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Article

Mid-Term Natural Regeneration of *Pinus halepensis* Mill. after Post-Fire Treatments in South-Eastern Spain

Mehdi Navidi [1], Manuel Esteban Lucas-Borja [2,*], Pedro Antonio Plaza-Álvarez [2], Bruno Gianmarco Carra [3], Misagh Parhizkar [4] and Demetrio Antonio Zema [3]

1 Faculty of Natural Resources, Urmia University, Urmia 30200, Iran
2 Department of Agroforestry Technology, Science and Genetics, School of Advanced Agricultural and Forestry Engineering, Campus Universitario s/n, Castilla La Mancha University, E-02071 Albacete, Spain
3 Department AGRARIA, "Mediterranea" University of Reggio Calabria, Località Feo di Vito, I-89122 Reggio Calabria, Italy
4 Department of Soil Science, Faculty of Agricultural Sciences, University of Guilan, Rasht 43000, Iran
* Correspondence: manuelesteban.lucas@uclm.es

Abstract: Straw mulching and salvage logging are common management techniques after forest wildfires. However, these post-fire actions may result in an additional disturbance in burned soils, which may hamper the natural regeneration of forest species, especially in Mediterranean areas. The results of the investigations on the impacts of these post-fire management techniques are still insufficient, and especially about post-fire regeneration of *Pinus halepensis* Mill. This tree species is typical of the western Mediterranean Basin and is hardly threatened by forest wildfires. To fill these literature gaps, this study explores the effects of salvage logging after straw mulching on the regeneration of *Pinus halepensis* Mill. throughout four years after a wildfire. These effects have been also related to the changes in the main chemical properties of the supporting soils. Compared to the burned but non-treated areas, after four years of fire and post-fire treatments, we found that: (i) mulched and non-logged sites showed a significantly higher number of seedlings (+66%) with larger diameter (+12%) and higher height (+25%); (ii) logging did not significantly increase this number (+74%), but, in mulched and logged sites, the seedlings had significantly lower diameters (−18%) and heights (−9%); (iii) an increase in the seedling number (+29%), and decreases in the plant diameter (−34%) and height (−15%) were observed in the non-mulched and logged areas; (iv) no significant differences in the other morphometric parameters of seedlings were detected among all post-fire treatments; (v) a clear gradient between the organic matter content of soils and the number of plants growing under the four treatments was evident. These results support the task of forest managers in accelerating the recovery of natural vegetation in burned pine forests in the Mediterranean environment.

Keywords: seedling number; seedling diameter; seedling height; straw mulching; salvage logging; wildfire

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1. Introduction

Wildfire is one of the most important factors that influence forest ecosystems [1,2]. This influence is particularly felt in the Mediterranean forests, where soils are shallow with low aggregate stability [3], and the weather is sensitive to future climate changes [4]. In this regard, long and dry summers in Mediterranean areas have led to an accumulation of dry biomass, increasing fires and their rate of propagation [5–8]. Moreover, the expected increase in mean temperature and reduction in precipitation will aggravate the fire risk and damage [9].

In the Mediterranean forests, post-wildfire regeneration of vegetation is slow, due to water scarcity and the intrinsic properties of arid soils, such as the low amounts of organic matter and nutrients [3]. Mediterranean soils show in general a scarce ability to recover after fire disturbance. Moreover, the intense rainfall usually occurring immediately after the fire at the beginning of the wet season seriously affects soil erosion and nutrient depletion and hinders early plant re-growth [10]. Ecosystem degradation is also severely threatened by wildfires, which results in an almost total loss of vegetation cover and changes in species composition [11]. The re-formation of plant communities and the reconstruction of forest ecosystems after severe fires can take a long time, also due to excessive erosion and changes in soil texture [12,13]. Plant regeneration rates can be strengthened or, in contrast, weakened by post-fire management actions, which are commonly adopted to reduce runoff and erosion in wildfire-affected areas [14–16]. The specific purpose of post-fire management is soil protection and vegetation regrowth in the so-called "windows of disturbance" immediately after the fire [17]. In this period, the soil is left bare due to vegetation burning and the changes in physico-chemical properties of soils are severe due to fire heating [18–20]. Thus, the soil is exposed to rainfall erosivity and therefore is prone to erosion with heavy on-site and off-site impacts. Over time, the pre-fire cover of vegetation is restored (often after several years or decades), and the runoff and erosion rates decrease [21,22].

Post-fire management techniques are numerous, and their suitability and effectiveness depend on many factors (soil, weather patterns, fire severity) [23,24]. Reforestation by planting pioneer plants can be an important action to mitigate soil erosion and enhance forest ecosystem recovery, but this technique requires many years and optimal edaphic conditions. Mulching is by far the most cost-effective post-fire management action, since the mulch can reduce soil loss from burnt forests [25,26]. The mulch material (mostly vegetal biomass, such as straw, chips, and pruning residues) is spread on the soil surface at variable cover and rate. Mulching effectively reduces water and wind erosion thanks to the decreased velocity of the overland flow, increased water infiltration, supplied organic matter, and local maintenance of soil humidity and temperature [27–29]. Straw mulch is one of the most common mulch materials, thanks to its availability and low cost [30–32]. Several studies have shown the effectiveness of mulching to contrast soil erosion in burnt forests (e.g., [32–38]). However, in some cases, the mulch cover can be removed by the wind in some areas, and become too thick in others, and this hampers vegetation regeneration [39,40]. In addition, seeds, agro-chemicals, and parasites may be transported by straw, with development of non-native vegetation and diseases to plants [41]. Moreover, some cases of lower effectiveness at governing post-fire soil hydrology are reported in the literature (e.g., [14,42,43]). From these examples, it is evident that straw mulching cannot be applied in forests without verifying whether this practice can accomplish its aims without any negative impacts on the different ecosystem components.

Salvage logging as a post-fire treatment is commonly applied in burnt forests, to recover timber [44], and secondarily to reduce wildfire risks (for instance, by creating contour-felled debris logs, removing flammable dead fuels, and altering fuel trajectories [45–47]). However, this technique may result in negative impacts on forest soils. For instance, the heavy machinery that drags the trunks exerts a high pressure over the burnt soil [48,49] and disturbs forest vegetation by decreasing regeneration [50]. As such, the soil damage due to salvage logging may worsen its hydrological response [51,52], due to the decrease in water infiltration and reduction in vegetation cover [52–54]. Despite the ample and eminent literature in recent decades (e.g., [51,52,55]), the effects of salvage logging after a wildfire on forest ecosystems have been poorly studied in Mediterranean countries, and moreover are still contrasting [56,57].

