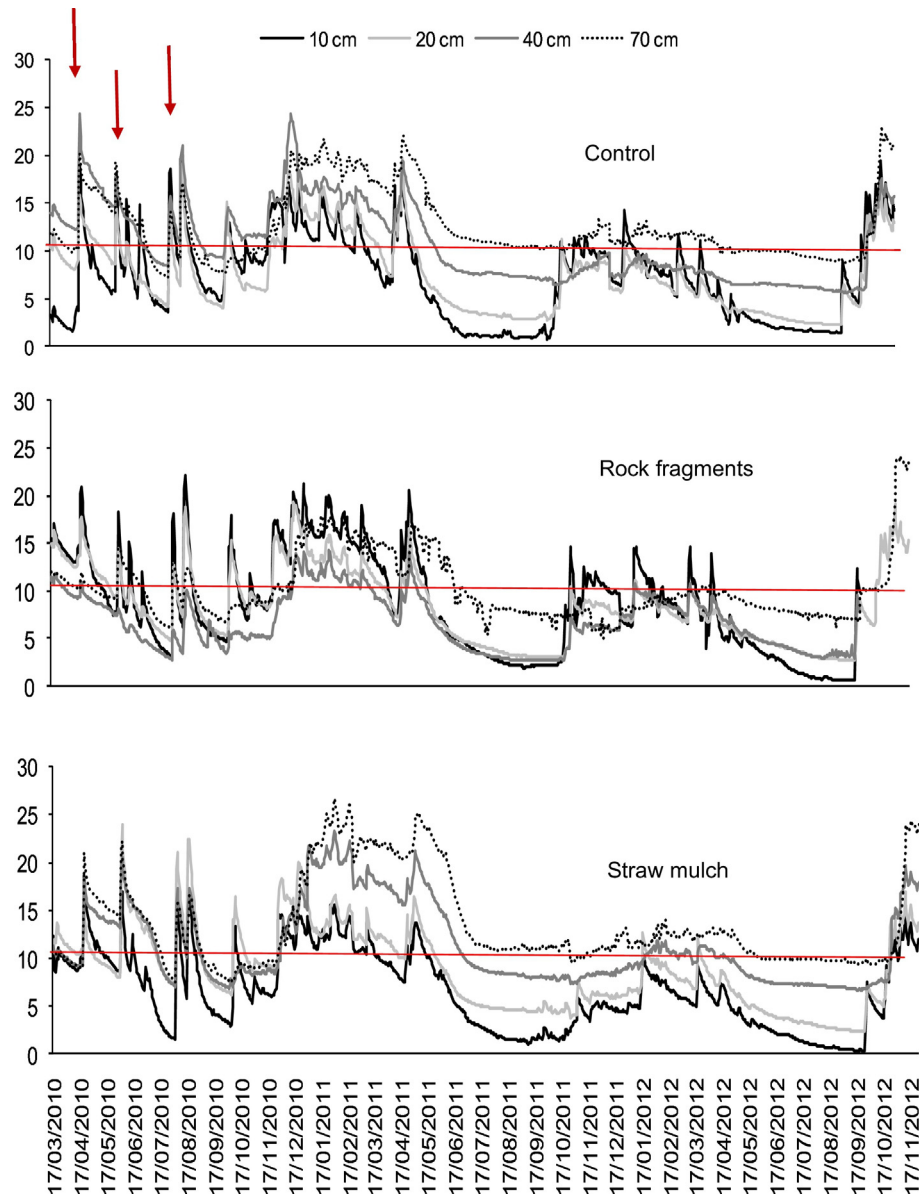


Fig. 2. Daily-averaged volumetric soil-water content (%) of control, rock-fragment, and straw-mulch treatments throughout the study period (March 2010 to November 2012). Horizontal line at 10.2% volumetric soil-water content indicates the wilting point (1500 kPa) measured in disturbed soil (WP). Red arrows indicate the timing of artificial irrigation events for all treatments. Data show mean values ($n = 3$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mean value occurred at 40 cm while the highest was found at 70 cm. Differences were found in θ under the straw mulch, with water content values increasing in depth (Fig. 1).

Table 2

Repeated-measures analysis of variance results showing differences in daily-averaged soil water content among three mulch treatments (control, rock fragments, and straw) at different depths (D), changes over time (T) and the interaction terms (D $\times$ T). Significant differences are indicated in bold ($p < 0.05$).

