Lucas-Borja, M. E., Van Stan, J. T., Heydari, M., Omidipour, R., Rocha, F., Plaza-Alvarez, P. A., ... & Muñoz-Rojas, M. (2021). Post-fire restoration with contour-felled log debris increases early recruitment of Spanish black pine (Pinus nigra Arn. ssp. salzmannii) in Mediterranean forests. Restoration Ecology, 29(4), e13338,

which has been published in final doi

10.1111/rec.13338

(https://onlinelibrary.wiley.com/doi/full/10.1111/rec.13338)

Post-fire restoration with contour-felled log debris increases early recruitment of Spanish Black pine (*Pinus nigra* Arn. ssp salzmannii) in Mediterranean forests

Manuel Esteban Lucas-Borja[1,*], John T. Van Stan II[2], Mehdi Heydari[3], Reza Omidipour[4], Francisco Rocha[5], Demetrio Antonio Zema[6], Miriam Muñoz-Rojas[7,8]

[1] *Higher Technical School of Agricultural and Forestry Engineering, Castilla-La Mancha University, Campus Universitario s/n, 02071 Albacete, Spain*

[2] *Applied Coastal Research Laboratory, Georgia Southern University, Savannah, GA, United States of America*

[3] *Forest Sciences Department, Faculty of Agriculture, Ilam University, Ilam 6939177111, Ilam Province, Iran*

[4] *Department of Rangeland and Watershed Management, Faculty of Agriculture, Ilam University, 69315-516, Ilam, Iran*

[5] *Instituto Superior Técnico, University of Lisbon, Lisbon, Portugal*

[6] *Department AGRARIA, Mediterranean University of Reggio Calabria, Località Feo di Vito, I-89122 Reggio Calabria, Italy*

[7] *Centre for Ecosystem Science, School of Biological, Earth and Environmental Sciences, The UNSW, Sydney, 2052 Sydney, NSW, Australia*

[8] *School of Biological Sciences, The University of Western Australia, Crawley, Western Australia 6009, Australia*

*Corresponding author: ManuelEsteban.Lucas@uclm.es

Author contributions: MELB and DAZ conceived and designed the research; MELB, MH, RO carried out the experiments; DAZ and MELB analyzed the data; MELB, DAZ, MH, RO, MM and JVS wrote and edited the manuscript.

RUNNING HEAD: Post-fire restoration of Spanish Black pine

Implications for Practice

- Post-fire contour felled log debris enhanced initial *Pinus nigra* Arn. ssp *salzmannii* seedling recruitment during the first growing season.
- *Pinus nigra* Arn. ssp *salzmannii* seed protection treatment can be favourable for supporting ecological restoration in pine Forests.
- There is a strong influence of climate in this species' seedling recruitment since the highest seedling emergence recorded during this study was under reduced drought conditions.

Abstract

Post-fire environmental conditions can heavily influence the natural regeneration of pine species in Mediterranean forests. Therefore, enhancing post-fire recovery of pine species is fundamental for effective ecological restoration of Mediterranean forests. In this study, the effects of a post-fire restoration treatment on the seedling emergence and survival of Spanish black pine (*Pinus nigra* Arn. ssp *salzmannii*) were investigated under a treatment consisting of manual cut of burnt tree canopies placed on the soil surface with their tree branches, following contour lines (contour-felled log debris, CFD) in comparison with a control site at plot scale. Both CFD and control plots were tested on three slope gradients and two experimental conditions, i.e. protected vs. non-

protected seeds. The initial seedling recruitment of Spanish black pine was improved by CFD treatment and seed protection, specifically through increased survival of emergent seedlings by about ten and fifteen times, respectively, compared to control. Seedling emergence was not significantly different between the treatments or controls; however, the highest seedling emergence in the study (18.9 ± 14.9%) was recorded under the least severe drought conditions. The study demonstrates that post-fire CFD and seed protection treatments in pine forests, can be favourable for supporting ecological restoration. However, the environmental conditions are important drivers for the success of these strategies. Since droughts are expected to be more frequent in the upcoming years, post-fire management strategies that include treatments like CFD and seed protection can be useful in the ecological restoration of Mediterranean pine forests.

Keywords: Seedling emergence; seedling survival; wildfire; Mediterranean forest; post-fire ecological restoration; contour-felled log debris.

Introduction

Wildfire is a natural disturbance factor in Mediterranean forests driving several important ecosystem processes (Pausas & Keeley, 2019; Heydari et al. 2020). However, changes in climate, such as increased extreme temperatures and longer periods of drought, are intensifying the effects of fire on forest ecosystems (Boer et al. 2020; Jolly et al. 2015). In addition to the influence of climate factors, landscape changes caused by human activities, e.g. increased tree density, have largely altered fire regimes in Mediterranean regions (Pausas, 2019). These regions has been exposed for millennia and to the effects of fire, which has modified the landscape and endowed many species with adaptive mechanisms that allow them to persist and regenerate after recurrent fires (Pausas, 2004; Alcaniz et al. 2020). Therefore, despite the adaptation of Mediterranean forests to fire, excessive frequency and severe events of fire may overcome the resistance and resilience of plants and soils, resulting in ecosystem degradation (Mitsopoulos et al. 2019; Moreira et al. 2020). Fire alters vegetation cover and its biodiversity (Pausas et al. 2014; Heydari et al. 2016; Moya et al. 2019; Moradizadeh et al. 2020), and can affect the physico-chemical and biological properties of soils, depending on severity, intensity or recurrence (DeBano 2000; Ginzberg & Steinberger 2004; Certini 2005; Heydari et al. 2012). Direct and indirect effects of fire on soils and plants can be critical for the functioning of forest ecosystems (Mitsopoulos et al. 2019). Thus, promoting post-fire recovery of forests is fundamental for an adequate management and planning of these ecosystems (Grau-Andres et al. 2019; Muñoz-Rojas & Pereira, 2019). The plants growing during the restoration phase will determine the future state of the ecosystems affected by fire with a clear control exerted on soil formation and degradation, and water dynamics (Moreira et al. 2011; Cerdà et al. 2017). Moreover, the natural self organization of the vegetation creates a more resilient ecosystem against droughts and floods and also prevents the soil surface to be bare and vulnerable for erosion (Keesstra et al. 2018).

