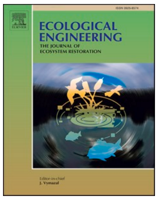
Ecological Engineering 178 (2022) 106579

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Post-fire restoration effectiveness using two soil preparation techniques and different shrubs species in pine forests of South-Eastern Spain

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ARTICLE INFO

Keywords:
Reforestation
Soil preparation
Species richness
Diversity
Wildfire
Post-fire management

ABSTRACT

Wildfires completely remove the vegetal cover, affect plant diversity and promote soil erosion in the forest ecosystems. Reforestation is essential to recover these important forest components, also in view of the forecasted climate change. Clear indications about suitable soil preparation techniques and a cautious choice of the planted species for successful reforestation actions are needed by forest managers. To improve this knowledge, this study, carried out seven years after a wildfire in a forest area of Central-Eastern Spain, evaluates: i) the short-term effectiveness of a post-fire reforestation work on growth and diversity of planted species, using ten types of shrubs and two soil preparation techniques (machinery planting spot, MPS, and linear subsoiling, LS); ii) the short-term effects of MPS and LS techniques on naturally regenerated plants. In the reforestation work, four of the ten planted species (*Pistacia lentiscus* L., *O. europaea* var. *sylvestris* L., *Rhamnus lycioides* L., *Rosmarinus officinalis* L.) showed the highest survival rate, while all individuals of *E. fragilis* Desf., *Arbutus unedo* L., *Viburnum tinus* L., and *P. angustifolia* L. were dead. Our results showed that *P. lentiscus* L. and *O. europaea* var. *sylvestris* were the species with the highest abundance in the soils treated with MPS and LS, respectively. In relation to naturally regenerated plants, higher number and height of plants were found in areas treated with LS. Both soil treatments influenced the plant diversity, although the species richness decreased in the treated soils compared to the burned and not treated areas. Overall, this study suggests that *P. lentiscus* appears as the most suitable reforestation species under the experimental conditions. Moreover, soil preparation is not ideal for reforestation after a wildfire, due to the lower regeneration, survival, and species richness found in treated plots in comparison to the burned and not treated areas.

1. Introduction

On an ecological approach, Mediterranean forests are threatened by many disturbing actions, such as climate change, deforestation, wildfires (Zema et al., 2020). Natural or anthropogenic fires modify the properties of the forest ecosystems, and these changes may trigger typical living traits of vegetation (Bodí et al., 2012). At the same time, fire disturbance adversely affects the hydrological processes in the Mediterranean forests, with a hazardous hydrological response to heavy storms, especially in hot and dry summers (Lucas-Borja et al., 2018; Zema et al., 2020). Moreover, the forest ecosystems, which have been able to maintain their evolution for millennia, have been affected by increasingly recurrent disturbances (Pausas, 2004), as a consequence of global change, both in climate and land use (Flannigan et al., 2000). Two other factors have recently summed up to these disturbances, such as the depopulation of the rural environment and the consequent lack of land management (Cerdá & Doerr, 2008).

Plants can develop evolutionary adaptation strategies, such as xerotiny, in the case of pine trees (typical of forest species that is defined as *fire-embracer*), regrowth or development of thick bark, in the case of oak trees (the so-called *fire-tolerance*), or existence of pyrophytic species, such as the *Cistaceae* (Pausas, 2011). The ecological restoration of

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https://doi.org/10.1016/j.ecoleng.2022.106579
Received 3 December 2021; Received in revised form 9 February 2022; Accepted 15 February 2022
Available online 21 February 2022

endangered forests completely depends on contexts in which either active reforestation or passive recovery become appropriate (White and Long, 2019). For example, different fire severities could promote non-forested communities, such as meadows, shrubfields, and open forests with significant hardwood components; moreover, reforestation in such areas may run counter to restoration of ecosystem functions. This is the case of the restoration actions with the invasive *Acacia saligna* from Australia, which have caused elevated soil nitrogen of South African fynbos, which disrupts the ecological functions, since the native shrubland is adapted to low levels of soil nutrients (Yelenik et al., 2004).

To face off this scenario and its negative impacts on the environment, a suitable forest planning by both hydrological control works and reforestation actions is needed to mitigate the effects on soils and natural capital (Aronson et al., 2007; Vallejo et al., 2009). These actions also accelerate the regeneration of biological processes through adequate revegetation (Esteve et al., 1990). Reforestation restores the pre-fire vegetation cover and helps to improve the soil's hydrological properties in areas affected by wildfires (Zema, 2021). However, the restored vegetation cover may be less dense and stable compared to the natural species, and its diversity may be much lower. Moreover, after seeding, the forest seedlings need much time (many months or years) to grow in new field conditions (Wittenberg et al., 2020).

Restoring the original diversity of forests is essential, because plant diversity increases the resilience of the forests against the face of possible disturbances, before the common monospecific reforestation (Cortina et al., 2004; Maestre and Cortina, 2004). Soil preparation techniques (e.g., tillage, conditioning, and terracing) are viable actions to support the restoration of plant growth and diversity, and are important to reduce the post-fire hydrological response of soil (e.g., (de Almeida et al., 2018; Meena et al., 2020; Nunes et al., 2018). However, when used for post-fire management, these techniques may be less beneficial for improving soil quality and hydrology (e.g., (Lopes et al., 2020) and expensive, when very large forest areas must be treated. In this direction, research must consider the integration of the most effective post-fire techniques for vegetation restoration with soil management techniques, to enhance the effectiveness of the reforestation works in terms of plant density and diversity.

Reforestation of wildfire-affected areas with shrubs species plays a key role among the anti-erosive actions (Zhang et al. 2008). This role is essential in Mediterranean areas, that are exposed to high wildfire risk; here, precipitation shortage may affect tree species regeneration and growth. Moreover, reforestation works show adverse characteristics towards post-fire plant regeneration (e.g., long periods of drought, shallow soils with low organic matter content, intense erosion rates) (Morán-Ordóñez et al., 2020). Woody plants may provide a favorable microclimate that facilitates regeneration and growth of their offspring as well as other plants (Holmgren and Sheffer, 2001). For example, *A. splendens* shrubs act as a nurse species, increasing the richness and facilitating the seedling recruitment in semiarid grasslands (Gonzalez and Ghermandi, 2019). The facilitation of recruitment depends on the availability of microsites that provide suitable conditions for seed germination and seedling establishment. The adaptability of any woody plant species in harsh environment depends on suitable conditions, which include adequate temperature, light, soil moisture, and protection from herbivory (Padilla and Pugnaire, 2006). Additionally, the beneficial plant-plant interactions (nurse-plant syndrome) also influence the adaptive nature of the reforested species in the restoration programs.