One of the essential issues of post-fire management in burnt forests under Mediterranean climatic conditions is the ecological impact of straw mulching and salvage logging (separately or in combination) on post-fire regeneration of vegetation. In this regard, some studies have shown that mulching and salvage logging exert a neutral effect on plant regeneration [58–63]. In contrast, other authors have reported detrimental effects on plant growth after soil mulching [64,65], and on seedling recruitment after salvage logging [66–69] in wildfire-affected areas. Furthermore, some researchers have highlighted how mulching mulch-retained moisture may benefit natural plant regeneration in water-stressed environments [70–73], while very few studies support the enhancement of plant regeneration after post-fire logging.

In Mediterranean forest ecosystems, which are characterized by wet periods alternating to hot summers with short and intense storms, there is little evidence of the effects of post-fire mulching applied before salvage logging on soil characterization, especially on widely spread species, such as *Pinus halepensis* Mill., a tree species that is typical of the western Mediterranean Basin, and hardly threatened by forest wildfires [74].

To fill this gap, this study explores the effects of salvage logging after straw mulching on the regeneration of *Pinus halepensis* Mill. throughout four years after a wildfire. These effects have been also related to the changes in the main chemical properties of the supporting soils. We hypothesize that in the mid-term: (i) the application of straw mulch without salvage logging after a wildfire increases the number and growth of *Pinus halepensis* Mill. seedlings in the burnt area; (ii) salvage logging may result in detrimental effects on the natural regeneration of *Pinus halepensis* Mill.

2. Materials and Methods

2.1. Study Area

The study area was the Sierra de las Quebradas forest (Liétor, Province of Albacete, Region of Castilla La Mancha, Central-Eastern Spain) under a semi-arid Mediterranean climate, BSk class, according to the Koeppen-Geiger classification [75]. The mean annual precipitation and annual temperature are 282 mm and 16 °C, respectively. The elevation ranges from 520 to 770 m and the aspect is W-SW. The soils, with a mean depth of less than 30 cm, are classified as Inceptisols and Aridisols, with a sandy–loamy texture [76].

The forest is mainly composed of *Pinus halepensis* Mill. with a mean density of 500 to 650 trees/ha and a mean height between 7 and 14 m. The main shrubs and herbaceous species are *Rosmarinus officinalis* L., *Brachypodium retusum* (Pers.) Beauv., *Cistus clusii* Dunal, *Lavandula latifolia* Medik., *Thymus vulgaris* L., *Helichrysum stoechas* (L.) Moench, *Macrochloa tenacissima* (L.) Kunth, *Quercus coccifera* L., and *Plantago albicans* L.

2.2. Experimental Design

In July 2016, a high-intensity wildfire burned a large part of the forest area. Serotonin was observed in the burned stands, which were affected by crown fire with a tree mortality close to 100%. Serotiny is a fire ecological adaptation of *Pinus halepensis* M., in which pine seed release occurs in response to the high temperatures of a fire. Immediately after the fire, in an area of about 5 ha, 12 rectangular plots (each of 20 m × 10 m, covering 200 m^2) were identified. The longest dimension of each plot was set along the highest slope. Plots were distributed to ensure their comparability, that is according to the slope (in the range 15% to 20%) and aspect (always north). Pseudo-replication was avoided adopting a reciprocal distance among the plots between 200 and 500 m.

In late September 2016, six replicated plots in the burned area, randomly chosen, were subjected to mulching treatments. The other burned plots were instead not treated and considered as control. The mulch material, barley straw, was cut in a neighboring farm and manually applied on the plot surface at a dose of 0.2 kg/m^2 (dry weight). This dose derives from indications by different authors, who achieved a ground cover over 80% and a mulch depth of 3 cm in plots of northern Spain [77]. Moreover, this dose of straw was successfully applied in croplands affected by high erosion rates [78].

Salvage logging was carried out in a single day of early December 2016 in the study area. The trees were cut using a mechanical chainsaw, and the burnt logs were removed from the logged areas by a tractor equipped with agricultural wheels and herringbone rubber tires. The tractor was a 4-cylinder model DT9880 (Landini, Fabbrico (RE), Italy)), which could reach a rated power of 69.2 kW and had a total weight of 4697 kg. The working speed was 6.0 to 8.0 km/h. In more detail, trees were cut with mechanical chainsaws, and burned logs were removed from plots by the described agricultural tractor. Tree biomass that remained in the plots after logging was composed by needles without any type of treatment.

The experimental design consisted of the following treatments: Mulching + Logging (three replicates, hereafter indicated as "M + L"), No Mulching + Logging (three replicates, "NM + L"), No Mulching + No Logging (three replicates, "NM + NL"), and Mulching + No Logging (three replicates, "M + NL"). The non-mulched + non-logged plots were used as control.

For each plot, the mean soil burn intensity was determined according to the methods by Vega et al. [79]. No needle cover was found on the ground surface of all plots, since all trees were completely burned by the wildfire.

2.3. Climate Data

A weather station (WatchDog 2000 Series model, Spectrum Technologies Inc., Aurora, IL, USA) was used to measure the daily precipitation and air temperature in the study area at each day the same hour (Table 1).

Table 1. Cumulative precipitation and mean air temperature on the seasonal scale in the study period (Sierra de Los Donceles forest, Castilla La Mancha, Spain).

Year	Season	Cumulative Precipitation (mm)	Mean Air Temperature (°C)
2017	Winter	119	8.1
	Spring	108	15.1
	Summer	13.3	25.5
	Autumn	20.2	17.3
2018	Winter	93.9	7.5
	Spring	129	10.1
	Summer	65.6	24.4
	Autumn	127	16.4
2020	Winter	92.9	9.1
	Spring	285	11.8
	Summer	11.5	25.3
	Autumn	161	17.5
2022	Winter	8.2	10.3
	Spring	240	11.4

2.4. Plant Survey for Analysis of Natural Regeneration

2.4.1. Field Measurements

The seedlings growing in each plot were visually counted at six dates between July 2017 and June 2022 on a linear transect placed along the plot profile. The linear transect was randomly placed inside the plot. A total of 20 seedlings from each plot were randomly selected, and their diameter and height were measured at four dates.

2.4.2. Lab Measurements

A total of 15 seedlings per plot were randomly selected in the field and manually collected. Then their morphometric characteristics (aerial part, roots, and needles) were measured in the laboratory 24 h later. This allowed the assessment of the quality of forest seedlings. Following the classification of Haase [80], the following morphometric characteristics of the seedling were measured: length of aerial part and roots as well as dry weight of the aerial part, roots, and needles. For the latter three variables, related to dry seedling, the plant samples were dried at 107 °C for 24 h.