In recent years, fire and ecosystem management has evolved along with social needs for maintaining and protecting ecosystem services, and new approaches need to be considered in post-fire restoration management (Roces-Diaz et al. 2020). The effectiveness of the ecological restoration strategies in Mediterranean systems depends on our understanding of post-fire initial recruitment processes, which can be directly affected by fire extent, tree mortality and post-fire management (Stevens-Rumann &

Morgan, 2019). After wildfire, seedling recruitment is a key process driving forest dynamics in Mediterranean conditions, especially in the context of global change (Miller et al. 2019; Pausas & Keeley 2014). Some Mediterranean pines species are able to regenerate through different post-fire strategies, including serotiny (*Pinus halepensis* M.), soil seed banks (*Pinus pinaster* Ait.) or wind seed dispersion into a fire-affected site (Kozlowski, 2002). For these species, new individuals continue to appear after fire for several years to allow forest ecosystem recovery and forest stand persistence (Oliver & Larson, 1996; Albrecht & McCarthy, 2006). However, a negative effect of severe wildfire has frequently been reported on the natural regeneration of the non-serotinous, obligate seeder *Pinus nigra* Arn. ssp *salzmannii* (Dunal) Franco (Spanish black pine) (Martín-Alcón & Coll, 2016).

Spanish black pine (*Pinus nigra Arn* ssp. *Salzmannii*) is the most widely distributed pine species along mountain areas of the Mediterranean Basin (Barbero et al. 1998). This species, frequently used in afforestation programs (Campo et al. 2019) has been included by European Union in the endangered habitats listing of natural habitats requiring specific conservation measures (Resolution 4/1996 in the Convention on the Conservation of European Wildlife and Natural Habitats), due to the lack of successful natural regeneration. Some of the challenges associated to the regeneration of Pinus nigra are irregular masting events, seed predation, drought, and land degradation (Del Cerro et al. 2009; Típscar-Oliver and Linares 2014). Post-fire conditions encompass the absence of tree canopy cover, microclimatic conditions (high temperature and lower water availability in soils), soil erosion, pre- and post-dispersal seed predation or herbivores (Del Cerro Barja et al. 2009; Calama et al. 2019). These factors can further inhibit natural regeneration of Spanish black pine, which lack mechanisms to overcome the effects of fire (Rodrigo et al. 2004).

During forest regeneration after fire, the first growing season is of vital importance for pine survival and growth, since first-year conditions may modulate forest stand persistence and composition after wildfire (Heydari et al. 2017; Calama et al. 2019). Although the success of natural forest regeneration depends on the whole tree lifespan, some stages, such as seedling emergence and survival, are critical for survival due to the vulnerability of seed and seedlings to biotic and environmental constraints during early life-stages of the Mediterranean pines (Lucas-Borja et al. 2012; Prévosto et al. 2012). In Mediterranean areas, drought and soil desiccation are major constraints to seedling emergence and survival in forest areas, where establishment after seed germination is severely limited by long and dry summer periods (Herrera, 1992; Haffey et al. 2018; Fernández-García et al. 2019).

To support the natural regeneration of Spanish Black pine and other similar pine species after wildfires, different post-fire management strategies may be effective (Castro et al. 2011). Some of the most frequent restoration strategies include (i) felling and laying burned trees on the ground along the slope contour to block overland flow and sediment delivery (log erosion barriers), (ii) cutting the main branches and leaving all the biomass *in situ* without mastication for the same purpose (contour-felled log debris, hereinafter indicated as CFD) (Napper, 2006; Robichaud, 2000; Shakesby, 2011) or straw mulching application to slope surface in order to improve microclimatic soil conditions (Bautista et al. 2009; Prats et al. 2012; Lucas-Borja et al. 2020). These techniques for hillslope stabilization aim to avoid soil degradation by increasing fertility and reducing runoff, and erosion rates (Gómez-Sanchez et al. 2019). Furthermore, these methods can help restoring the ecosystem structure and function by minimising losses in soil carbon and nutrient contents (Shakesby 2011; Fontúrbel et al. 2016).

Recent research has also evidenced their potential for increasing seedling density and height in *Pinus halepensis* and *Pinus pinaster* forest stands after wildfire (Lucas-Borja et al. 2020).

Despite the potential of these techniques for post-fire restoration of forest ecosystems, studies that investigate their effects on natural regeneration of Mediterranean pines, including Spanish black pine, after wildfires are still scarce (Lucas-Borja et al. 2020). Specifically, the impacts of these techniques on soil cover, seed predation and microclimate conditions need to be assessed, to fully evaluate the relative and cumulative effects of fire and post-fire management processes. Overall, there are substantial gaps in identifying the most effective approaches to apply these post-fire strategies. Arguably, a critical knowledge gap in this vein is the effect of post-fire strategies on initial seedling recruitment of pines–one of the most important and fragile Mediterranean species (Gomez-Sánchez et al. 2019).

Commento [YYY1]: Porqué hemos quitado esta parte que me parecìa interesante?

In this study, seedling emergence and survival of Spanish black pine are investigated in CFD plots in comparison with a non-treated forest during the first three growing seasons (2010, 2011 and 2012) following a severe wildfire. Both the treated and control plots were monitored in three different slopes, e.g. low, medium and high gradient, and two experimental conditions, e.g. protected vs. non-protected seeds. Due to the masting condition (the synchronous production of large seed crops within a population every six years) of Spanish black pine, a sowing experiment was used to ensure seed availability of Spanish black pine for this experiment. The working hypothesis of this study is that seedling emergence and survival of Spanish black pine will be higher in CFD plots in combination with seed protection, due to the better microclimatic conditions (higher water content and lower temperature of soil) and more limited seed predation compared to the control forest.

Methods

Study site

The study area was located in the Cuenca Mountain (Castilla-La Mancha, central-eastern Spain). Spanish black pine is naturally distributed in this area between 1000 and 1500 m above sea level and dominates the forest stand composition (Del Cerro Barja et al. 2009).

Commento [YYY2]: Aqui pondria una o dos frases sobre "degradation to forests with Spanish pine" que pide el AE.

Spanish black pine forests in the Cuenca Mountains have traditionally been managed using the shelterwood system, with a shelter-period of 20-25 years and a rotation period of 100-125 years. This method consists of a uniform opening of the canopy for regeneration purposes without site preparation (Lucas-Borja et al. 2011). A natural forest of Spanish black pine, which was affected by a high-severity wildfire in July 2009, was selected as the experimental site at 1416 m a.s.l. ("Las Majadas" site, 40°15′58″N; 1°56′08″W). The mean annual rainfall in the study area is 950 mm (115 mm during summer) and the mean annual temperature is 9.6 °C. Air temperature typically ranges from −4.5 °C (mean minimum temperature of the coldest month) to 28.3 °C (mean maximum temperature of the hottest month). The mean three-month drought-period temperature (June, July and August) is 15.7 °C. Calcareous soils are dominant in the Cuenca Mountains; the prevalent soil types of the experimental site are classified as Typical Xerorthent, according to Soil Survey Staff (1999). The ground vegetation is mainly composed by herbaceous (*Eryngium campestre* L., *Geranium selvaticum* L., *Festuca rubra* L. and *Cirsium acaule* L.) and small shrub (mainly *Thymus bracteatus* L.) species.