Treatment		Depth (D)	Time (T)	D $\times$ T
Control	df	3	868	2604
	F	704.225	9.531	0.394
	p	<0.001	<0.001	1
	df	3	620	1860
Rocks	F	182.016	6.154	0.437
	p	<0.001	<0.001	1
	df	3	987	2961
	F	2366.933	16.916	1.004
Straw	p	<0.001	<0.001	0.442

3.3. Monthly-averaged differences within mulch treatments

During the first spring and summer after the mulch application (2010), monthly-averaged θ showed fluctuations for all treatments and depths (Fig. 3), due to the irrigation events. Starting in November 2010, precipitation increased, as did θ for all treatments and depths. In particular, the straw mulch had a greater response, especially at 70 cm depth. From May 2011, θ clearly decreased in all treatments. In the control and straw-mulch treatments, θ decreased in a stratified way throughout the soil profile (10 < 20 < 40 < 70 cm). Soil moisture increased with the return of the rainy season after summer 2011; although only slightly because of the relatively low rainfall. Both the control and rock-fragment mulch displayed the largest increases in θ , especially at 10 cm. From about mid-July 2011 to late October 2012, θ at both 40 and 70 cm depths remained relatively stable (changing <5%) for the control and straw-mulch treatments. This pattern did not hold for the rock-fragment mulch. The return of new rains in the autumn of 2012 raised θ values for all treatments and depths.

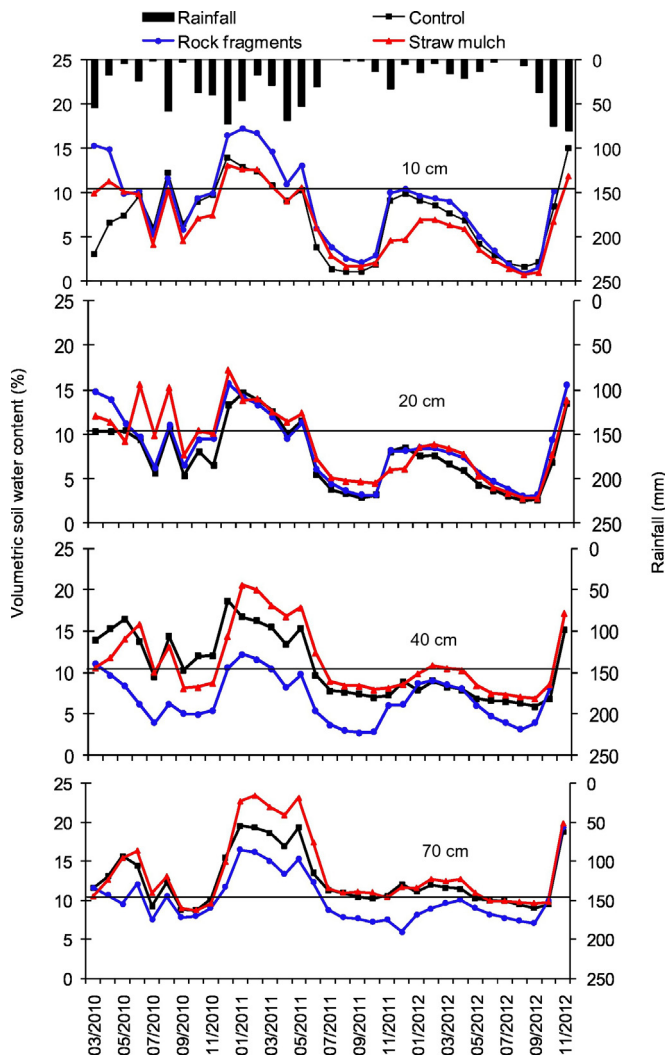


Fig. 3. Monthly-averaged volumetric soil-water content (%) for control, rock-fragment, and straw-mulch treatments at soil depths of 10, 20, 40, and 70 cm. Black bars indicate monthly precipitation and horizontal line at 10.2% volumetric soil-water content indicates the wilting point (1500 kPa) measured in disturbed soil (WP). Data show mean values ($n = 3$).