2.5. Soil Temperature and Water Content

Soil temperature and water content were daily measured in each plot at the same hour using the HOBO MX2307 (Onset Computer Corporation Inc., Bourne, MA, USA) sensor, which was calibrated before use.

2.6. Soil Sampling and Analysis

In June 2022, triple samples of soil were manually collected from the topsoil (0–10 cm of depth) in randomly chosen plots. Soil samples were then stored in a refrigerator at 4 °C until the laboratory analysis for two days after sampling. The following properties were measured on each soil sample: (i) pH and electrical conductivity (EC), both measured in an aqueous solution at a ratio of 1:5, w/v, using a portable multiparameter instrument (Hanna Instruments); (ii) organic matter (OM) content, using the potassium dichromate oxidation method (Nelson and Sommers 1996); (iii) total nitrogen content (TN), using the Kjeldahl method [81].

2.7. Statistical Analyses

A two-way ANOVA was applied to seedling parameters (number, diameter, and height, considered as dependent or response variables) to evaluate the statistical significance of the differences among the four treatments and survey dates. Moreover, a one-way ANOVA was applied to the climatic variables (soil temperature and water content), morphological characteristics of seedlings (diameter, and height of seedlings, length and dry weight of aerial part and roots of seedlings, and needles), and soil chemical properties (pH, EC, OM, and TN), which were considered as dependent or response variable, to evaluate the statistical significance of the differences among the four treatments. The pairwise comparison by LSD test (at $p < 0.05$) was also used. In order to satisfy the assumptions of equality of variance and normal distribution, the data were square root-transformed when necessary. In this case, the Shapiro–Wilk test was again applied to check the normal distribution of the samples. The statistical analysis was carried out using XLSTAT release 19.1 (Addinsoft, Paris, France) software.

3. Results

3.1. Soil Temperature and Water Content

According to one-way ANOVA, soil temperature was not significantly different among the treatments (F = 0.004, $p = 0.999$), while, in contrast, significant differences (F = 25.47, $p < 0.0001$) were found for the soil water content (Table 1). In more detail, the soil temperature was slightly higher in M + L and M + NL plots (15.7 ± 7.75 and 15.7 ± 7.71 °C, respectively) compared to NM + L and NM + NL soils (15.6 ± 7.60 and 15.6 ± 7.65 °C) (Table 2).

The same pattern was noticed for SWC, whose highest value was observed in M + L and M + NL plots (0.02% ± 0.01% in both cases) and the lowest in NM + L and NM + NL soils (0.01% ± 0.01%) (Table 3).

Table 2. Results of ANOVA applied to soil temperature and water content, diameter, height, length of aerial part and of roots, and dry weight of aerial part and of roots among post-fire treatments in Sierra de Los Donceles forest (Liétor, Castilla La Mancha, Spain).

Factor	Degrees of Freedom	Sum of Squares	Mean Squares	F	Prob > F
			Soil temperature		
Treatment	3	0.663	0.221	0.004	0.999
			Soil water content		
Treatment	3	0.017	0.006	25.468	<0.0001
			Seedling diameter		
Date	3	5738	1913	162.932	<0.0001
Treatment	9	525	58	4.971	<0.0001
Treatment × date	3	431	144	12.243	<0.0001

Table 2. *Cont.*

Factor	Degrees of Freedom	Sum of Squares	Mean Squares	F	Prob > F
			Seedling height		
Date	3	58,992,694	19,664,231	398.033	<0.0001
Treatment	9	1,768,114	196,457	3.977	<0.0001
Treatment × date	3	2,479,934	826,645	16.733	<0.0001
			Length of aerial part of seedlings		
Treatment	3	134	44.6	0.747	0.531
			Root length of seedlings		
Treatment	3	46.0	15.3	0.421	0.739
			Dry weight of aerial part of seedlings		
Treatment	3	10.3	3.43	0.200	0.896
			Dry weight of roots of seedlings		
Treatment	3	0.04	0.01	0.021	0.996
			Dry weight of needles		
Treatment	3	2.53	0.84	0.109	0.954

Table 3. Soil temperature and water content (mean ± standard deviation) after post-fire treatments in Sierra de Los Donceles forest (Liétor, Castilla La Mancha, Spain).

Variables	Treatments			
	M + L	M + NL	NM + L	NM + NL
Soil temperature (°C)	15.7 ± 7.75 [a]	15.7 ± 7.71 [a]	15.6 ± 7.60 [a]	15.6 ± 7.65 [a]
Soil water content (SWC, %)	2.02 ± 0.02 [a]	2.03 ± 0.02 [a]	1.01 ± 0.01 [b]	1.01 ± 0.01 [b]

Notes: M + L = Mulching + Logging; M + NL = Mulching + No Logging; NM + L = No Mulching + logging; NM + NL = No Mulching + No Logging. Lowercase letters indicate significant differences according to the LSD test ($p < 0.05$).

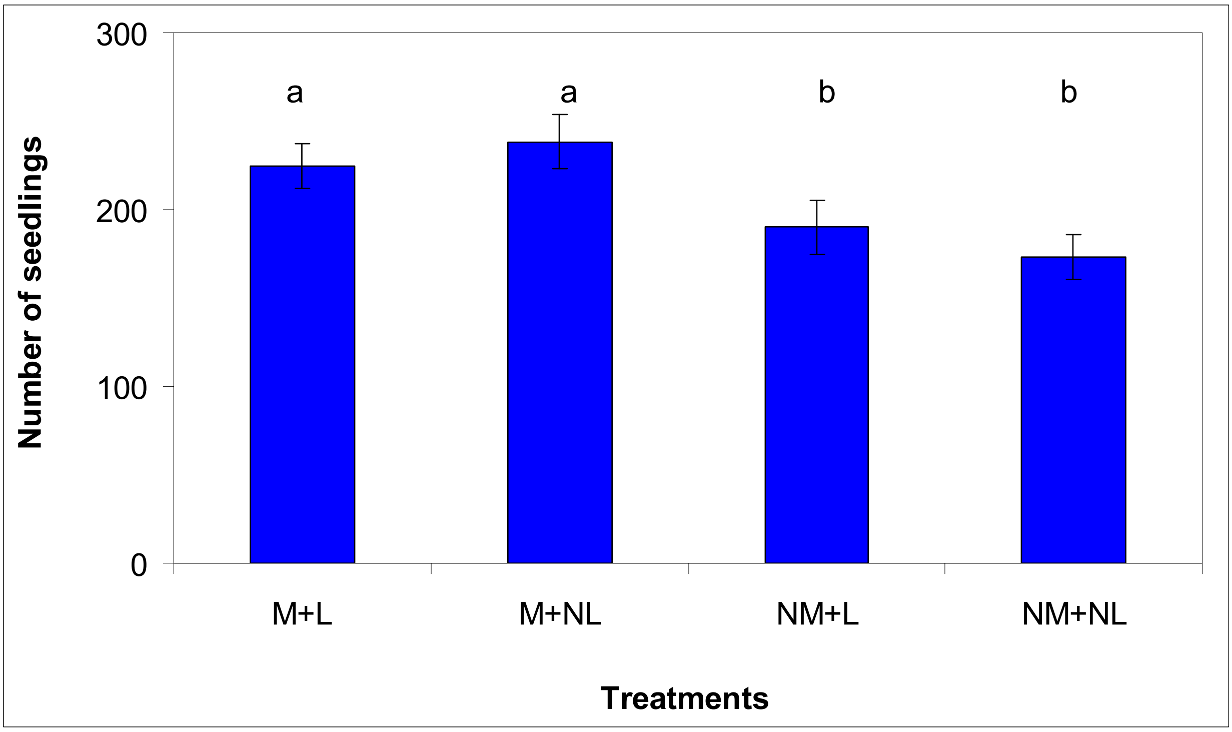
3.2. Natural Regeneration of Pinus halepensis Mill