After the wildfire of summer 2009 and before sowing, soil in the experimental plots was covered by woody debris (55%), stones (20%), resprouting plant species (5%), while the remaining area (20%) was bare (data source: Cuenca Mountain forest services, field survey of February 2009). Daily air temperature and precipitation were recorded throughout the entire study period, using a meteorological station (model METEODATA 1256C) near the experimental site; these data were compared to the 3-decadal (1980-2010) historical records provided by AEMET (Spanish Meteorological Agency). Annual water budget was estimated by the standardized precipitation-evapotranspiration index (SPEI, Vicente Serrano et al. 2010), based on the sum of monthly differences between precipitation (P) and potential evapo-transpiration (PET).

Experimental layout

Two months after the wildfire, between September 2009 and December 2009, a post-fire management treatment was applied in the study area. The treatment consisted of the manual cut of burnt trees, leaving tree canopies on the soil surface following contour lines (contour-felled log debris, hereinafter CFD). Trunks were manually piled (groups of about 10-20 logs) and the woody debris was left *in situ* without mastication**.** A split-plot design was carried out with three factors:

1) slope (determined by using a Suunto clinometer, model PM-5/360 PC), e.g. low (1-2%, hereinafter L), medium (3-15%, M) and high (15-35%, H) gradient.
2) treatment, e.g. CFD (woody debris cover) and control, the latter with bare soil, that is without woody debris cover (hereinafter C)
3) seed protection, e.g. protected (P) *vs.* non-protected seeds (NP). Seed protection described below.

In January 2010, nine representative areas of about 7 ha were selected in the study site (3 slopes × 3 replicates). Sixteen 4 × 4 m permanent plots were set up at each of the nine areas. The plots were randomly distributed within each forest area, with a minimum distance apart of 300 m and included four treatments: (i) CFD and seed protection; (ii) CFD without seed protection; (iii) no treatment with CFD and seed protection ; and (iv) no treatment with CFD and no seed protection (control condition). Each plot consisted of four sowing points. At each sowing point, 20 *Pinus nigra* Arn. ssp *salzmanni* seeds were sown (1 cm deep) at the beginning of March of 2010, 2011 and 2012. All seeds were located inside each quadrat with high precision, using a wire mesh to avoid overestimations due to naturally dispersed seeds. Protected sowing points were protected imposing a wire trap of one cm^2 mesh size, to exclude seed predation and seedling herbivory from birds and rodents. Overall, per each on the three monitoring years (2010, 2011 and 2012), three samples of 288 discrete locations were collected, i.e. 3 slopes x 3 replicates x 4 treatments x 4 sowing points, for a total of 864 samples. Seedling emergence was surveyed once a year at the end of March. Seeds were considered emerged when the cotyledons were visible. Seedling survival was monitored once a year quantified by counting and labelling all live seedlings within each sub-plot (at the end of November). Seeds used in this experiment were previously collected in

Commento [YYY3]: Es correcto?

Commento [YYY4]: Es correcto?

spring 2009 from the same experimental area, using 20 regular traps and then stored in paper bags in a refrigerator at 4 ºC. A germination potential test was performed under controlled conditions in the laboratory (Lucas-Borja et al. 2011) before sowing, to check the viability of the collected seeds. Average germination rates were in all cases about 80%. The emergence rate was calculated as the number of emerged seeds compared to the total number of sown seeds. The survival rate was obtained as the percentage of seedlings that survived in the first year of the experiment versus the number of emerged seeds.

Statistical analysis

Prior to the analyses, the variables, emergence and survival rates, were log-transformed to meet assumptions of normality and homoscedasticity of residuals. The statistical significance of the experimental treatments was tested using three-way ANOVA with repeated measures. This was separately applied to seedlings survival and emergence rate of Spanish black pine (dependent variables) and the slope (low, medium and high gradient), treatment (CFD vs. control) and seed protection (protected *vs.* non-protected seeds) factors (independent variables) for the three monitoring years. The data of 2010, 2011 and 2012 were considered as repeated measures. Statistical analysis of samples was carried out by the XLSTAT (release 2020.1) software.

Results

Precipitation and air temperatures

Precipitation over the period 2010-2012 was below the long-term average (except for December 2010 and April and November 2012), showing the drought condition of the study area during the monitoring period (Figure 1). The temperature anomaly was less pronounced, and the mean temperatures in 2010-2012 were similar to the long-term average (Fig. 2). The SPEI index also showed the dry condition of the study area during eight months (between March and October) for 2010 (lower), 2011 (intermediate) and 2012 (higher) (Figure 2).

Seedling emergence

Seedling emergence after several weeks (from sowing, early March, to measuring, late March) for Spanish black pine was significantly higher in 2010 (18.9 ± 14.9%) compared to 2011 (11.2 ± 12.5%) and 2012 (11.2 ± 12.5%) (Table 1). The seedling emergence rate was significantly and primarily affected by slope as well as by its interactions with treatment. Conversely, the treatment and seed protection alone, and the other interactions among the studied factors were not significant (Table S1). The highest seedling emergence rate (19.0 ± 15.9%) was found in medium-slope for the control plots without seed protection, while the minimum value (7.8 ± 9.0%) was recorded in high-slope for the control plots with seed protection). In more detail, the treatment with CFD produced a lower seedling emergence rate (13.2 ± 13.6%) compared to control (14.4 ± 12.9%), although not significantly (Figure 3). Conversely, the lower is the plot slope, the significantly higher is the seedling emergence (15.9 ± 13.7%, high slope, 15.6 ± 15.0%, medium slope, 9.9 ± 11.1%, low-slope plot, although the difference between the two latter is not significant) (Figure 3). Seed protection increased on the average the seedling emergence rate (14.1 ± 13.4% vs. 13.5 ± 13.1%), also in this case not significantly.

Seedling survival

Seedling survival of Spanish black pine was significantly higher in 2010 (3.5 ± 14.2%) and 2012 (2.5 ± 13.5%) compared to 2011 (0.5 ± 6.6%) (Table 1). The seedling survival was significantly affected by treatment and seed protection, and their interaction. Conversely, the effects of slope or the other interactions among factors were not significant (Table S1). The low-slope and CFD-treated plots with seed protection showed the highest seedling survival (7.71 ± 21.5%), while seedling survival rate was zero (i.e., all small pine plants died) for four of the plots: three control plots (bare soil at all the investigated slopes and without seed protection) and the plot treated with CFD on high slope without seed protection (Figure 3). The treatment with CFD significantly increased seedling survival rates compared to the control (3.93 ± 12.7% vs. 0.40 ± 2.67%, respectively) and seed protection significantly increased survival compared to sites without seed protection (4.06 ± 13.8% vs. 0.27 ± 1.66%) (Figure 3). Conversely, the seedling survival rate on plots with different slope was very similar and not significant (2.04 ± 7.09%, high slope, 2.34 ± 9.25%, medium slope, 2.12 ± 6.67%, low-slope plot) (Figure 3).