3.4. Soil-moisture changes during drying processes

Our characterization of a 93-day drydown period, starting in late spring 2011 (May 3rd) yielded similar trends for both the control and straw treatments. In both of these treatments, daily-averaged θ in the upper soil layer (10 cm) remained above WP (10.2%) for just <18 days. At 20 and 40 cm, daily-averaged θ dropped below WP by the end of 93 days in all treatments, but the straw mulch tended to retain more water for a longer time period (especially at 40 cm). For both the control and straw treatments, daily-averaged θ at 70 cm in depth maintained values above WP for the 93-day period examined (Fig. 4). This was not the case for the rock-fragment mulch, which fell below WP in all depths by the end of 93 days, and showed a different drying pattern. Despite these trends, no statistical differences were found in any case (data not shown).

The ratio analysis of the same drydown time period showed that both mulch treatments improved the daily-averaged θ over the control at 10 cm. This was especially evident after 49 days (Fig. 1 in Supplementary material). At 20, 40, and 70 cm, only θ under straw mulch showed clear differences with regard to the control. For rock fragments, ratio

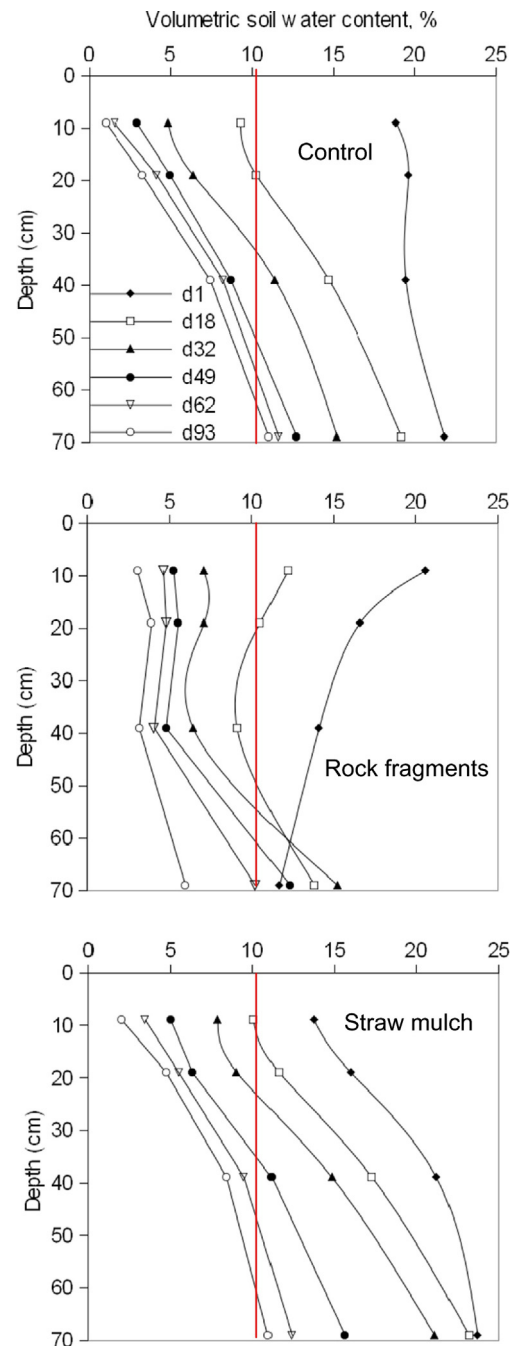


Fig. 4. Daily-averaged volumetric soil-water content (%) throughout the soil profiles (mean data, $n = 3$) for rock-fragment, straw, and control treatments following the last rainfall event in spring until the summer drought 2011 (d1 = 3rd May, d18 = 20th May, d32 = 3rd Jun, d49 = 20th Jun, d62 = 3rd Jul, and d93 = 3rd Aug). Vertical line at 10.2% volumetric soil-water content indicates the wilting point (1500 kPa) measured in disturbed soil (WP).

values ≤ 1 indicated this treatment was ineffective or worse compared to the control at these latter depths.

3.5. Soil-moisture correlations with monthly precipitation and monthly mean temperature

Monthly precipitation showed a positive and significant correlation ($p < 0.05$) with monthly-averaged θ for all treatments and depths (Fig. 2a in Supplementary material). Mean-monthly temperature, however, showed a negative and significant correlation with monthly

averaged θ for all treatments and depths to 40 cm (inclusive); and for the control at 70 cm (Fig. 2b in Supplementary material). For both precipitation and temperature, the values of the correlation coefficients decreased in depth.