3.2.1. Number of Seedlings

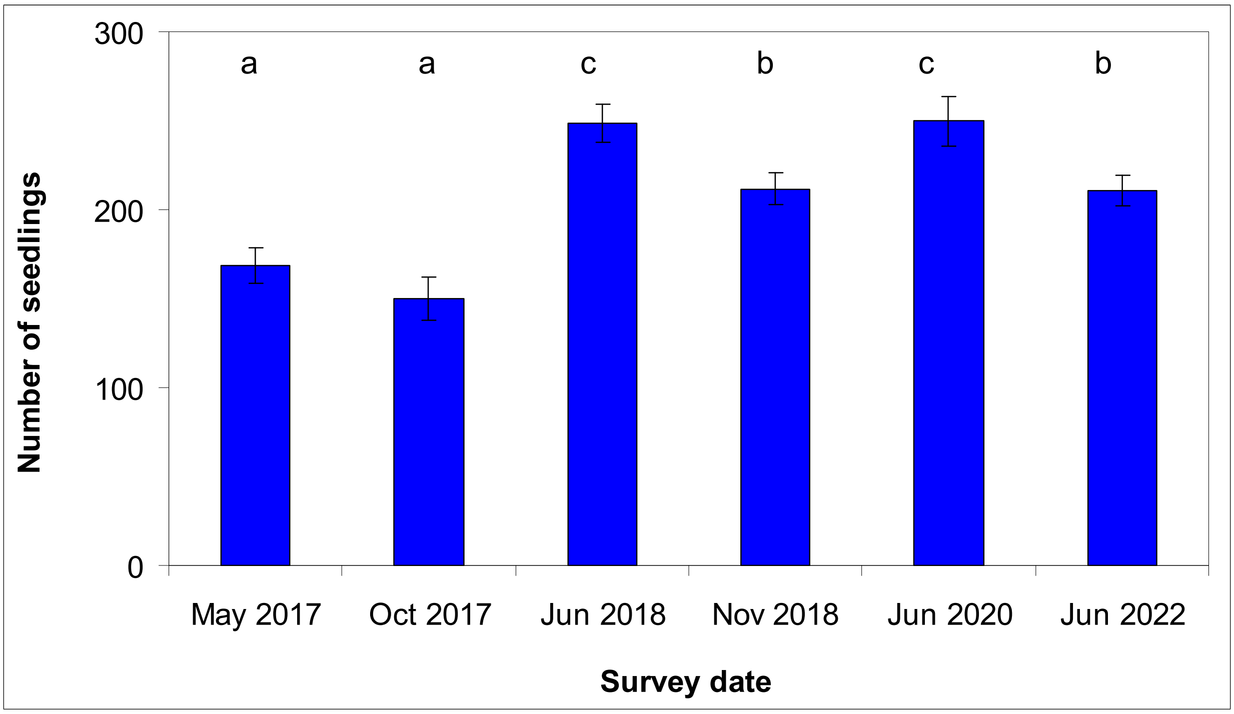
Significant differences in the number of seedlings among the treatments (F = 14.854, $p < 0.0001$) and survey dates (F = 18.180, $p < 0.0001$) were detected, but the interactions between these variables were not significant (F = 0.385, $p = 0.977$) (Table 2).

If averaged among the four survey dates, the highest number of seedlings were found in the M + NL plots (238 ± 40); this number was not significantly different compared to the values measured in the M + L plots (225 ± 30). The number of seedlings in the NM + L (190 ± 27) and NM + NL (173 ± 15) plots was significantly lower compared to the mulched soils, while the reciprocal differences were not statistically different (Figure 1a).

About the number of seedlings, the lowest number was found in October 2017 (150 ± 3, mean of values measured under all four treatments) and the highest in June 2020 (250 ± 32). The number of seedlings measured in the first two surveys was significantly different from the values at the following dates (Figure 1b).



(**a**)



(**b**)

Figure 1. Number of seedlings of *Pinus halepensis* Mill. (mean ± standard deviation) averaged among treatments (**a**) and survey dates (**b**). Different letters indicate significant differences according to the LSD test ($p < 0.05$). Legend: M + L = Mulching + Logging; NM + L = No Mulching + Logging; NM + NL = No Mulching + No Logging; M + NL = Mulching + No Logging.

3.2.2. Diameter of Seedlings

The differences in the diameter of seedlings were significant both among the treatments (F = 12.243, $p < 0.0001$) and survey dates (F = 162.932, $p < 0.0001$) as well as their interaction (F = 4.971, $p < 0.0001$) (Table 2).

As expected, the diameter of seedlings increased over time. However, while the increase recorded in November 2018 was not significantly different from the first measurement (June 2018), the differences in seedling diameter became significant in the following surveys (June 2020 and 2022). The last measurement was significantly different compared to all the previous dates (Figure 2).