Discussion

The potential of post-fire stabilisation for post-fire restoration of forest ecosystems is high, but their effects on natural regeneration of Spanish black pine have not been studied with particular emphasis on seed predation and hillslope morphology. This study aiming at evaluating how and to what extent CFD is beneficial to seed emergence and survival for this species in combination with seed protection and on different slopes. The results highlight that initial seedling recruitment of Spanish black pine can be improved by CFD treatment and seed protection. In general, we found that the slope has a strong influence on seedling emergence, whereas survival is largely controlled by the seed protection and CFD treatment.

More specifically, the experiment indicates that seedling emergence rates were not influenced by treatment and, in some years and for all slopes, the control plots showed higher (although not significant) seedling emergence compared to the CFD treatment. A possible explanation may be related to the critical role of solar radiation in seedling emergence of Spanish black pine (Lucas-Borja et al. 2016; Lucas-Borja et al. 2017). In the plots covered by woody debris, sunlight is restricted in cold late winter/early spring (out of the experimental conditions), which can result in reduced emergence. Moreover, despite the generally lower seedling emergence, significantly higher survival rates were surveyed after the CFD treatment compared to the control for all the treated slopes (low, medium and high gradient). This result is in accordance with the well-known beneficial effect of shrubs on the recruitment of seedlings located under their canopies (Emborg, 1998; Heydari et al. 2017). For example, Lucas-Borja et al. (2016) demonstrated that shrub facilitation has visible effects on seedling emergence of Spanish black pine, but only in the drier years and under 25-30 m^2 ha^{-1} of basal area. Conversely, in wetter years, shrub cover does not promote seedling survival and canopy cover is not an influential factor.

In those CFD plots, where seedling emergence was higher compared to control, soil protection was not sufficient in a drought-stress environment to ensure seed survival in the year following sown, since almost all seedlings (99.9%) died by the end of the year. A similar response has been evidenced in previous studies that pointed to bleak prospects for successful natural regeneration of Spanish black pine in dry years (Lucas-Borja et al. 2016). The differences in seedling emergence and survival detected in this study as the effect of CFD confirm that the natural regeneration of Spanish black pine must overcome contrasting conditions, one condition suitable for seedling emergence (i.e., slope conditions) and another condition suitable for survival (i.e., ground cover and seed protection) (Tiscar Oliver, 2007).

Pre- and post-dispersal seed predation has severe consequences on plant recruitment, because predation acts as a substantial obstacle against the natural regeneration of Spanish black pine (Sagra et al. 2017). In this study, seed protection had a beneficial and significant effect for early recruitment, since seedling survival rates increased in all slopes and under CFD treatment. Seed protection is particularly important during non-masting years (characterised by low seed availability for predators), because predation can completely prevent seed recruitment of Spanish black pine and other Mediterranean pine species (Lucas-Borja et al. 2012; Moreira et al. 2016). For example, Lucas-Borja et al (2018b) found that *Pinus nigra* seed production ranged over time from 2 to 189 seeds m^{-2} and from 0 to 17 seeds m^{-2} in masting and non-masting years, respectively. However, seed protection did not play a significant effect on seedling emergence rates, in agreement with previous researches in the Cuenca Mountains (Lucas-Borja et al. 2012) and in other Mediterranean areas (Calama et al. 2019). These studies pointed out the relative importance of seedling herbivory compared to seed predation.

Significant impacts of slope on seedling emergence but not in survival of Spanish black pine were detected. These differences for seedling emergence were not expected, since Spanish black pine is well-adapted to steep slopes and calcareous soils (Calama et al. 2019). Nonetheless, since CFD plots generally showed higher seedling survival rates compared to bare plots, this may indicate that the treatment can help to reduce soil erosion and nutrient transport down slope, which can affect high and medium slopes.

With regard to the variability of natural regeneration over time, also in this study the early seedling recruitment was strongly dependent on the monitoring year. Higher seedling emergence and survival were recorded in 2010, characterized by the highest SPEI and lowest drought conditions throughout the experiment. Climate is arguably the main factor controlling seedling emergence and survival in water-limited environments (Gómez-Aparicio et al. 2004; Adili et al. 2013; Muñoz-Rojas et al. 2016). This is evidenced by the contrasting responses for seedling emergence and survival of Spanish black pine over time reported in different studies, which generally showed the importance of climate factors, e.g. rainfall and temperature, to drive these responses. For example, recent studies carried out in Mediterranean arid and semi-arid ecosystems underlined drought as one of the most important factors limiting early seedling recruitment (Lloret et al. 2004; Bateman et al. 2018; Lewandrowski et al. 2018; Mirzaei et al. 2018). Water stress during summer appears to be the leading cause of seedling mortality in many pine species of the Mediterranean region (Rodríguez-García et al. 2011; Lucas-Borja et al. 2017). Specifically, Spanish black pine requires high water content and low temperature of soil to regenerate (Lucas-Borja et al. 2011; Calama et al. 2019). The small tree logs and branches area spread over the ground of CFD treatment may act as a barrier that reduce drought by lowering solar radiation and soil temperature and increasing its water content (Castro et al. 2009).

DZ: COMPARISONS WITH LITERATURE

Seedling emergence rates in this study were on average similar as the lowest values (i.e. 9-20%, low or dense basal areas) reported by Lucas-Borja et al. (2016) in the same forest (Cuenca Mountains) in dry years and with shrub facilitation. Moreover, in the same area emerged seedlings between 39 and 76% were detected again by Lucas-Borja et al. (2016) and again Lucas-Borja et al. (2018a) under medium shrub cover, and soil preparation (scalping) and seed protection treatments, respectively. In these studies, the mean rates of seedling survival were higher than those reported in this study (10-20%, Lucas-Borja et al. 2016, except under medium shrub cover, and 18-35%, Lucas-Borja et al. 2018a) and similar to those reported by Lucas-Borja et al. (2016), 0.5-4% in scalped, although these authors found higher values in undisturbed soils. Similar research about the effect of post - fire management treatments (e.g. felling most of the trees, cutting the main branches, and leaving all the biomass in situ without mastication) on the recruitment of *Pinus pinaster* at a Mediterranean mountain showed an increase of 47.3% in seedling survival compared to the untreated sites three years after wildfire (Castro et al. 2011).

The absence of seedling survival of Spanish black pine in bare and non-protected soil has direct implications for forest management, as the increased impacts of wildfires and climate change will challenge the success of natural regeneration. Time from wildfire plays a vital role in successful early recruitment of vegetal species, since ash, pH, electrical conductivity, organic matter, respiration, and herbal cover of soil may change over time (Muñoz-Rojas et al. 2016). Moreover, predator abundance may vary over time after fire (e.g. absence of bird nesting sites), although rodents and birds are known to rapidly colonize burnt areas (Ordóñez & Retana 2004; Sagra et al. 2017). Gaining a better understanding of how post-fire management strategies alter initial recruitment of Spanish black pine is essential for predicting changes in forest stand persistence under global change scenarios. The information herein obtained could lead to more efficient forest management practices, to effectively increase health and functions of forest ecosystem.