Extensive afforestation programs have been conducted in several catchments of Spain to protect headwater areas, regulate stream flow, reduce flash floods, control soil erosion, and provide forest products. However, in other regions with Mediterranean-type climate, such as South-Western Australia, South Africa, and California, the strongest emphasis on restoration actions has been given the control of invasive alien species. To address the challenges posed by tdrought in post-fire species establishment, restoration and soil management must be adaptive, managing the landscape to facilitate species recruitment.

Restoration plans in degraded lands usually require improving the water use efficiency for plant survival and growth. A wide range of soil preparation techniques has been developed to ensure sufficient water supply to plant seedlings and improve the physico-chemical properties of soil. In addition, some different plant species may be better adapted to post-fire conditions than others. To integrate the literature about the effects of different soil preparation techniques on post-fire plant recovery, it is important to evaluate whether a technique is effective or not on real-scale case studies and in the short-term. To this aim, this study evaluates: i) the short-term effectiveness of a post-fire reforestation work on growth and diversity of planted species, using ten types of shrubs and two soil preparation techniques (machinery planting spot, MPS, and linear subsoiling, LS); ii) the short-term effects of MPS and LS techniques on naturally regenerated plants. The field investigation has been carried out in a forest area of Central-Eastern Spain. We have hypothesized that the MPS and LS techniques: (i) would lead to a variability in the seedling survival and growth of each of the ten different types of shrubs in post-fire reforestation; and (ii) have a profound influence on naturally regenerated plants performance and diversity.

2. Materials and methods

2.1. Study area

The study area is located in the municipality of Hellín (Castilla La Mancha, Central-Eastern Spain, X: 613500, Y: 4250000, ETRS89 UTM zone 30 N) (Figure 1).

According to the classification by Koppen (Kottek et al., 2006), the area has a semiarid Mediterranean climate, BSk class. The average annual temperature and precipitation are 16 °C and 350 mm, respectively. Rainfalls are concentrated in spring and autumn, often with heavy torrential rains. Five to six months (from late spring to early autumn) are very hot and dry.

In July 2012, Sierra de los Donceles forest was devastated by a fraudulent wildfire, which burned about 6500 ha. In Sierra de los Donceles catchment, an area of about 3 km^2 (Prado Piñero y Hoya de los Ballesteros) was selected in the middle of the wildfire-affected forest at a distance of more than 2 km from unburned sites (July 2019).

On a geological approach, the municipality of Hellín is characterized by a high geological complexity, with large differences in elevation (300 to 650 m a.s.l.) and a mean slope of about 20% with a very high variability (from 3% to 100%). The area is framed in the Prebetic zone, mostly presenting dolomitized limestones, marls, and clays (Gómez-Sánchez et al., 2017). According to the Spanish geologic map of Spain of 1982, three types of lithological materials are identified in the study area: (i) Jurassic; Dogger + Lias, represented by dolomitic limestones with intercalations of green and red marls (undifferentiated); (ii) Tertiary, Neogene, Miocene-Upper Miocene: Turolian, in the case of Dolomites and massive oolitic limestones; and (iii) Quaternary; Holocene, in particular alluvial fans, conglomerates, crusted sands and silts.

Heavy rains are a common driver for removal of much of the topsoil. However, due to the long interactions between climate and soil in the study area, all samples in the area showed thin soil layers, with no more than 25 cm of depth in all sampled sites.

On an ecological approach, pre-fire and post-fire vegetation features can be differentiated, and these differences may be the result of the natural or anthropogenic alterations in the plant community. More specifically, pre-fire vegetation is dominated by *Pinus halepensis* Mill. of natural origin in the valleys, and by reforested species - together with *Pinus brutia* Ten., – during the '1980s. Shrub and herbaceous vegetation include *L. latifolia* Medik., *T. vulgaris* L., *Macrochloa tenacissima* (L.) Kunth., *Q. coccifera* L., *Rosmarinus officinalis* L., *Belostoma retusum* (Pers.) Beauv., *C. clusii* Dunal., *H. stoechas* (L.) and *P. albicans* L. It is worth noting the presence of an understory that is densely covered by *M. tenacissima* (L.) Kunth, used by the paper industry in the area during the second half of the last century (Sánchez Sanz, 1982). Post-fire

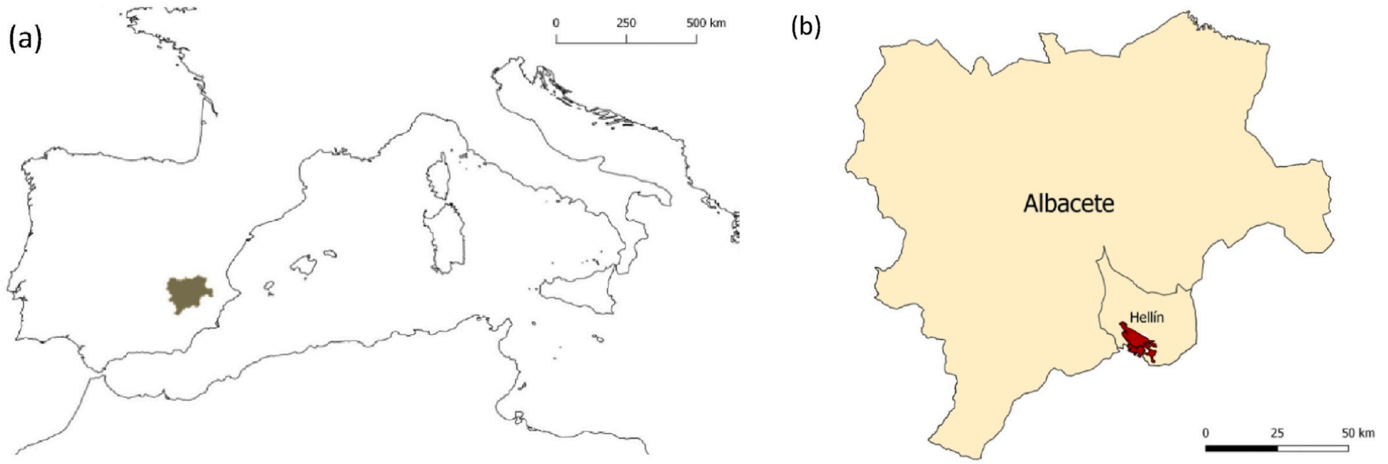

Fig. 1. - Geographical location of the study site (Prado Piñero y Hoya de los Ballesteros, Albacete, Castilla La Mancha, Spain).

vegetation consists of degraded Mediterranean forest, where the ability of new seedlings to re-sprout and recruit after the fire is a common characteristic in this type of environment (Pausas, 2004). This ability maintains persistent forest stands in environments with recurrent fires (Pausas, 2011), consisting of pyrophytic species, such as *Cystaceae* of the genus *Fumana* sp., leguminous shrubs for grazing, such as *Pistacia lentiscus* L., and perennial grasses, such as *B. retusum* (Pers.) Beauv. and *M. tenacissima* (L.) Kunth.