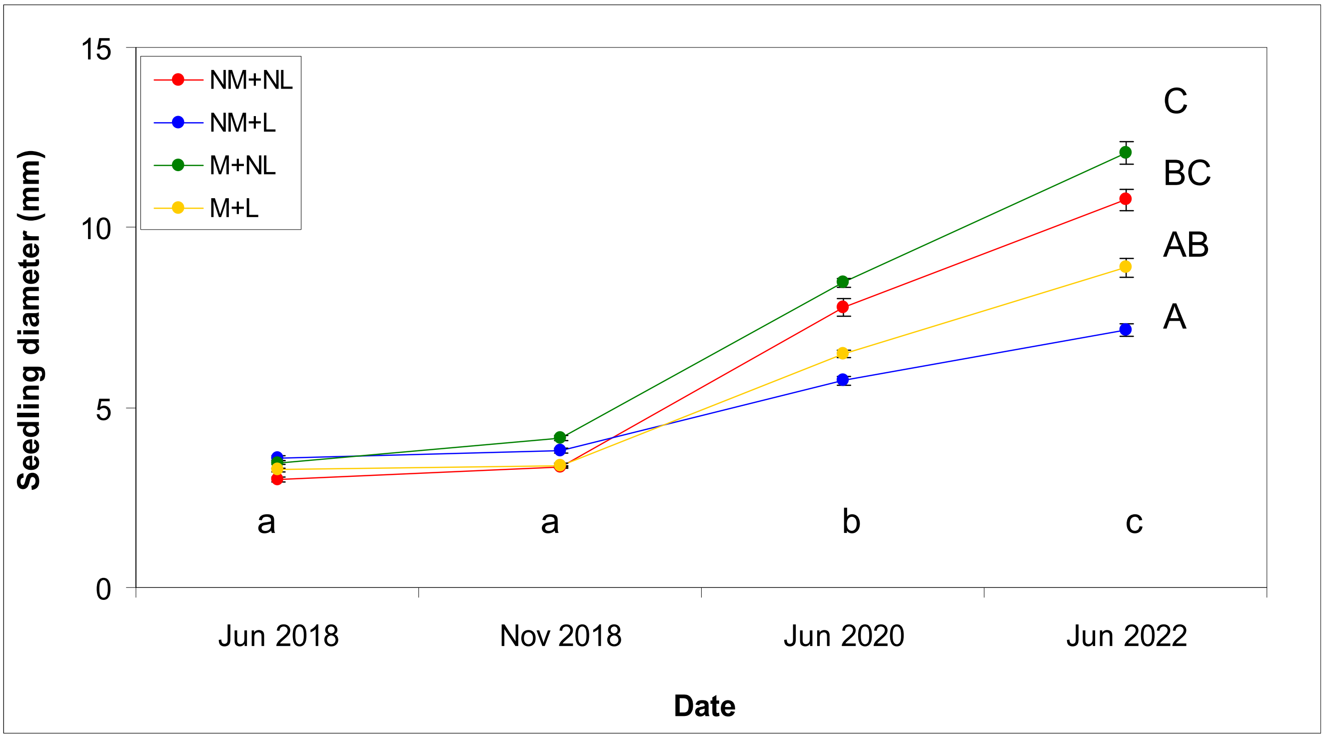


Figure 2. Variation of diameter of seedlings (mean ± standard deviation) of Pinus halepensis Mill. growing in plots subjected to four treatments in Sierra de Los Donceles forest (Liétor, Castilla La Mancha, Spain). Different lowercase and capital letters indicate significant differences among survey dates and treatments, respectively, according to the LSD test ($p < 0.05$). Legend: M + L = Mulching + Logging; NM + L = No Mulching + Logging; NM + NL = No Mulching + No Logging; M + NL = Mulching + No Logging.

The seedlings growing in the M + NL plots showed the highest diameter (12.1 ± 0.3 mm) at the end of the survey period. This value was not significantly different compared to the diameter surveyed in NM + NL plots (10.77 ± 0.30 mm), but noticeably and significantly higher compared to the seedlings of M + L (8.88 ± 0.27 mm) and NM + L (7.15 ± 0.16 mm) plots, the latter showing the lowest diameter (Figure 2).

3.2.3. Height of Seedlings

As detected for the diameter, the treatment (F = 16.733, $p < 0.0001$) and survey date (F = 398.033, $p < 0.0001$) factors as well as their interaction (F = 3.977, $p < 0.0001$) significantly influenced the height of seedlings (Table 2).

Also for the height of seedlings, a temporal increase was detected, and the height measured in the last surveys (June 2022) was significantly different compared to the previous date (June 2020) and the first two measurements (June and November 2018) (Figure 3).