Overall, this study demonstrated that the ecological restoration treatment carried out as post-fire soil management, based on the manual cut of burnt tree canopies and placement on the soil surface following contour lines, significantly increased (combined with seed protection) seedling survival on low-slope areas as well as medium and high slopes, although the treatment was not able to increase seedling emergence after wildfire compared to bare soil. Therefore, soil treatment with CFD and seed protection by wire mesh are suggested for a more successful early recruitment of Spanish black pine. Moreover, it is worthy to note that the highest seedling emergence recorded during this study was under reduced drought conditions (per SPEI metric), which indicates that there is a strong influence of climate in this species' seedling recruitment.

LITERATURE CITED

Adili, B, El Aouni MH, Balandier P (2013) Unravelling the influence of light, litter and understorey vegetation on *Pinus pinea* natural regeneration. Forestry, 86(3), 297-304

Albrecht MA & McCarthy BC (2006) Effects of prescribed fire and thinning on tree recruitment patterns in central hardwood forests. Forest Ecology and Management, 226(1-3), 88-103

Alcañiz M, Úbeda X, Cerdà A (2020) A 13-Year Approach to Understand the Effect of Prescribed Fires and Livestock Grazing on Soil Chemical Properties in Tivissa, NE Iberian Peninsula. *Forests,* 11, 1013.

Barbéro M, Losiel R, Queézel P, Richardson DM, Romane F (1998) Pines of the Mediterranean Basin. In: Richardson D.M. (Ed.), Ecology and biogeography of Pinus, Cambridge University Press, Cambridge.

Bateman A, Lewandrowski W, Stevens JC, Muñoz-Rojas M (2018) Ecophysiological indicators to assess drought responses of arid zone native seedlings in reconstructed soils. Land Degradation and Development, 29(4), 984-993

Bautista S, Robichaud PR, Bladé C (2009) Post-fire mulching. Fire effects on soils and restoration strategies 5, 353-372.

Boer MM, de Dios VR, Bradstock, RA (2020) Unprecedented burn area of Australian mega forest fires. Nature Climate Change, 10(3), 171-172

Calama Sainz R, Manso González R, Lucas Borja ME, Espelta Morral JM, Piqué Nicolau M, Bravo Oviedo F, Peso Taranco CED, Pardos Mínguez, M (2017) Natural regeneration in Iberian pines: A review of dynamic processes and proposals for management. Forest Systems, 26, 2, eR02S.

Calama R, Conde M, de-Dios-García J, Madrigal G, Vázquez-Piqué J, Gordo FJ, Pardos M (2019) Linking climate, annual growth and competition in a Mediterranean forest: *Pinus pinea* in the Spanish Northern Plateau. Agricultural and Forest Meteorology, 264, 309-321

Campo J, Stijsiger RJ, Nadal - Romero E, & Cammeraat E. (2019) The effects of land abandonment and long - term afforestation practices on the organic carbon stock and lignin content of Mediterranean humid mountain soils. European Journal of Soil Science, 70(5), 947-959.

Castro FX, Tudela A, Sebastià, MT (2003) Modeling moisture content in shrubs to predict fire risk in Catalonia (Spain). Agricultural and Forest Meteorology, 116(1-2), 49-59

Castro J, Allen CD, Molina-Morales M, Marañón-Jiménez S, Sánchez-Miranda Á, Zamora R (2011) Salvage logging versus the use of burnt wood as a nurse object to promote post-fire tree seedling establishment. Restoration Ecology, 19(4), 537-544

Cerdà A, Lucas-Borja ME, Úbeda X, Martínez-Murillo JF, Keesstr, S. (2017) Pinus halepensis M. versus Quercus ilex subsp. Rotundifolia L. runoff and soil erosion at pedon scale under natural rainfall in Eastern Spain three decades after a forest fire. *Forest ecology and management,* 400, 447-456.

Certini G (2005) Effects of fire on properties of forest soils: a review. Oecologia, 143(1), 1-10

DeBano LF (2000) The role of fire and soil heating on water repellency in wildland environments: a review. Journal of hydrology, 231, 195-206

Del Cerro Barja A, Lucas-Borja ME, Garcia EM, Serrano FL, Abellán MA, Morote, FG, López RN (2009) Influence of stand density and soil treatment on the Spanish Black Pine (*Pinus nigra* Arn ssp Salzmannii) regeneration in Spain. Forest Systems, 18(2), 167-180

Fernández C, Vega JA, Fontúrbel T (2016) Reducing post-fire soil erosion from the air: performance of heli-mulching in a mountainous area on the coast of NW Spain. Catena, 147, 489-495

Fernández-García V, Fulé PZ, Marcos E, Calvo L (2019) The role of fire frequency and severity on the regeneration of Mediterranean serotinous pines under different environmental conditions. Forest Ecology and Management, 444, 59-68

Ginzburg O, Steinberger Y (2012) Effects of forest wildfire on soil microbial-community activity and chemical components on a temporal-seasonal scale. Plant and soil, 360(1-2), 243-257

Gómez-Aparicio L, Zamora R, Gómez JM, Hódar JA, Castro J, Baraza, E (2004) Applying plant facilitation to forest restoration: a meta-analysis of the use of shrubs as nurse plants. Ecological applications, 14(4), 1128-1138

Gómez-Sánchez E, Lucas-Borja ME, Plaza-Álvarez PA, González-Romero J, Sagra J, Moya D, De Las Heras J (2019) Effects of post-fire hillslope stabilisation techniques on chemical, physico-chemical and microbiological soil properties in Mediterranean forest ecosystems. Journal of Environmental Management, 246, 229-238

Grau-Andrés R, Gray A, Davies GM, Scott EM, Waldron S (2019) Burning increases post-fire carbon emissions in a heathland and a raised bog, but experimental manipulation of fire severity has no effect. Journal of Environmental Management, 233, 321-328

Haffey C, Sisk TD, Allen CD, Thode AE, Margolis EQ (2018) Limits to ponderosa pine regeneration following large high-severity forest fires in the United States Southwest Fire Ecology, 14(1), 143-163

Heydari M, Faramarzi M, Pothier D (2016) Post-fire recovery of herbaceous species composition and diversity, and soil quality indicators one year after wildfire in a semi-arid oak woodland. Ecological Engineering, 94, 688-697

Heydari M, Moradizadeh H, Omidipour R, Mezbani A, Pothier D (2020) Spatio-temporal changes in the understory heterogeneity, diversity, and composition after fires of different severities in a semiarid oak (*Quercus brantii* Lindl) forest. Land Degradation and Development, 31(8), 1039-1049

Heydari M, Omidipour R, Abedi M, Baskin C (2017) Effects of fire disturbance on alpha and beta diversity and on beta diversity components of soil seed banks and aboveground vegetation. Plant Ecology and Evolution, 150(3), 247-256

Heydari M, Salehi A, Mahdavi A, Adibnejad M (2012) Effects of different fire severity levels on soil chemical and physical properties in Zagros forests of western Iran. Folia Forestalia Polonica, series A, 54 (4): 241–250

Jolly WM, Cochrane MA, Freeborn PH, Holden ZA, Brown TJ, Williamson GJ, Bowman DM (2015) Climate-induced variations in global wildfire danger from 1979 to 2013. Nature communications, 6(1), 1-11

Keesstra S, Nunes J, Novara A, Finger D, Avelar D, Kalantari Z & Cerdà A (2018) The superior effect of nature based solutions in land management for enhancing ecosystem services. Science of the Total Environment, 610, 997-1009.