3.6. Relationship between soil moisture and holm oak growth

From May 2011 to November 2012, the mean CG of saplings ($n = 3$) did not vary significantly among treatments ($p = 0.7789$, $df = 2$; $F = 0.27$). In general, the same mean CG pattern was found for all treatments (Fig. 5). The summer of 2011, holm oak saplings stopped growing in the control treatment at a profile-averaged θ of 7.7% (17 June), rock-fragment treatment at 7.6% (13 June), and straw mulch at 8.8% (25 June). However, the soil moisture was above these values during the growing periods at 70 cm (Fig. 5). During the measuring period, the data showed 3 GPs (spring 2011 and 2012, and fall 2012) and 2 DPs (summer 2011 and 2012). In general, there were more days of decreasing growth or shrinking (272 ± 4.99) than growing days (168 ± 4.99) over the study period ($p = 0.0000$, $df = 1$; $F = 211.04$). In particular, the control treatment showed

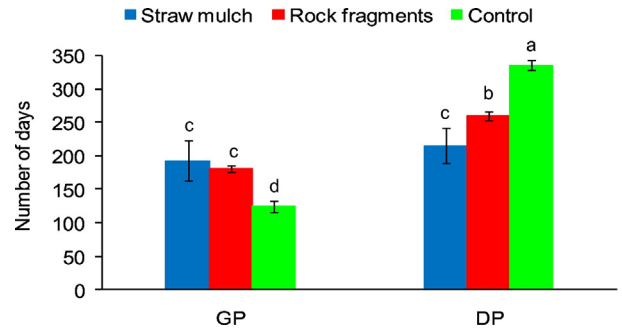


Fig. 6. Number of days (mean $\pm$ SE) of growing period (GP) and decreasing period (DP) for control, rock-fragment, and straw-mulch treatments recorded between May 2011 and November 2012. Different letters indicate significant differences (two-way ANOVA results) among mulch treatments $\times$ periods (Tukey's analysis, $p < 0.05$).

significantly fewer GP days (124.5 ± 4.5) and more DP days (335.5 ± 4.5) than did the mulch treatments ($p = 0.0000$, $df = 2$; $F = 54.16$; see Fig. 6).