2.2. Description of the reforestation works in the area

To facilitate the survival of the small seedlings after planting, two soil treatments were carried out during the spring of 2013:

- machinery planting spot (hereinafter indicated by "MPS"), consisting of the extraction of a soil portion to bed the plants in the hole. The extracted soil core had an area of 40 cm × 40 cm or 60 cm × 60 cm and a depth of 30, 40, and 60 cm. The planting machinery was equipped with an excavator bucket, to open holes on steep slopes (70% to 100%) or stony soil. These holes favour the plant establishment, since the soil is oxygenated and wetted more easily and the plant develops the root system more quickly. The purpose of machinery planting spots is to create desirable planting spots in mineral soil or in mixed mineral-organic soil. In addition, increased soil temperature and moisture resulting from this treatment may provide advantages for seedling growth. Planting spots are normally below the original ground level, therefore temporary standing water may occur. Thus, different planting spots may be chosen depending on, for example, the moisture regime at the site.
- linear subsoiling ("LS"), consisting of breaking the soil horizons without mixing, facilitating the deepening of plant roots and water infiltration. Subsoiling is for dry soils, reclaimed mined sites or for soils that have a compacted surface layer, but more often below the soil surface, which restricts root growth and plant development.

MPS or LS were alternatively implemented, depending on the possibility to use one type of machinery or another. MPS was applied in steeper slopes (from 20 to 30%) at a depth of about of 40 cm, using an excavator (Figure 2a). LS was applied in the areas with lower slope and east-west orientation, following the contour lines and using ripper depths of 60 cm. A single-toothed 65-cm ripper with furrows spaced 240 cm apart (Figure 2b).

The total area of the soil treatments within the study area was in the range 21.58 (MPS) to 14.82 ha (LS), totaling 36 ha. A further control area, which was burned, was not subjected to soil treatments and established for monitoring the growth and diversity of naturally-regenerated plants. Finally, plants of ten forest species with the highest number of *P. lentiscus* were bedded under the two soil conditions (MPS and LS) at a density of 500 plants per ha for all species. More in detail, the number of the planted shrubs was 8000 for *P. lentiscus*, 3000 for *O. europaea, Rhamnus lycioides, Nerium oleander,* 2000 for *R. officinalis*, and 1000 for *P. angustifolia, E. fragilis, Viburnum tinus, Arbutus unedo,* and *Rhamnus alaternus*.

2.3. Experimental design

In the study area, 70 plots were randomly distributed to take into account the high variability of aspect and slope. Fourty plots were installed in the area treated with MPS (1.13 ha), 20 plots in the area with LS (0.75 ha), and the 10 remaining plots in the control area (five adjacent to the MPS plots, and another five close to the LS plots) (Figure 3). The plot shape was circular, with 10 m of radius and 314 m^2 of area. The reciprocal distance among the plots was between 100 and 300 m, to have as similar conditions as possible; the differentiating factor was only the soil treatment. In each plot, three transects were located with N-S orientation: a central transect of 20 m (on the circle diameter), and two other transects at 5 m from the central transect, each one with a length of 15 m. The soil slope was measured in all plots using a clinometer (Suunto).

2.4. Vegetation sampling and analysis

Due to the physiographic complexity of the study area, each individual of species was sampled for the reforested area, while sampling was carried out in transects for natural regeneration. The sampling procedure was therefore divided into two steps: (i) collection of data about the reforestation effectiveness and natural regeneration; and (ii) analysis of post-fire regeneration and difference in diversity between the burned and treated (MPS and LS), and burned and untreated areas. All the plants found in each plot were counted, and the height (by a plastic graduated tape), basal diameter (by a caliper), and as well as the physiological status were surveyed, the latter classified as living and dead (plants without or with less than 50% of foliar mass).

2.5. Statistical analysis

A two-way ANOVA was carried out, to evaluate the significance of differences in the reforestation and natural regeneration, the latter in comparison to the control plots (independent variables). The ANOVA factors were soil condition and slope for reforestation, and number, height of plants and species richness for natural regeneration.

The reciprocal relationships among the ten plant species used for the

Fig. 2. Soil preparation using machinery planting spots (a) and linear subsoiling (b) in the study area (Prado Piñero y Hoya de los Ballesteros, Albacete, Castilla La Mancha, Spain).

reforestation works were evaluated adopting a combination of other statistical techniques. First, the statistical differences in forest species were determined by the multivariate permutational analysis of variance (PERMANOVA) (Anderson, 2005), using the soil treatments (MPS and LS) as factors. PERMANOVA tests the simultaneous response of one variable to one or more factors in an experimental design based on any resemblance measure, using the permutation method. The sums of squares type were type III (partial) and the two-level (soil treatments) factor was a fixed effect. The permutation method used was the unrestricted permutation of raw data and the number of permutations was