Kozlowski TT (2002) Physiological ecology of natural regeneration of harvested and disturbed forest stands: implications for forest management. Forest Ecology and Management, 158(1-3), 195-221

Lewandrowski W, Erickson TE, Dalziell EL, Stevens JC (2018) Ecological niche and bet-hedging strategies for Triodia (R Br) seed germination. Annals of Botany, 121(2), 367-375

Lloret F, Peñuelas J, Estiarte M (2004) Experimental evidence of reduced diversity of seedlings due to climate modification in a Mediterranean-type community. Global Change Biology, 10(2), 248-258

Lucas-Borja ME, Candel-Pérez D, Morote FAG, Onkelinx T, Tíscar PA, Balandier P (2016) *Pinus nigra* Arn ssp salzmannii seedling recruitment is affected by stand basal area, shrub cover and climate interactions. Annals of Forest Science, 73(3), 649-656

Lucas-Borja ME, Candel-Pérez D, Onkelinx T, Fule PZ, Moya D, Gómez R, De Las Heras J (2017) Early Mediterranean pine recruitment in burned and unburned *Pinus nigra* Arn ssp *salzmannii* stands of central Spain: Influence of species identity, provenances and post-dispersal predation. Forest Ecology and Management, 390, 203-211

Lucas-Borja ME, Fonseca T, Parresol BR, Silva-Santos P, García-Morote FA, Tíscar-Oliver PA (2011) Modelling Spanish black pine seedling emergence: establishing management strategies for endangered forest areas. Forest Ecology and Management, 262(2), 195-202Lucas-Borja ME, Fonseca T, Linares JC, Morote FG, Serrano FL (2012) Does the recruitment pattern of Spanish black pine (*Pinus nigra* Arn ssp salzmannii) change the regeneration niche over the early life cycle of individuals? Forest Ecology and Management, 284, 93-99

Lucas-Borja ME, Tiscar PA, Plaza-Alvarez PA, Cózar JS, Gonzalez-Romero J, Moya D, de las Heras J (2018a) Prescribed burning lowers the initial recruitment rates of three pine species that inhabit a mid-altitude Mediterranean mountain. Forest Ecology and Management, 427, 325-332

Lucas-Borja ME, Vacchiano G (2018b) Interactions between climate, growth and seed production in Spanish black pine (*Pinus nigra* Arn ssp *salzmannii*) forests in Cuenca Mountains (Spain). New Forests 49, 399–414

Lucas-Borja ME, Plaza-Álvarez PA, Ortega R, Miralles I, González-Romero J, Sagra J, Moya D, Zema DA, de las Heras J (2020) Short-term changes in soil functionality after wildfire and straw mulching in a Pinus halepensis M forest. Forest Ecology and Management, 457,117700

Martín-Alcón, S, Coll L, (2016) Unraveling the relative importance of factors driving post-fire regeneration trajectories in non-serotinous *Pinus nigra* Forests. Forest Ecology and Management, 361, 13-22

Miller RG, Tangney R, Enright NJ, Fontaine JB, Merritt DJ, Ooi MK, Ruthrof KX, Miller BP (2019) Mechanisms of fire seasonality effects on plant populations. Trends in Ecology and Evolution, 34(12), 1104-1117

Mirzaei JM, Heydari M, Prevosto B (2017) Effects of vegetation patterns and environmental factors on woody regeneration in semi-arid oak-dominated forests of western Iran. Journal of Arid Land, 9(3), 368-378

Mitsopoulos, I, Chrysafi, I, Bountis, D and Mallinis, G, (2019) Assessment of factors driving high fire severity potential and classification in a Mediterranean pine ecosystem. Journal of Environmental Management, 235, 266-275

Moradizadeh H, Heydari M, Omidipour R, Mezbani A, Prévosto B (2020) Ecological effects of fire severity and time since fire on the diversity partitioning, composition and niche apportionment models of post-fire understory vegetation in semi-arid oak forests of Western Iran. Ecological Engineering, 143, 105694

Moreira X, Abdala-Roberts L, Zas R, Merlo E, Lombardero MJ, Sampedro L, Mooney KA (2016) Masting behaviour in a Mediterranean pine tree alters seed predator selection on reproductive output. Plant Biology, 18(6), 973-980

Moreira F, Viedma O. Arianoutsou M, Curt T, Koutsias N, Rigolot E, Mouillot F (2011) Landscape–wildfire interactions in southern Europe: implications for landscape management. J. Environ. Manage. 92 (10), 2389–2402.

Moreira F, Ascoli D, Safford H, Adams MA, Moreno JM, Pereira JM, ... & Curt T (2020). Wildfire management in Mediterranean-type regions: paradigm change needed. Environmental Research Letters, 15(1), 011001.

Moya D, González-De Vega S, Lozano E, García-Orenes F, Mataix-Solera J, Lucas-Borja ME, de Las Heras J (2019) The burn severity and plant recovery relationship affect the biological and chemical soil properties of *Pinus halepensis* Mill stands in the short and mid-terms after wildfire. Journal of Environmental Management, 235, 250-256

Muñoz-Rojas M, Pereira P (2019) Fire in the environment. Journal of Environmental Management, 253, p109703

Muñoz-Rojas M, Erickson T, Martini D, Dixon K, Merritt D (2016) Climate and soil factors influencing seedling recruitment of plant species used for dryland restoration. Soil, 2, 287-298

Muñoz-Rojas M, Erickson T, Martini D, Dixon K, Merritt D (2016) Climate and soil factors influencing seedling recruitment of plant species used for dryland restoration Soil, 2, 287-298

Muñoz-Rojas M, Erickson TE, Martini D, Dixon KW, Merritt DJ (2016) Soil physicochemical and microbiological indicators of short, medium and long term post-fire recovery in semi-arid ecosystems. Ecological Indicators, 63, 14-22

Napper C (2006) Burned area emergency response treatments catalog US Forest Service, San Dimas Technology and Development Center, USA.

Oliver CD, Larson BC 1996 Forest stand dynamics (p 520) New York: Wiley

Ordóñez JL, Retana, J (2004) Early reduction of post-fire recruitment of *Pinus nigra* by post-dispersal seed predation in different time-since-fire habitats. Ecography, 27(4), 449-458

Pausas JG (2004). Changes in fire and climate in the eastern Iberian Peninsula (Mediterranean basin). Climatic change, 63(3), 337-350.