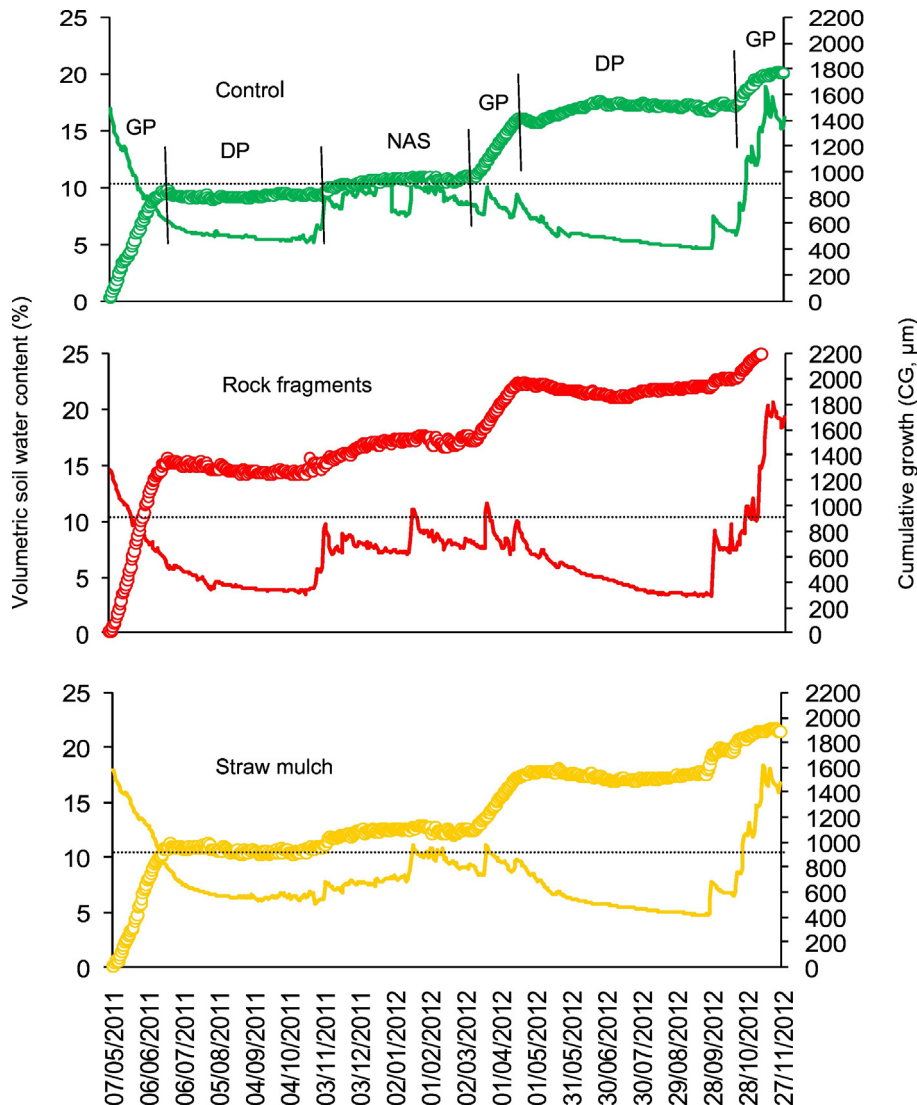


Fig. 5. Mean daily-cumulative growth (circles, $n = 3$) and daily-averaged volumetric soil-water content recorded at 70 cm depth for the control, rock-fragment, and straw mulch treatments from May 2011 to November 2012. Horizontal, dashed line at 10.2% volumetric soil-water content indicates the wilting point (1500 kPa) measured in disturbed soil (WP). GP = growing period, DP = decreasing period, NAS = Non active season.

4. Discussion

4.1. General patterns in soil moisture

Overall, the soil-moisture values logged in this study were similar to those found in other mulch studies in different world regions in similar environments (Cotillas et al., 2009; Ma and Li, 2011; Rhoades et al., 2012; Pulido et al., 2014). Our data also followed the expected Mediterranean cycle of wet and dry periods, for all the treatments and depths analyzed, with a very rapid recharge during the autumn-winter and a less rapid drying during the spring-summer periods. This is also consistent with observations by Cubera and Moreno (2007) in western Spain on the seasonal changes of soil-water content around holm oak trees up to 2 m in depth. Autumn-winter precipitation (2010–2011) quickly refilled soil-water storage, with maximum precipitation values in January 2011 and immediate increases in volumetric soil-water content for all treatments and depths. This was not the case during the second autumn-winter period (2011–2012), when meteorological precipitation was 35% lower.

During the summer drought of 2011, θ decreased for all treatments and depths (Figs. 2 and 3). This drop was more prominent at 10 and 20 cm soil depth than at 40 and 70 cm, which is characteristic for the Mediterranean-type climate (Padilla and Pugnaire, 2007). After the rainfall events of autumn-winter 2011–2012, θ in the upper soil layers rose while those at 40 and 70 cm remained more or less constant. This indicates that rainfall in this period was not sufficient to infiltrate into the deeper soil and replenish water storage. This is confirmed with data from the following autumn (2012) showing greater precipitation, and immediate and high infiltration rates, especially in soil depth.

In any case, from summer 2011 to autumn 2012 the soil-moisture contents fell, in general, below the WP. Unexpectedly, we found an exception in the straw mulch and control at 70 cm. This indicates that the water storage, especially in depth, can persist even during long dry periods, likely favored by the characteristics of the soil in this study. For an establishing seedling, root systems that are able to grow and reach these layers have higher probabilities of survival and growth (Padilla and Pugnaire, 2007; Pinto et al., 2012). While at times the soil water was below the characteristic wilting point for this type of soil, holm oak has been shown to be quite resistant to these types of stress. Fotelli et al. (2000) observed that 2-yr-old seedlings were tolerant to conditions well below the wilting point (1500 kPa), with measured predawn water potentials of -3700 kPa. In spite of it, these results indicate that the desirable holm oak stocktype for these dry environments should have a root container as long as possible, preferably >40 cm deep. New research focusing in this direction would be highly recommended.

Correlation among monthly-averaged θ and precipitation was strong and showed a similar pattern for mulching and control treatments at 10 and 20 cm in depth, but correlation coefficients proved weaker at deeper soil layers, especially under straw-mulching and control treatments, displaying a higher independence from rainfall events with regard to rock fragments (see Fig. 2a and b in Supplementary material). Something similar happened with the correlation among monthly-averaged θ and monthly air temperature, with low or even no correlation at 70 cm in depth. Therefore, dynamics of soil moisture content at deeper soil layers seems to be more influenced by other factors such as soil type, parent material, presence of caliche horizon, gravel content, etc., and in some extent by mulching, specially rock-fragment cover which can lightly change these relationships.