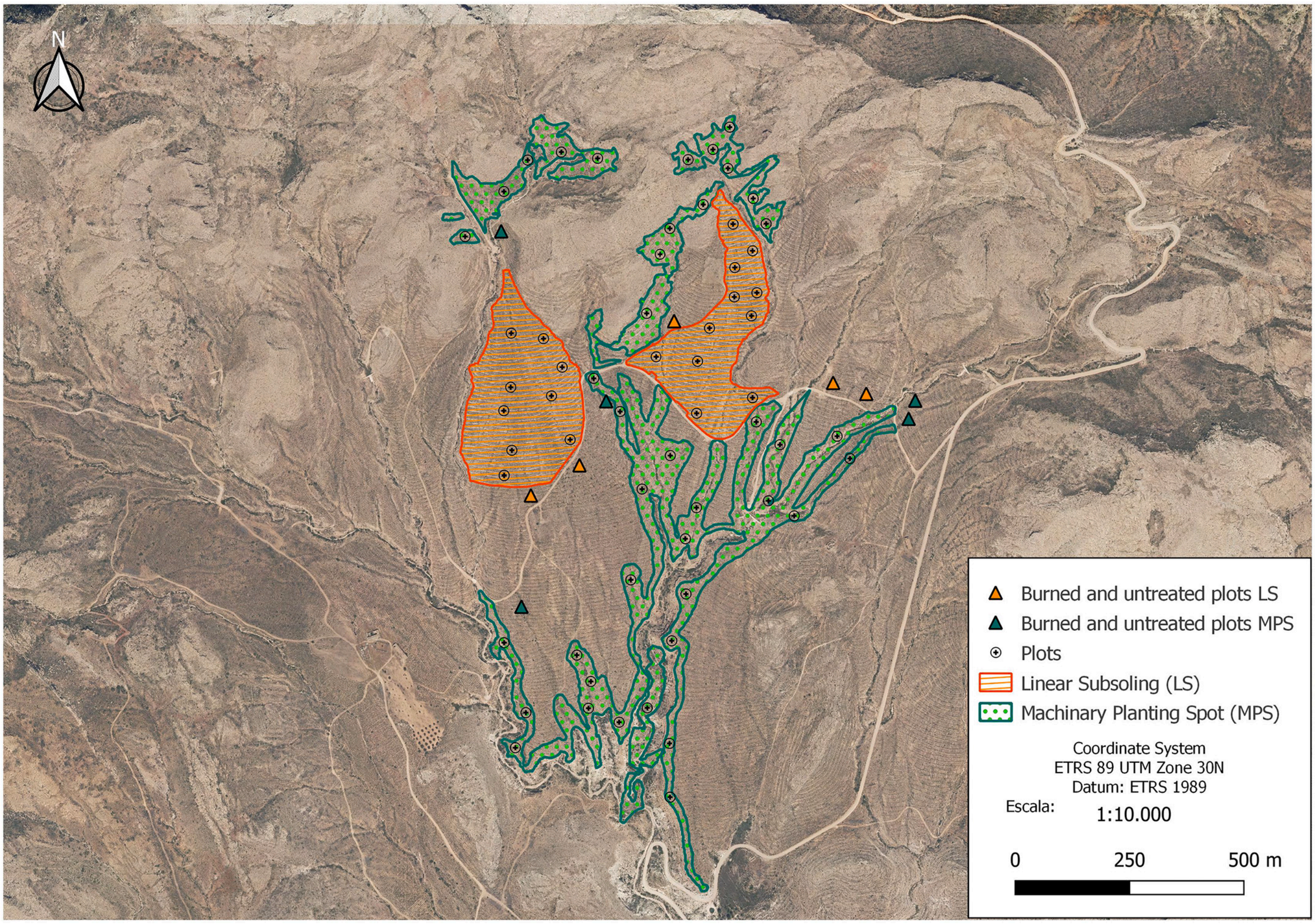

Fig. 3. Spatial distribution of the burned and untreated plots as well as plots treated using machinery planting spot, MPS and linear subsoiling, LS and for surveying shrub planted species in the study area together with plots used for evaluating plant performance and diversity (Prado Piñero y Hoya de Los Ballesteros, Albacete, Castilla La Mancha, Spain). Source: Google Earth V. 7.3.3.7786 (July 21, 2020). Prado Piñero y Hoya de Los Ballesteros, Albacete, Castilla La Mancha, Spain. 38.3909641 N, −1.6957586E, Eye alt. 620 m. DigitalGlobe 2020. https://earth.google.com [September 10, 2020].

999. Then, an analysis of similarities (ANOSIM), described by (Clarke, 1993), was carried out for the forest species, and the multivariate resemblances were analyzed, according to the soil treatments for both reforestation and natural regeneration.

For the statistical analyses, the software PRIMER V7® with PERMANOVA add-on (Anderson, 2005) and Statgraphics Centurion XVI® (StatPoint Technologies, Inc., Warrenton, VA, USA) were used. A significance level of 0.05 was used unless otherwise indicated.

3. Results

3.1. Short-term effectiveness of a post-fire reforestation work on planted species

Of the ten shrub species used in reforestation, only significant samples of six species were found to survive. Of the latter samples, four showed the highest survival rate (*Pistacia lentiscus* L., *O. europaea* var. *sylvestris* L., *Rhamnus lycioides* L., *Rosmarinus officinalis* L.), while the remaining two had the lower value rate (*Nerium oleander* L. and *Rhamnus alaternus* L.). Four species (*E. fragilis* Desf., *Arbutus unedo* L., *Viburnum tinus* L., *P. Angustifolia* L.) were not present in the inventory, and *A. unedo* L. even did not appear in the plots.

The two-way ANOVA showed that the slope or soil treatment significantly affected the number of survived plants ($p = 0.20$ and 0.56, respectively). The soil treatment with the lowest number of plant death was MPS (5.85 ± 0.56 vs. 6.55 ± 0.89 of LS). Moreover, according to ANOVA, none of the analyzed factors (soil treatment and slope) significantly influenced this number ($p > 0.40$). Despite this lack of significance, LS resulted in the highest number of dead plants (12.5 ± 1.65 vs. 10.6 ± 1.04 of MPS) (Table 1).

ANOSIM applied to the species planted in areas treated with MPS yielded a similarity of 28.4, and *Pistacia lentiscus* L. was the species with the highest abundance (mean of 2.27), contributing by 56.0% to the whole similarity (Table 2).

For the LS treatment, a similarity of 49.9 was found among the species. *O. europaea* var. *sylvestris* was the species with the highest abundance (mean of 2.15), contributing by 34.8% to the whole sample,

Table 1
Statistics of survived plants under different soil treatments (machinery planting spot and linear subsoiling) in the study area (Prado Piñero y Hoya de Los Ballesteros, Albacete, Castilla La Mancha, Spain).

Soil treatments	Sampled plants	Mean	(%)	Std. Dev.	(%)
Survival					
Machinery planting spot	40	5.85	14.6	0.56	1.4
Linear subsoiling	20	6.55	32.8	0.89	4.4
Death					
Machinery planting spot	40	10.57	26.4	1.04	2.6
Linear subsoiling	20	12.45	62.3	1.65	8.3

Table 2
Abundance and similarity of ten plant species used for reforestation under two soil treatments (machinery planting spot and linear subsoiling) in the study area (Prado Piñero y Hoya de Los Ballesteros, Albacete, Castilla La Mancha, Spain).

Plant species	Average abundance	Contribution (%)	Cumulated contribution (%)
Machinery planting spot (similarity = 28.4)			
Pistacia lentiscus	2.27	56.01	56.01
O. europaea var. *sylvestris*	1.11	15.6	71.61
Rosmarinus officinalis	0.81	10.9	82.5
E. fragilis	0.59	8.78	91.29
Linear subsoiling (similarity = 49.9)			
O. europaea var. *sylvestris*	2.15	34.76	34.76
R. officinalis	2.05	31.35	66.11
P. lentiscus	1.3	24.47	90.59

followed by *Rosmarinus officinalis* (mean abundance of 2.05) and *P. lentiscus* (1.30) (Table 2). Overall, 40.8% of dead plants and 22.3% of survived plants were found in MPS areas, while these percentages were 23.8% and 13.1% respectively for LS treatment (Table 3).