Pausas JG (2019). Generalized fire response strategies in plants and animals. Oikos, 128(2), 147-153.

Pausas JG, Keeley JE (2014) Evolutionary ecology of resprouting and seeding in fire-prone ecosystems. New Phytologist, 204(1), 55-65

Pausas JG, Keeley JE (2019) Wildfires as an ecosystem service. Frontiers in Ecology and the Environment, 17(5), 289-295

Prats SA, MacDonald LH, Monteiro M, Ferreira AJ, Coelho CO, Keizer JJ (2012). Effectiveness of forest residue mulching in reducing post-fire runoff and erosion in a pine and a eucalypt plantation in north-central Portugal. Geoderma 191, 115-124

Prévosto B, Amandier L, Quesney T, de Boisgelin G, Ripert C (2012) Regenerating mature Aleppo pine stands in fire-free conditions: site preparation treatments matter. Forest Ecology and Management, 282, 70-77

Robichaud PR (2000) Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. Journal of Hydrology, 231, 220-229

Roces-Díaz JV, Vayreda J, De Cáceres M, García-Valdés R, Banqué-Casanovas M, Morán-Ordóñez A, ... & Martínez-Vilalta J. (2020) Temporal changes in Mediterranean forest ecosystem services are driven by stand development, rather than by climate-related disturbances. Forest Ecology and Management, 480, 118623.

Rodrigo A, Retana J, Picó FX (2004) Direct regeneration is not the only response of Mediterranean forests to large fires. Ecology, 85(3), 716-729

Rodríguez-García E, Bravo F, Spies TA (2011) Effects of overstorey canopy, plant–plant interactions and soil properties on Mediterranean maritime pine seedling dynamics. Forest Ecology and Management, 262(2), 244-251

Sagra J, Moya D, Plaza-Álvarez PA, Lucas-Borja ME, Alfaro-Sánchez R, De Las Heras J, Ferrandis P (2017) Predation on early recruitment in Mediterranean forests after prescribed fires. Forests, 8(7), 243

Shakesby RA (2011) Post-wildfire soil erosion in the Mediterranean: review and future research directions. Earth-Science Reviews, 105(3-4), 71-100

Soil Survey Staff (1999), Soil Taxonomy A basic system of soil classification for making and interpreting soil surveys, 2nd edition Agricultural Handbook 436, Natural Resources Conservation Service, USDA, Washington DC, USA, pp 869

Stevens-Rumann CS, Morgan P (2019) Tree regeneration following wildfires in the western US: a review. Fire Ecology, 15(1), 15

Tiscar Oliver PA (2007) Dinámica de regeneración de Pinus nigra subsp salzmannii al sur de su área de distribución: etapas, procesos y factores implicados. Investigación Agraria: Sistemas y Recursos Forestales 16(2), 124-135

Tíscar-Oliver PA & Linares JC (2014) Large-scale regeneration patterns of Pinus nigra Subsp. salzmannii: poor evidence of increasing facilitation across a drought gradient. Forests 5, 1–20.

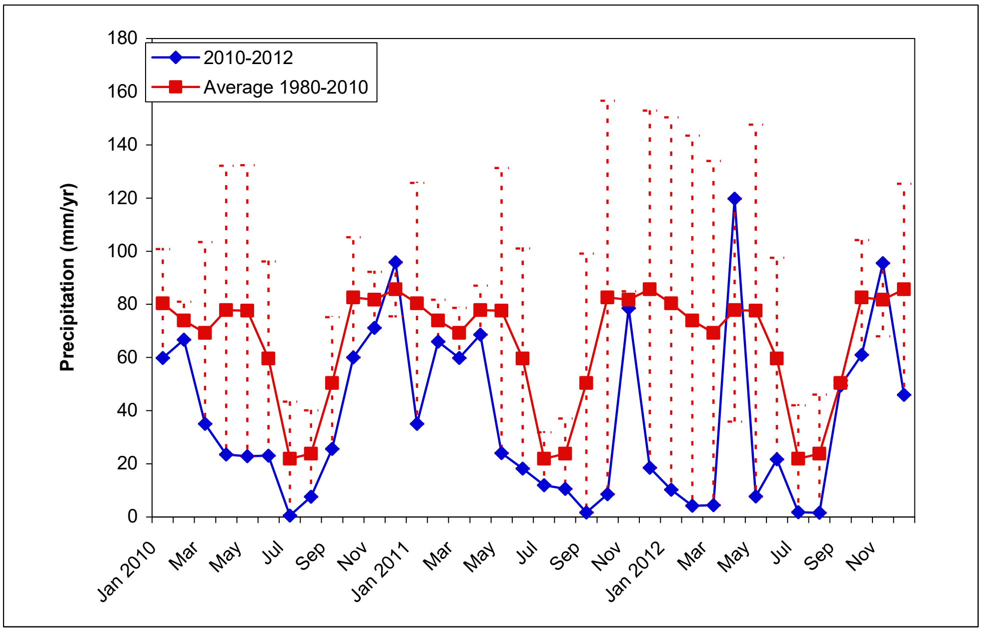
Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. Journal of climate, 23(7), 1696-1718

TABLES

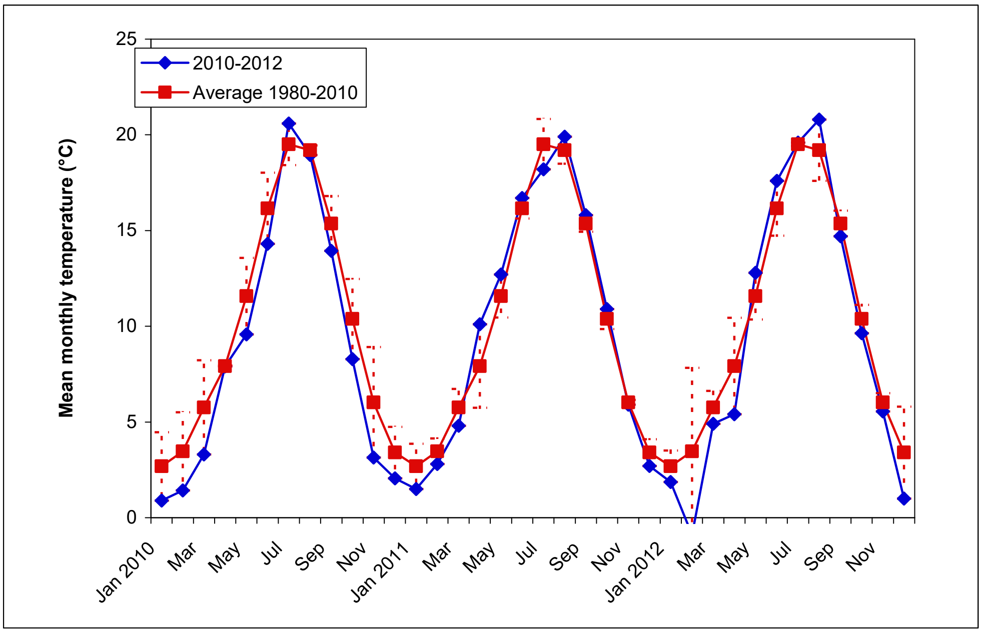
Table 1. Seedling emergence and survival rates of Spanish black pine after the wildfire of 2009 in Cuenca Mountains (Spain). Different letters indicate significant differences ($p < 0.05$) after ANOVA with repeated measures