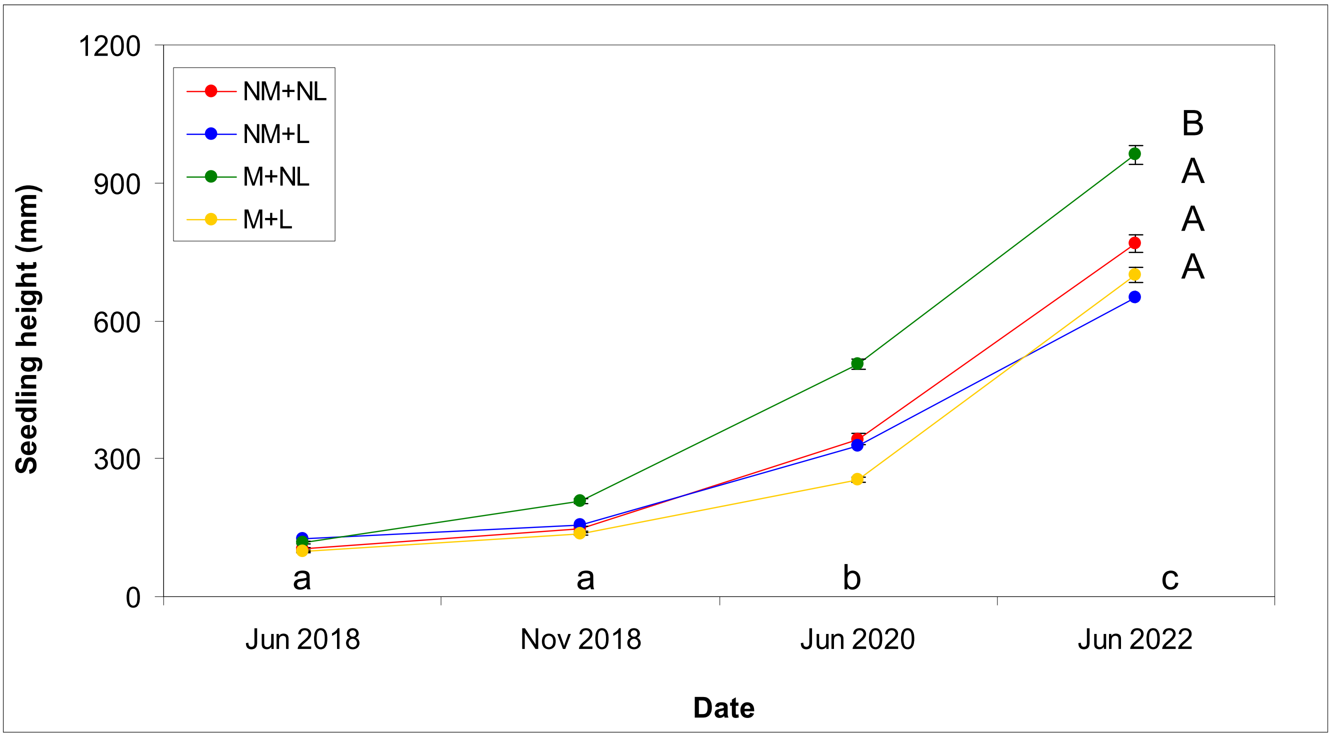


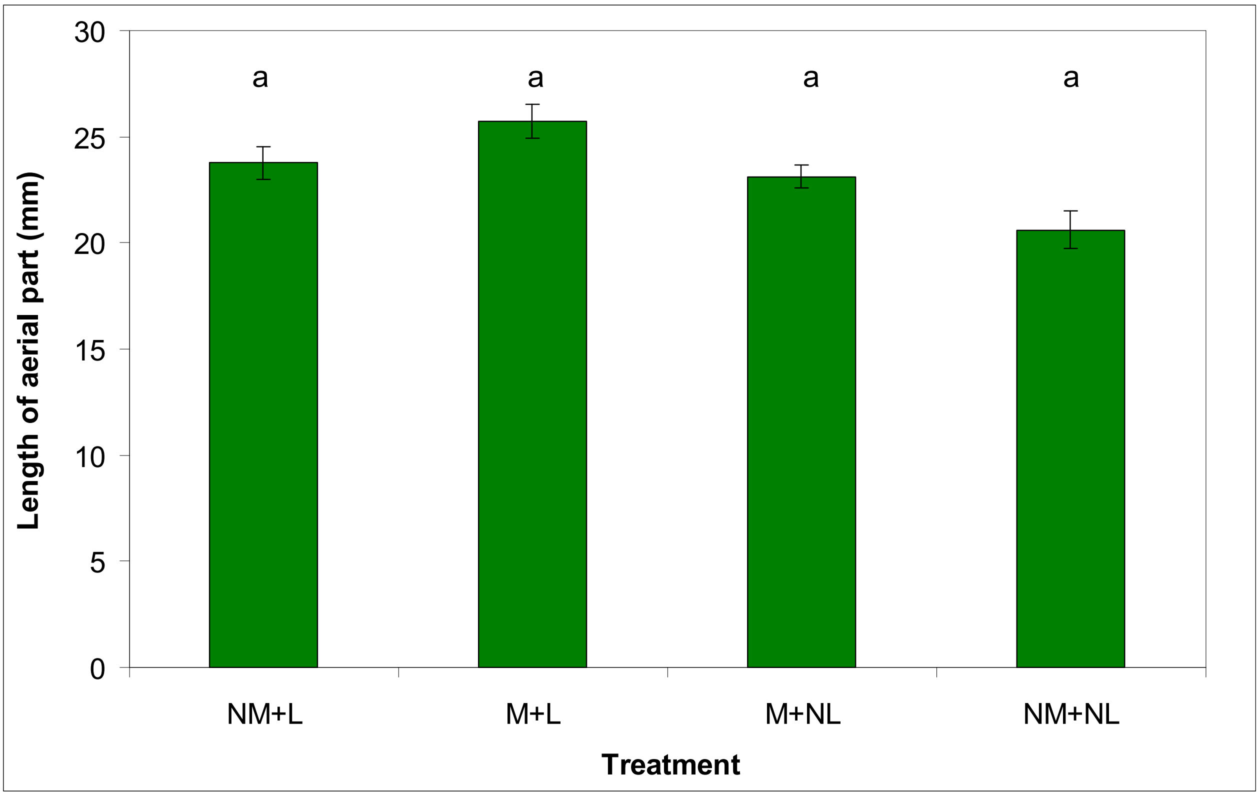
Figure 3. Variation of the height of seedlings (mean ± standard deviation) of *Pinus halepensis* Mill. growing in plots subjected to four treatments in Sierra de Los Donceles forest (Liétor, Castilla La Mancha, Spain). Different lowercase and capital letters indicate significant differences among survey dates and treatments, respectively, according to the LSD test ($p < 0.05$). Legend: M + L = Mulching + Logging; NM + L = No Mulching + Logging; NM + NL = No Mulching + No Logging; M + NL = Mulching + No Logging.

The tallest seedlings (961 ± 20.7 mm, survey of June 2022) were detected in M + NL plots, and this height was significantly different compared to all other treatments. The seedlings growing in NM + L plots showed instead the lowest height (652 ± 12.1 mm). Moreover, the differences in seedling height among NM + NL (769 ± 19.1 mm), NM + L, and M + L (700 ± 16.6 mm) were not significant (Figure 3).