The analysis of the tables of presence/absence showed average similarities of 37.7 and 65.8 for MPS and LS treatments, respectively. *P. lentiscus* L. was the species with the highest presence under MPS treatment (mean abundance of 0.73), contributing by 50.6% to the whole similarity . For LS treatment, *O. europaea* var. *sylvestris*, *P. lentiscus,* and *R. officinalis* gave similar contributions (34.6%, 27.2%, and 26.5%, respectively) to the whole sample (Table 4).

3.2. Short-term effects of the soil preparation techniques on naturally regenerated plants

In the plots subjected to the LS treatment, a higher regeneration rate was detected compared to the MPS plots, both in number (significant at p-level < 0.01 of ANOVA) and in height (not significant, $p = 0.094$) of the regenerated plants. In more detail, 13.6 ± 7.7% of plants regenerated in LS plots, while this percentage was equal to 4 ± 4.3% in MPS areas. Both percentages were lower compared to the burned and untreated areas (19.8 ± 13.4%). Compared to the latter soil condition (0.61 ± 0.22 m), the height of regenerated plants was higher in the LS plots (0.82 ± 0.26 m) and lower in the MPS areas (0.58 ± 0.22 m) (Table 5).

ANOVA showed that MPS and LS treatments significantly ($p < 0.001$) influenced the species richness of the studied area. On soils subjected to MPS and LS, 9.02 ± 2.33 and 6.9 ± 2.79 species were detected, respectively, while the species richness was 11.2 ± 2.57 on burned and untreated soils (Table 6).

ANOSIM showed that the similarity between couples of soil conditions was not significant ($p > 0.05$), although the area treated with MPS and the control showed a noticeable similarity (19.8%) (Table 7).

Processing the data of species richness by ANOSIM separately for each soil condition, the following consideration can be drawn (Table 8):

- in the soils subjected to MPS, *R. officinalis, Macrochloa tenacissima,* and *Pinus halepensis* are the species that most contributed to this similarity (contribution >15%);
- under LS treatment of soils, *M. tenacissima, R. officinalis,* and *P. halepensis* were the most contributing species (contribution >15%);
- for the untreated soils, six species showed a contribution to this similarity higher than 10% (*F. thymifolia, M. tenacissima, T. capitatum, R. officinalis,* and *H. syriacum*).

Table 3
Number and percentage of plants dead and survived under two soil treatments (machinery planting spot and linear subsoiling) after reforestation in the study area (Prado Piñero y Hoya de Los Ballesteros, Albacete, Castilla La Mancha, Spain).

Soil treatment	Dead		Alive	
	(n.)	(%)	(n.)	(%)
Machinery planting spot	424	40.8	232	22.3
Subsoiling	248	23.8	136	13.1
Total	672	64.6	368	35.4

Table 4
Table of presence/absence of ten species used for reforestation under two soil treatments (machinery planting spot and linear subsoiling) in the study area (Prado Piñero y Hoya de Los Ballesteros, Albacete, Castilla La Mancha, Spain).

Species	Average abundance	Average similarity	Contribution (%)	Cumulated contribution (%)
Machinery planting spot (similarity = 37.7)				
Pistacia lentiscus	0.73	19.1	50.6	50.6
O. europaea var. sylvestris	0.43	5.32	14.1	64.7
E. fragilis	0.35	4.61	12.2	77.0
R. s officinalis	0.41	4.54	12.0	89.0
Rhamnus lycioides	0.30	2.29	6.1	95.1
Linear subsoiling (similarity = 65.8)				
O. europaea var. sylvestris	0.85	22.75	34.6	34.6
P. lentiscus	0.75	17.93	27.2	61.8
Rosmarinus officinalis	0.75	17.45	26.5	88.3
R. lycioides	0.50	7.68	11.7	100

Table 5
Statistics of the number and height of naturally regenerating plants under different soil conditions (burned and untreated, and soil treatments using machinery planting spot and linear subsoiling) in the study area (Prado Piñero y Hoya de Los Ballesteros, Albacete, Castilla La Mancha, Spain).

		Soil condition		
		Burned and untreated	*Machinery planting spot*	*Linear subsoiling*
Sampled plants		11	64	30
Number	*Mean*	2.18	2.56	4.07
	Std. Dev.	1.47	2.72	2.30
	Min	1	0	1
	Max	6	20	9
Height	*Mean*	0.61	0.58	0.82
	Std. Dev.	0.22	0.22	0.26
	Min	0.35	0.20	0.21
	Max	0.90	1.20	1.30

Table 6
Statistics of species richness (number of species) under different soil conditions (burned and untreated, and soil treatments using machinery planting spot and linear subsoiling) in the study area (Prado Piñero y Hoya de Los Ballesteros, Albacete, Castilla La Mancha, Spain).

Soil treatment	Sample number	Mean	Std. Dev.	Min	Max
Machinery planting spot	40	9.03	2.33	3	13
Linear subsoiling	20	6.90	2.79	4	14
Burned and untreated (control)	10	11.20	2.57	8	17
Total	70	8.73	2.82	3	17

Table 7

Comparison of species richness between couples of soil conditions (burned and untreated, and soil treatments using machinery planting spot and linear subsoiling) for the reforestation works in the study area (Prado Piñero y Hoya de Los Ballesteros, Albacete, Castilla La Mancha, Spain).

Groups	Significance R	*P*-value level (%)
Machinery planting spot vs. *Linear subsoiling*	0.103	1.1
Machinery planting spot vs. *Burned and untreated*	0.062	19.8
Linear subsoiling vs. *Burned and untreated*	0.503	0.1

Table 8

Contribution of soil conditions (burned and untreated, and soil treatments using machinery planting spot and linear subsoiling) to species richness after reforestation works in the study area (Prado Piñero y Hoya de Los Ballesteros, Albacete, Castilla La Mancha, Spain).