Year	Seedling emergence rate (%)		Seedling survival rate (%)	
	Mean	Std Dev	Mean	Std Dev
2010	18.9 a	14.9	3.5 a	1.4
2011	11.2 b	12.5	0.5 c	6.6
2012	11.2 b	12.5	2.5 b	1.3

FIGURES


2010-2012
Average 1980-2010
Precipitation (mm/yr)
0
20
40
60
80
100
120
140
160
180
Jan 2010
Mar
May
Jul
Sep
Nov
Jan 2011
Mar
May
Jul
Sep
Nov
Jan 2012
Mar
May
Jul
Sep
Nov

(a)


2010-2012
Average 1980-2010
Mean monthly temperature (°C)
0
5
10
15
20
25
Jan 2010
Mar
May
Jul
Sep
Nov
Jan 2011
Mar
May
Jul
Sep
Nov
Jan 2012
Mar
May
Jul
Sep
Nov

(b)

Figure 1. Annual precipitation (a) and mean monthly temperature (b) (mean and standard error) for the periods of 1980–2010 and 2010-2012 in Cuenca Mountains (Spain)

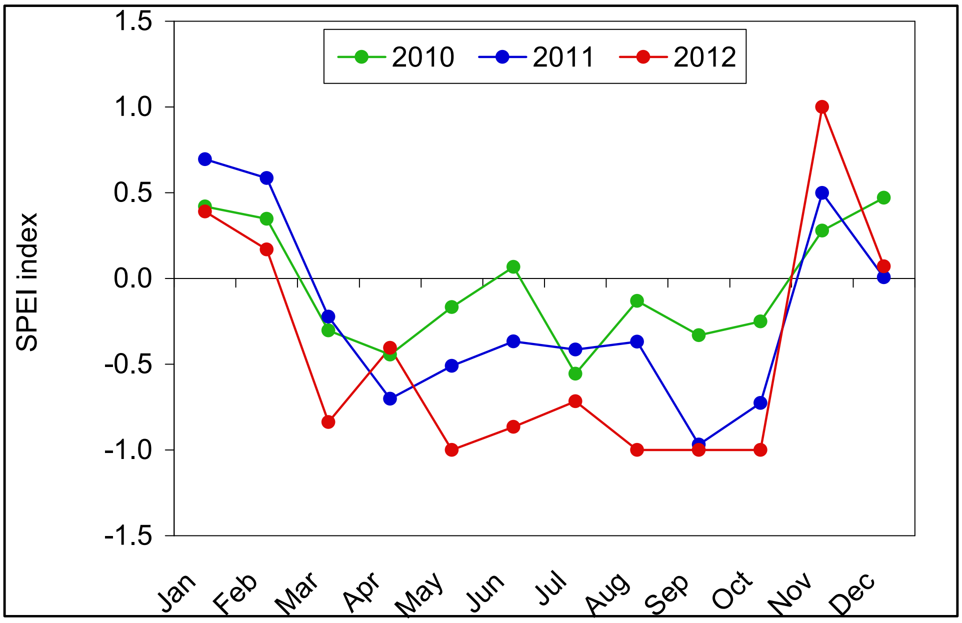


Figure 2. Standardized Precipitation-Evapotranspiration Index (SPEI), estimated from a standardized sum of monthly differences between precipitation and potential evapotranspiration, in Cuenca Mountains (Spain)

Commento [YYY5]: Old figures (to be cancelled)

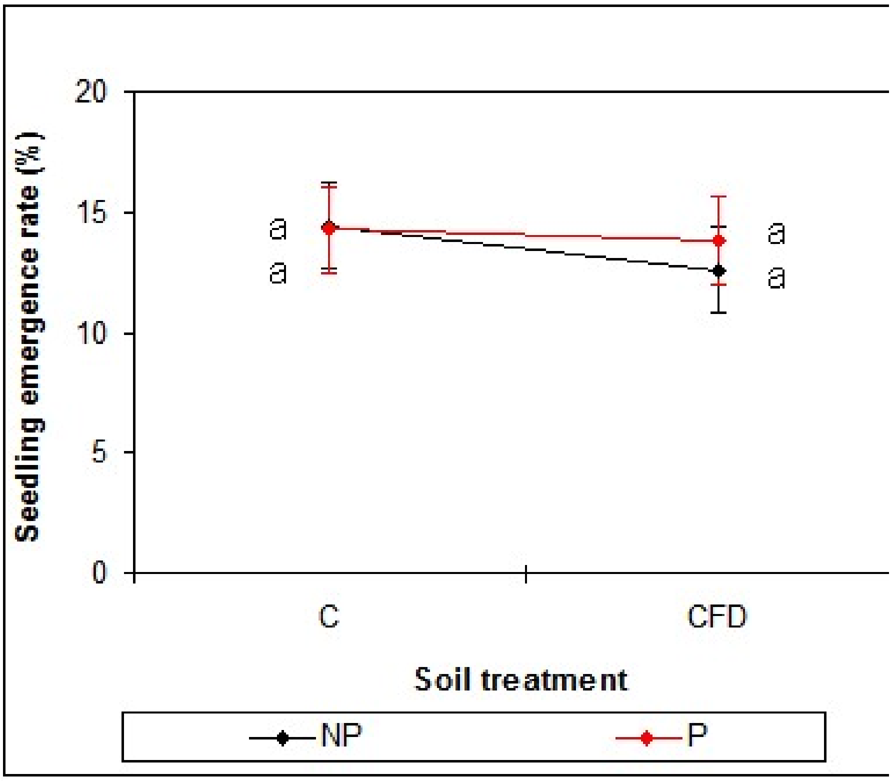


Figure 3. Interaction plots of treatments (CFD or bare soil, C) and seed protection (non protected seeds, NP, or protected seeds, P) or slopes (lower charts, low, L, medium, M, or high, H, gradient) for seedling emergence (a) and survival rates (b) of Spanish black pine after the wildfire of 2009 in Cuenca Mountains (Spain).; different letters indicate significant differences ($p < 0.05$) after ANOVA with repeated measures. Error bars indicate standard error (variability over time and among slopes in interaction treatment x seed protection, and variability over time and between seed protection in interactions treatment x slope).