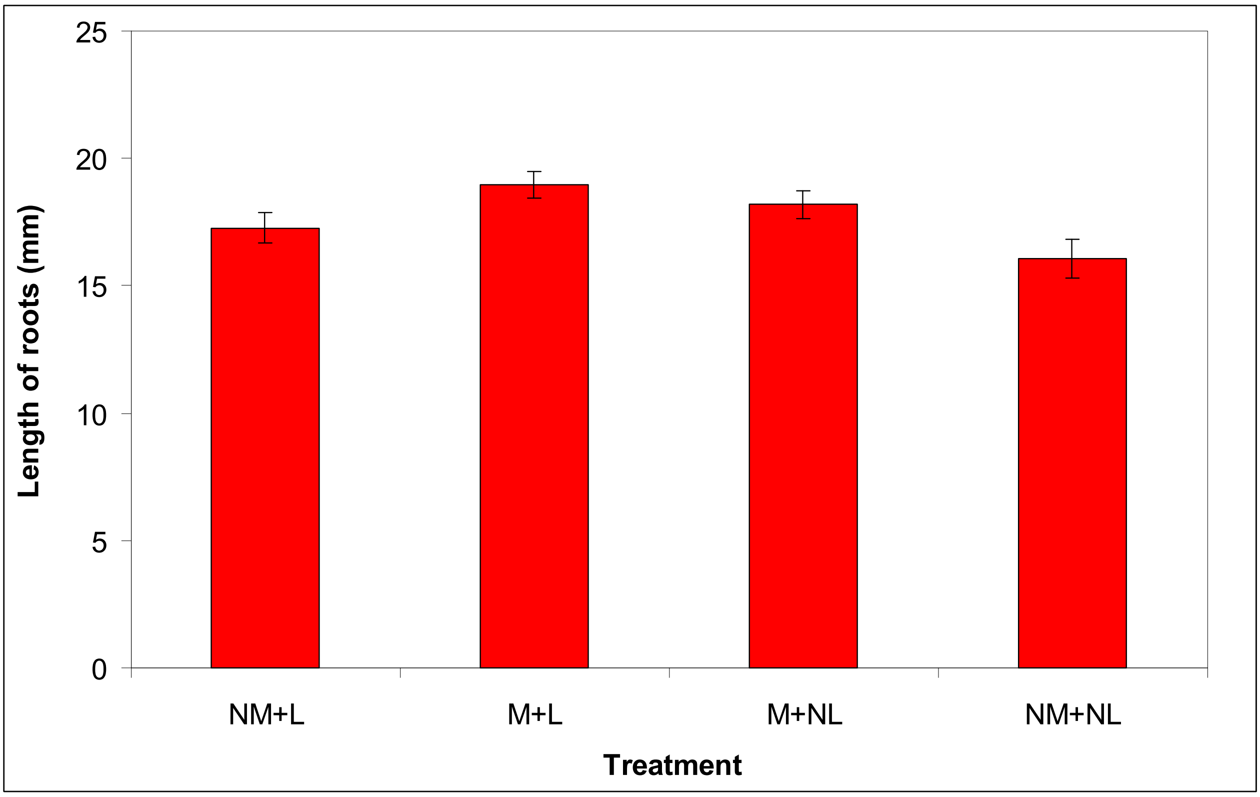
3.2.4. Morphometric Characteristics of Seedlings

The processing of the morphometric data of seedlings using one-way ANOVA showed that the differences in all the measured parameters were n significant among the soil treatments. In more detail, the following values of the ANOVA parameters F and p were found: F = 0.747, p = 0.531 (length of aerial part); F = 0.421, p = 0.739 (length of root); F = 0.200, p = 0.896 (dry weight of aerial part); F = 0.021, p = 0.996 (dry weight of roots); and F = 0.109, p = 0.954 (dry weight of needles) (Table 2).

The aerial part of seedlings growing in the M + L and NM + NL plots showed the highest and lowest lengths (25.7 ± 0.83 mm and 20.6 ± 0.90 mm, respectively), and the same trend was noticed for the length of roots (19.0 ± 0.50 mm and 16.1 ± 0.76 mm) (Figure 4). The highest dry weights of aerial part and needles were measured in M + NL plots (4.44 ± 0.27 g and 3.20 ± 0.19 g, respectively), while the lowest values were found in the seedlings of NM + L plots (3.17 ± 0.38 g and 2.51 ± 0.28 g). The seedling roots of M + L and NM + L plots had the maximum and minimum dry weights (1.03 ± 0.07 g and 0.95 ± 0.07 g, respectively (Figure 4). However, the differences among all measured values of the morphometric parameters of seedlings were never significant.

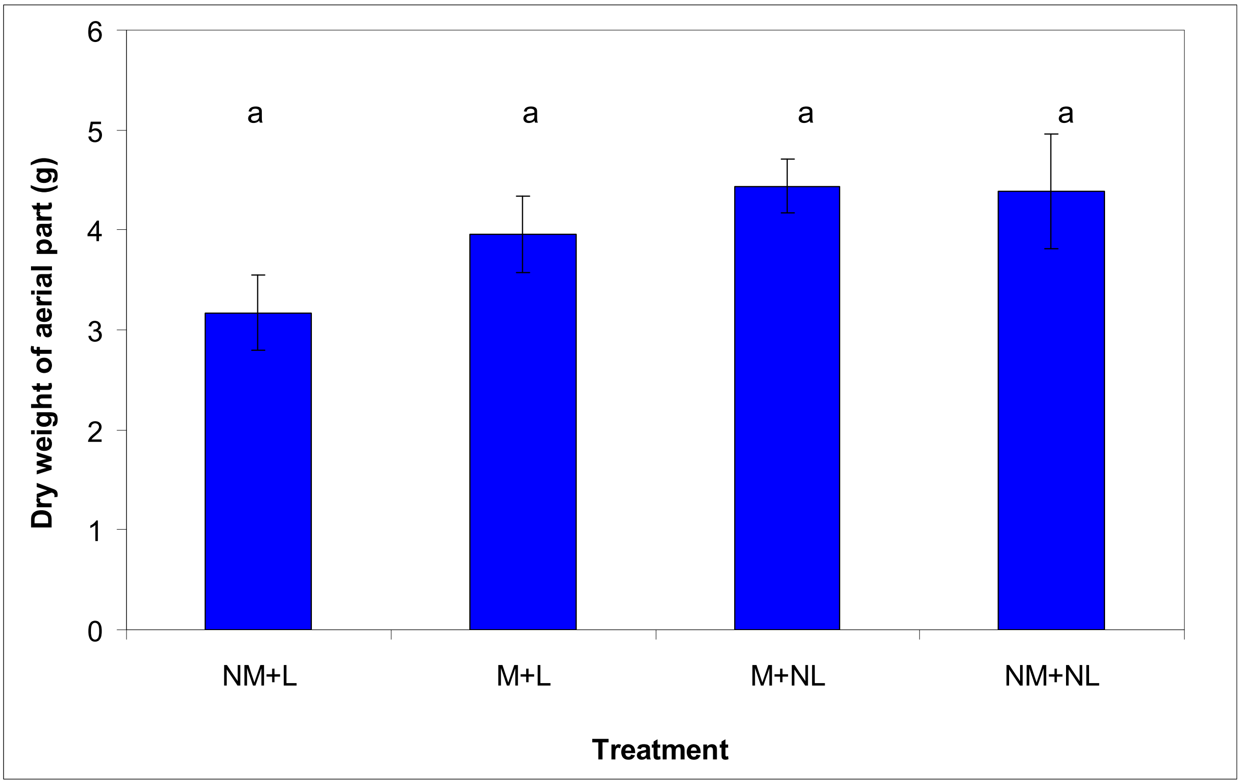


(a)