Species	Average abundance	Contribution (%)	Cumulated contribution (%)
Machinery planting spot			
Rosmarinus officinalis	1.00	20.5	20.5
Macrochloa tenacissima	1.00	20.5	40.9
Pinus halepensis	0.88	15.4	56.4
F. thymifolia	0.70	8.7	65.1
H. syriacum	0.58	6.0	71.1
A. cytisoides	0.58	5.9	77.0
Pistacia lentiscus	0.48	4.0	81.0
G. spartioides	0.43	3.6	84.6
L. fruticosa	0.40	2.9	87.5
T. antoninae	0.35	2.6	90.1
Linear subsoiling			
M. tenacissima	1.00	24.1	24.1
R. officinalis	0.95	21.8	45.9
P. halepensis	0.80	16.5	62.4
A. cytisoides	0.80	14.1	76.4
T. antoninae	0.60	8.8	85.2
G. spartioides	0.55	6.6	91.8
Burned and untreated			
F. thymifolia	1.00	14.6	14.6
M. tenacissima	1.00	14.6	29.1
T. capitatum	0.90	11.8	40.9
R. officinalis	0.90	11.5	52.4
H. syriacum	0.90	11.4	63.8
A. horridus	0.70	6.9	70.6
P. halepensis	0.70	6.3	77.0
G. spartioides	0.60	4.4	81.3
S. sediforme	0.50	3.5	84.8
A. cytisoides	0.50	3.1	87.9
F. hispidula	0.50	3.1	91.0

4. Discussions

4.1. Short-term effectiveness of a post-fire reforestation work on planted species

Different factors affect the survival and growth of seedlings in the Mediterranean region. First, soil hydrophobicity and moisture are two key factors influencing the survival and growth of regenerated plants, particularly in the dry season. Each soil preparation technique was carried out at different soil depths (40 cm for MPS and 60 cm for LS), and this may have influenced plant development and growth, since the microclimatic conditions may depend on soil depth. Soillope may also be another influential factor. Second, the difference in the survival rates of plants between the soil treatments may be explained by the capacity of each technique to trap soil moisture and cause a favorable microenvironment for individual species to take up water. Mechanical site preparation usually affects nutrient mobilization and distribution through the transport of soil moisture. This agrees with the study of Bayen et al. (2016), which reports that soil treatments affect the capacity of individual species to survive, and its water uptake is influenced by the root system size and distribution (Grossnickle, 2005).

In this study, six shrub species survived out of the ten species used in reforestation. Although the highest number of dead plants was found in the LS area, the soil treatments did not significantly affect the survival rate. However, the MPS treatment determined the lowest number of plant survival compared to LS. Moreover, the total number of both dead and alive plants after reforestation was higher in MPS areas compared to LS . This variation could be due to the resource requirement of the individual reforested species and available moisture content of soil under the treatments. The study conducted by Matías et al. (2011) reported that the soil moisture in summer significantly affected the seedling survival and growth in a Mediterranean mountain ecosystem. Fireline intensities could also affect the level of shrub recruitment in semi-arid woodland (Hodgkinson, 1991).

Finally, the vegetation in the areas subjected to LS showed a noticeable similarity, to which *Olea europaea* var. *sylvestris* mainly contributed, while, under the MPS treatment, the most contributing species was *P. lentiscus* L. The results of the study are consistent with those of Newmaster et al. (2007), where different intensities of mechanical site preparation (MSP) treatments created a variety of microsites and influenced species richness and abundance (percent cover) of woody plants. Moreover, MSP treatments also decreased species richness of the understorey plant communities and increased the number of non-native species in lowland floodplain forests of the Czech Republic (Sebesta et al., 2021).

These results are the key message of this study, which have demonstrated that the soil preparation is not ideal for reforestation after a fire, due to the lower regeneration, survival, and species richness in comparison to the burned and not treated areas.

4.2. Short-term effects of the soil preparation techniques on naturally regenerated plants

After the reforestation works in the study area, the number of regenerated plants was higher in burned and untreated sites compared to the plots subjected to the soil preparation techniques. Moreover, the latter influenced the number and height of plants. Comparing the effectiveness of the two soil preparation techniques, the number and height of regenerating plants were higher under the LS treatment, but only the difference in number was significant. These results indicate that the MPS treatment may not be the optimal method for ecologically-sustainable approaches to conserve understorey vegetation diversity in post-fire forest management, at least in the experimental conditions. On this regard, it is worth to mention that some of the plant species may be affected by the machinery impact on soil surface, which alters plant diversity after wildfires (Carrari et al., 2022). Furthermore, the significant difference in height of the regenerated plants in the LS treatment may arise from the nutrient mobilization in soil and species-specific impacts on ecosystem processes. Unfortunately, this investigation has been carried out in rather homogenous soil types, which hampers the analysis of the feasibility of the two techniques for different terrains.

Restoration of natural fire regimes is one of the greater challenges in landscape management of the Mediterranean forest ecosystem. Soil treatments are commonly used in many degraded lands for reintroducing native plants and recovering critical ecosystem functions. The present study has shown that both MPS and LS treatments have significantly lowered the species richness of the treated area compared to the burned and untreated soils. The comparison of the similarity of species richness between the experimented soil conditions was not significant, and the area treated with MPS and the burned and not treated areashowed a noticeable similarity.

This study also confirms the negative response of regenerated plant diversity and richness to the mechanical treatment, which is in agreement with Haeussler et al. (1999), who reported that high-severity mechanical treatments appear to cause a substantial change to plant communities, while moderate treatments can improve plant growth. Similarly, Košulič et al. (2020) stated that intensive management actions in forests, such as the mechanical site preparation, significantly contributed to decrease the plant diversity. Moreover, Haeussler et al. (1999) demonstrated that medium and high-severity mechanical soil treatments affect species diversity by reducing or eliminating species that recover slowly from soil disturbance.

The relative abundance of plant species in a community depends on the specific requirement of the resources. Species distributions and abundance across plant communities can be explained by the tolerance to resource availability among coexisting species (Schreeg et al., 2005) and the variation in tolerance of species becomes significant for species with different life forms (e.g., trees or shrubs) or from different successional stages (e.g., pioneers, mid-successional or late-successional).

In this study, in the MPS and LS treatments, *R. officinalis, M. tenacissima,* and *P. halepensis* were the species that most contributed to the overall similarity within the plant communities. *M. tenacissima* species had the highest contribution in both soil treatments. In contrast, in the untreated soils, five species (*F. thymifolia, M. tenacissima, T. capitatum, R. officinalis,* and *H. syriacum*) influenced the similarity with a contribution higher than 10%. Each plant species responds differently to mechanical soil treatments: for example, some species may benefit from mechanical treatments and sometimes favour the growth of other species. The use of heavy machinery in soil treatments can even affect the soil hydrological properties through compaction of the topsoil and consequently influences the seedling survival and growth. However, the effects of soil treatments with higher severity on sensitive species could be minimized by leaving untreated patches (Haeussler et al., 1999).