4.2. Mulching effects on soil moisture

Several studies in the literature analyze the mulching effects of straw and rock fragments. These studies investigate the mulching of outplanted seedbeds, seedlings, or saplings with the aim of promoting vegetation recovery after fire (Kruse et al., 2004), forest operations

(thinning, clearing, etc.), land abandonment (Dostálek et al., 2007), mine reclamation, or forest-stand restoration (Valdecantos et al., 2009; Fehmi and Kong, 2012). Similarly, straw and rock-fragment mulches have been used to boost crop production in agriculture, and to control runoff and erosion in drylands (Chase and Boudouresque, 1987; Acharya et al., 1998; Jordán et al., 2010). In general, straw and rock-fragment mulches improve the soil-moisture content (see Athy et al., 2006, for an exception). Unlike our study, most of these studies have analyzed soil moisture over short periods of time (one growing season), in the upper layers of the soil profiles, or have recorded discontinuous measurements (Pérez 2009; Abu-Zreig et al., 2011; Pulido et al., 2014; Valdecantos et al., 2014). This is more relevant in Mediterranean areas where there is a lack of precise information concerning the long-term effects of straw and rock-fragment mulches for forest-restoration proposals. In this work, we provide mean daily and monthly data (recorded every 30 min) over three growing seasons, measured at four soil depths (10, 20, 40, and 70 cm).

Straw mulch showed a higher capacity for soil-moisture storage throughout the soil profile (except at 10 cm). This agrees with Jordán et al. (2010) and Rhoades et al. (2012), who found greater soil moisture under straw-mulched soils. Jordán et al. (2010) attributed these mulch effects to the improved soil porosity, aggregate stability, more abundant organic matter, lower bulk density, and thus enhanced infiltration and available water capacity. However, these studies were performed only in the upper 10 cm of the soil profile. While our average (daily and monthly) θ values at 10 cm were indeed lower, it is possible that improved infiltration allowed a greater amount of soil moisture to leach deeper into the soil profile, thereby leaving less in the upper 10 cm, especially during winter and spring of 2011, when precipitation increased θ under straw mulch to a maximum of 15%. Soil moisture continuously augmented in the deeper soil layers with 70 cm in depth reaching 26% θ . The control and rock-fragment treatments received the same precipitation but showed larger θ maximums in the shallower profile and smaller θ in the deeper profiles (Fig. 2). A possible benefit of better infiltration, as seen with the straw mulch, is longer soil-moisture storage at depth after precipitation ceases (see Fig. 4). Valdecantos et al. (2009) made similar observations in mulched planting holes compared to unmulched ones, especially in periods when water availability was lower. These authors, as well Rhoades et al. (2012), linked this increased soil-moisture content primarily to reduced temperature at soil surface under the mulch layer.

With regard to lithic mulches (gravels, pebbles, cobbles, blocks, basaltic tephra, etc.), different authors have reported reduced runoff and erosion, reduced soil temperature, greater water infiltration, and lower evaporation due to the disruption of capillarity (see Zhang et al., 2016 for a review), all of which increase soil moisture with depth, creating a more suitable environment for plant establishment and growth than in unmulched soils (Pérez, 1998; Li, 2003; Tejedor et al., 2003; Yuan et al., 2009; Ma and Li, 2011). Also, it has been reported that soil moisture increases with stone cover (Abu-Zreig et al., 2011), with stone size (Pérez, 1998), or thickness of rock mulch layers (Ma and Li, 2011).

In our study, rock-fragment mulch proved better at preserving soil moisture, compared to the control, but only for soil depths ≤ 20 cm (Fig. 1). This contradictory result could be due to the greater water-holding capacity of the caliche used as the lithic mulch in our experiment, revealing excessive rainfall interception. This rock mulch could be acting as a sponge, ameliorating the soil-water moisture only in the upper soil profile (10–20 cm) but hindering water infiltration to deeper soil layers. In fact, Hennessy et al. (1983) demonstrated that water absorption and retention by hard caliche rocks was rapid and water content at saturation was 13% by weight (24.7% by volume). In this sense, more research is needed on the effects of different parent materials when used as lithic mulch. Moreover, Pérez (2000), and Li et al. (2000, 2005) reported a threshold of mulch thickness to avoid excessive water interception, especially during low-intensity events of rainfall.