Overall, the functionality of each species must be clearly understood, to increase the success level of reforestation efforts. The knowledge on the effect of disturbance regimes at multiple scales helps to understand the abundance and spatio-temporal dynamics of species diversity in post-fire reforestation (Sebesta et al., 2021). Thus, an adaptive restoration approach is widely suggested (Ramón Vallejo et al., 2012), based on plant abundance, similarity of the species at the plot scale, improved plant quality, suitable techniques for water use efficiency of the native plant species in the regions affected by different fire regimes.

5. Conclusions

In the post-fire reforestation work, using shrubs and two soil preparation techniques (machinery planting spot and linear subsoiling),of the ten planted species, four (*P. lentiscus* L., *O. europaea* var. *sylvestris* L., *Rhamnus lycioides* L., *R. officinalis* L.) showed the highest survival rate, while many species (*E. fragilis* Desf., *Arbutus unedo* L., *Viburnum tinus* L., *P. angustifolia* L.) were practically dead. Neither the slope nor soil treatment significantly affected the number of survived plants, and the lowest mortality of plants was recorded under the MPS treatment. *P. lentiscus* L. and *O. europaea* var. *sylvestris* were the species with the highest abundance in the soils treated with MPS and LS, respectively. Both soil treatments influenced the diversity of the reforested area, although the species richness decreased in treated soils compared to the burned and untreated areas. While in the latter soils, one of the ten planted species contributed to species similarity, in the soils subjected to both MPS and LS, *R. officinalis, M. tenacissima,* and *P. halepensis* were the species that most contributed to this similarity.

The number and height of regenerating plants were higher under the LS treatment compared to the areas treated with MPS. However, the number of regenerated plants and species richness were the highest in burned and untreated sites. Thise results indicate that the soil treatments after reforestation works, especially the MPS treatment, may not be the optimal method for ecologically-sustainable approaches to conserve understorey vegetation diversity in post-fire forest management, at least in the experimental conditions.

Overall, the findings of this study help the delicate tasks of forest managers in restoration activities after wildfires, suggesting that soil preparation is not convenient, due to the lower regeneration, survival, and species richness. *P. lentiscus* appears as the most suitable reforestation species under experimental conditions.

CRediT author statement

Conceptualization and Data Curation (Manuel Esteban Lucas-Borja, Maria Elena Gómez-Sánchez), Formal analisys and fieldwork (Rubén García Matallana, Maria Elena Gómez-Sánchez, Manuel Esteban Lucas-Borja), Writing – original draft (Manuel Esteban Lucas-Borja, S. M. Mijan Uddin, Demetrio Antonio Zema), Writing review and editing (Manuel Esteban Lucas-Borja, S. M. Mijan Uddin, Demetrio Antonio Zema).

Declaration of Competing Interest

None.

References

Anderson, M.J., 2005. Permutational Multivariate Analysis of variance, 26. Department of Statistics, University of Auckland, Auckland, pp. 32–46.

Aronson, J., Renison, D., Rangel-Ch, J.O., Levy-Tacher, S., Ovalle, C., Del Pozo, A., 2007. Restauración del Capital Natural: sin reservas no hay bienes ni servicios. Ecosistemas. 16, 15–24.

Bayen, P., Lykke, A.N., Thiombiano, A., 2016. The success of three soil restoration techniques on seedling survival and growth of three plant species in the Sahel of Burkina Faso (West Africa). J For Res 27, 313–320. https://doi.org/10.1007/s11676-015-0159-0.

Bodí, M.B., Cerdà, A., Mataix-Solera, J., Doerr, S.H., 2012. A review of fire effects on vegetation and soil in the Mediterranean Basin. In: Boletín de la Asociación de Geógrafos Españoles.

Carrari, E., Biagini, P., Selvi, F., 2022. Early vegetation recovery of a burned Mediterranean forest in relation to post-fire management strategies. Forestry: An International Journal of Forest Research cpab057. https://doi.org/10.1093/forestry/cpab057.

Cerdà, A., Doerr, S.H., 2008. The effect of ash and needle cover on surface runoff and erosion in the immediate post-fire period. Catena 74, 256–263.

Clarke, K.R., 1993. Non-parametric multivariate analyses of changes in community structure. Aust JEcol 18, 117–143. https://doi.org/10.1111/j.1442-9993.1993.tb00438.x.

Cortina, J., Bellot Abad, J.F., Vilagrosa, A., Caturla Cardona, R.N., Maestre, F.T., Rubio, E., Ortiz de Urbina, J.M., Bonet, A., 2004. In: Vallejo, R.V., Alloza, J.A. (Eds.), Restauración en semiárido. Capítulo 12, en“ Avances en el estudio de la gestión del monte mediterráneo”, pp. 345–406.

de Almeida, W.S., Panachuki, E., de Oliveira, P.T.S., da Silva Menezes, R., Sobrinho, T.A., de Carvalho, D.F., 2018. Effect of soil tillage and vegetal cover on soil water infiltration. Soil Tillage Res 175, 130–138. https://doi.org/10.1016/j.still.2017.07.009.

Esteve, M.A., Ferrer, D., Ramírez-Díaz, L., Calvo, J.F., Suárez Alonso, M.L., 1990. Restauración de la vegetación en ecosistemas áridos y semiáridos: algunas reflexiones ecológicas.

Flannigan, M.D., Stocks, B.J., Wotton, B.M., 2000. Climate change and forest fires. Sci Total Environ 262, 221–229. https://doi.org/10.1016/S0048-9697(00)00524-6.

Gómez-Sánchez, E., De Las Heras, J., Lucas-Borja, M., Moya, D., 2017. Ajuste de metodologías para evaluar severidad de quemado en zonas semiáridas (SE peninsular): Incendio Donceles 2012. Revista de Teledetección 49, 103–113. https://doi.org/10.4995/raet.2017.7121.

Gonzalez, S.L., Ghermandi, L., 2019. Dwarf shrub facilitates seedling recruitment and plant diversity in semiarid grasslands. PLoS One 14, e0212058. https://doi.org/10.1371/journal. pone.0212058.

Grossnickle, S.C., 2005. Importance of root growth in overcoming planting stress. New For 30, 273–294. https://doi.org/10.1007/s11056-004-8303-2.

Haeussler, S., Bedford, L., Boateng, J.O., MacKinnon, A., 1999. Plant community responses to mechanical site preparation in northern interior British Columbia. Can J For Res 29, 1084–1100. https://doi.org/10.1139/x99-057.

Hodgkinson, K.C., 1991. Shrub recruitment response to intensity and season of fire in a semi-arid woodland. J Appl Ecol 28, 60–70. https://doi.org/10.2307/2404113.

Holmgren, M., Sheffer, M., 2001. El Niño as a wt window of opportunity for the restoration of degraded arid ecosystems. Ecosystems 4, 151–159. https://doi.org/10.1007/s100210000065.

Košulič, O., Hamřík, T., Lvončík, S., 2020. Patterns of change in the species composition of vascular plants during different succession stages and management intensity of a lowland floodplain forest. Biologia 75, 1801–1813. https://doi.org/10.2478/s11756-020-00536-5.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World Map of the Köppen-Geiger climate classification updated. Meteorol Z 15, 259–263. https://doi.org/10.1127/0941-2948/2006/0130.

Lopes, A.R., Prats, S.A., Silva, F.C., Keizer, J.J., 2020. Effects of ploughing and mulching on soil and organic matter losses after a wildfire in Central Portugal. Cuadernos de investigación geográfica/Geographical Research Letters 46 (1), 303–318. https://doi.org/10.18172/cig.3768.

Lucas-Borja, M.E., Zema, D.A., Carrà, B.G., Cerdà, A., Plaza-Alvarez, P.A., Cózar, J.S., Gonzalez-Romero, J., Moya, D., de las Heras, J., 2018. Short-term changes in infiltration between straw mulched and non-mulched soils after wildfire in Mediterranean forest ecosystems. Ecol Eng 122, 27–31. https://doi.org/10.1016/j.ecoleng.2018.07.018.

Maestre, F.T., Cortina, J., 2004. Are Pinus halepensis plantations useful as a restoration tool in semiarid Mediterranean areas? For Ecol Manag 198, 303–317. https://doi.org/10.1016/j.foreco.2004.05.040.

Matías, L., Gómez-Aparicio, L., Zamoraa, R., Castro, J., 2011. Effects of resource availability on plant recruitment at the community level in a Mediterranean mountain ecosystem. Perspect Plant Ecol Evol Syst 13, 277–285. https://doi.org/10.1016/j.ppees.2011.04.005.

Meena, R.S., Lal, R., Yadav, G.S., 2020. Long-term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363, 114164. https://doi.org/10.1016/j.geoderma.2019.114164.

Morán-Ordóñez, A., Duane, A., Gil-Tena, A., De Cáceres, M., Aquilué, N., Guerra, C.A., Geijzendorffer, I.R., Fortin, M.-J., Brotons, L., 2020. Future impact of climate extremes in the Mediterranean: Soil erosion projections when fire and extreme rainfall meet. Land Degrad Dev 31, 3040–3054. https://doi.org/10.1002/ldr.3694.

Newmaster, S.G., Parker, W.C., Bell, F.W., Paterson, J.M., 2007. Effects of forest floor disturbances by mechanical site preparation on floristic diversity in a Central Ontario clearcut. For Ecol Manag 246, 196–207. https://doi.org/10.1016/j.foreco.2007.03.058.

Nunes, J.P., Bernard-Jannin, L., Rodriguez Blanco, M.L., Santos, J.M., Coelho, C., Keizer, J.J., 2018. Hydrological and erosion processes in terraced fields: observations from a humid Mediterranean region in northern Portugal. Land Degrad Dev 29, 596–606. https://doi.org/10.1002/ldr.2550.

Padilla, F.M., Pugnaire, F.I., 2006. The role of nurse plants in the restoration of degraded environments. Frot Ecol Enviro 4, 196–202. https://doi.org/10.1890/1540-9295(2006)004[0196:TRONPI]2.0.CO;2.

Pausas, J.G., 2004. Changes in fire and climate in the eastern Iberian Peninsula (Mediterranean basin). Clim Chang 63, 337–350. https://doi.org/10.1023/B:CLIM.0000018508.94901.9c.

Pausas, J.G., 2011. Fire Shapes Plant Traits: Introduction & Evidence from the Mediterranean Basin.

Ramón Vallejo, V., Smanis, A., Chirino, E., Fuentes, D., Valdecantos, A., Vilagrosa, A., 2012. Perspectives in dryland restoration: approaches for climate change adaptation. New For 43, 561–579. https://doi.org/10.1007/s11056-012-9325-9.

Sánchez, Sanz., 1982. El esparto en Albacete, Universidad Autónoma de Madrid. Facultad de Filosofía y Letras. Museo de Artes y Tradiciones Populares. Narria: Estudios de artes y costumbres populares 27, 12–16. ISSN: 0210-9441.

Schreeg, L.A., Kobe, R.K., Walters, M.B., 2005. Tree seedling growth, survival, and morphology in response to landscape-level variation in soil resource availability in northern Michigan. Can J For Res 35, 263–273. https://doi.org/10.1139/X04-168.

Sebesta, J., Rogers, P.C., Madera, P., Koutecki, T., Dufour, S., Repka, R., 2021. Long-term effects of mechanical site preparation on understorey plant communities in lowland floodplain forests. For Ecol Manag 480, 118651. https://doi.org/10.1016/j.foreco.2020.118651.

Vallejo, V.R., Bautista, S., Alloza, J.A., 2009. Restauración de montes quemados en condiciones mediterráneas. Recursos Rurais 5, 55–60. https://doi.org/10.15304/rr.id5303.

White, A.M., Long, J.W., 2019. Understanding ecological contexts for active reforestation following wildfires. New For 50, 41–56. https://doi.org/10.1007/s11056-018-9675-z.

Wittenberg, L., van der Wal, H., Keesstra, S., Tessler, N., 2020. Post-fire management treatment effects on soil properties and burned area restoration in a wildland-urban interface, Haifa Fire case study. Sci Total Environ 716, 135190. https://doi.org/10.1016/j.scitotenv.2019.135190.

Yelenik, S.G., Stock, W.D., Richardson, D.M., 2004. Ecosystem Level Impacts of Invasive Acacia saligna in the South African fynbos. Restor Ecol 12, 44–51. https://doi.org/10.1111/j.1061-2971.2004.00289.x.

Zema, D.A., 2021. Postfire management impacts on soil hydrology. Curr Opin Environ Sci 21, 100252. https://doi.org/10.1016/j.coesh.2021.100252.

Zema, D.A., Nunes, J.P., Lucas-Borja, M.E., 2020. Improvement of seasonal runoff and soil loss predictions by the MMF (Morgan-Morgan-Finney) model after wildfire and soil treatment in Mediterranean forest ecosystems. Catena 188, 104415. https://doi.org/10.1016/j.catena.2019.104415.

Zhang, Jianwei, Webster, Jeff, Powers, Robert, F., Mills, John., 2008. Reforestation after the Fountain fire in northern California: an untold success story. J Forest Vol. 106 (8), 425–430.