Despite the lack of deep infiltration indicated by our results concerning to rock fragments, outplanted nursery seedlings may still benefit. Nursery seedlings are often produced in containers that are short in root length. For the first growing season, this equates to the area where a large proportion of water uptake for physiological functioning occurs, as seen in Pinto et al. (2016a, 2016b). Jiménez et al. (2016) found higher survival and growth of 1-year-old holm oak seedlings in planting beds mulched with straw and rock (caliche) compared to their control, nine years after outplanting. This finding might also be of interest for plantations with small seedlings of conifers and other species with superficial root systems.

4.3. Mulching effect on holm oak growth

In dry Mediterranean areas, soil moisture is considered the main limiting factor to survival and growth. In our study, soil-water content was improved by mulch treatments (partially in the case of rock fragments); however, no statistical differences were found in the mean cumulative growth of the holm oak saplings. We attribute the lack of significant data to one of, or a combination of, several factors. After outplanting, we irrigated the saplings 3 times during the dry season. These irrigations caused noticeable increases in soil moisture throughout the soil profile. Because holm oaks are physiologically adapted to dry areas (Tognetti et al., 1998), very slow growing (Ibáñez et al., 1999), and opportunistic regarding soil moisture (Fotelli et al., 2000), we suggest that these irrigations to canceled initial establishment differences due to treatments. Another factor may have been the low number of replicates ($n = 3$), which, in combination with the intrinsic high genetic variability of the *Quercus* genus (Michaud et al., 1992), likely caused very high variability in holm oak responses to treatments.

Also, because (as mentioned above) holm oak is a slow-growing species, the study period may not have been long enough to detect the mulching effect on sapling growth, and more sampling periods may be needed to detect mulch effects. Jiménez et al. (2016) found no differences in growth among mulched holm oak seedlings until four years after outplanting. In another study, using the same holm oak sapling nursery stock as in this study, Jiménez et al. (2014) observed higher survival with straw mulch ($n = 36$) than the control ($n = 43$) and rock (caliche) mulch ($n = 27$), but they detected no growth differences among treatments three years after outplanting. Despite the differences in soil moisture among mulching treatments, our digital dendrometer data revealed that both mulches, especially the straw, provided more mean growing days and fewer decreasing days (days under physiological stress) than in control. This might be because holm oak saplings could be taking water mainly from the uppermost soil layers (10, 20 cm). In fact, decreasing growth periods were detected with soil moisture still remaining above wilting point at 70 cm depth, signifying that their roots had not likely reached this soil layer.

5. Conclusions

This 3-year field experiment demonstrates that the application of straw or rock-fragment (caliche) mulches changed the spatial and temporal soil-moisture distribution pattern throughout the soil profile. This was especially true for straw mulch, which favored water infiltration and soil-water storage at 20, 40, and 70 cm in depth. By contrast, the rock-fragment mulch ameliorated the soil moisture only at 10 and 20 cm in depth with respect to the control, decreasing the water storage in deeper soil layers, likely because the greater rainfall interception (by water absorption and retention of the caliche rocks). Nevertheless, both types of mulch lengthened the number of growing period days and shortened the number of days of physiological stress in the holm oak saplings. With these results, and given the particular field conditions of this experiment, straw mulch would be recommended for plantations of seedlings or saplings with longer initial root systems (i.e. deep containers, > 20 cm), whereas mulches with caliche-type rock fragments

would be more suitable for small seedlings with shorter initial root systems (i.e. shorter containers, < 20 cm), or for species with superficial root systems. These findings also illustrate the need for more research on the effects of the parent materials of lithic mulch as well as their thickness under different climatic conditions.

Acknowledgements

We thank the Agriculture, Fisheries and Environmental Council (Junta de Andalucía) for financial support provide by Convenio de Colaboración no. 372 and the members of the Forest Management for Conservation Research Group (PAIDI AGR-245) from the IFAPA and EEZ-CSIC for their invaluable assistance. M.N. Jiménez was sponsored by the Operating Programme of the European Social Found for Andalucía (2007–2013). We also thank to two anonymous reviewers for their valuable comments and suggestions to improve the manuscript. Thanks to David Nesbitt for checking the English.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.catena.2017.01.021. These data include the Google map of the most important areas described in this article.

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