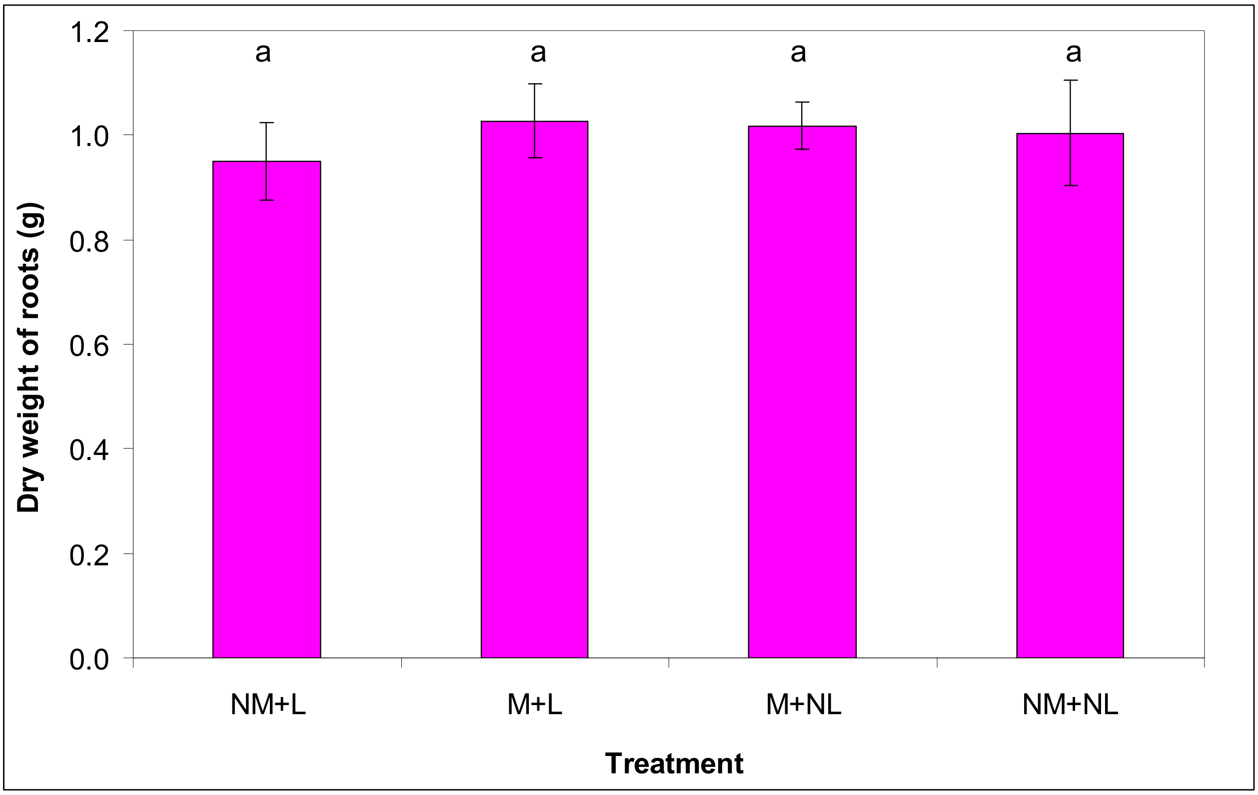


(b)

Figure 4. *Cont.*

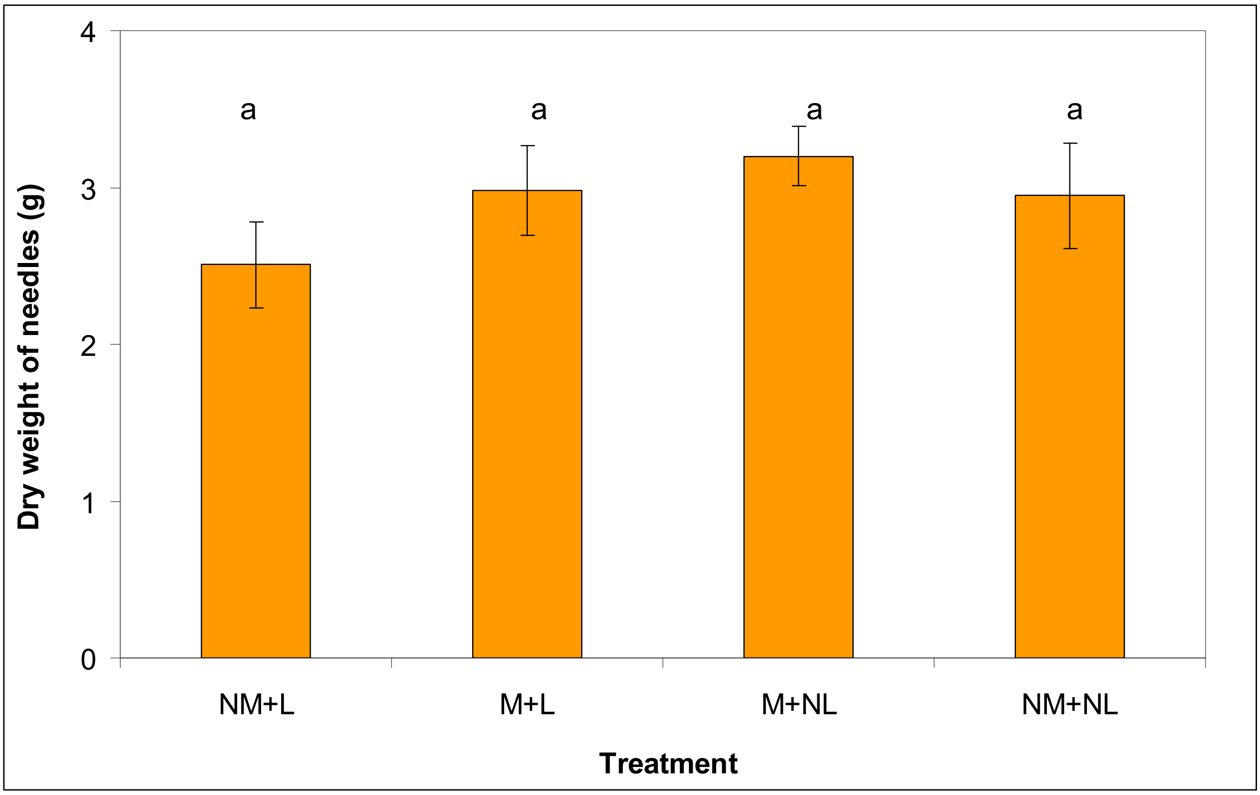


(c)



(d)

Figure 4. *Cont.*

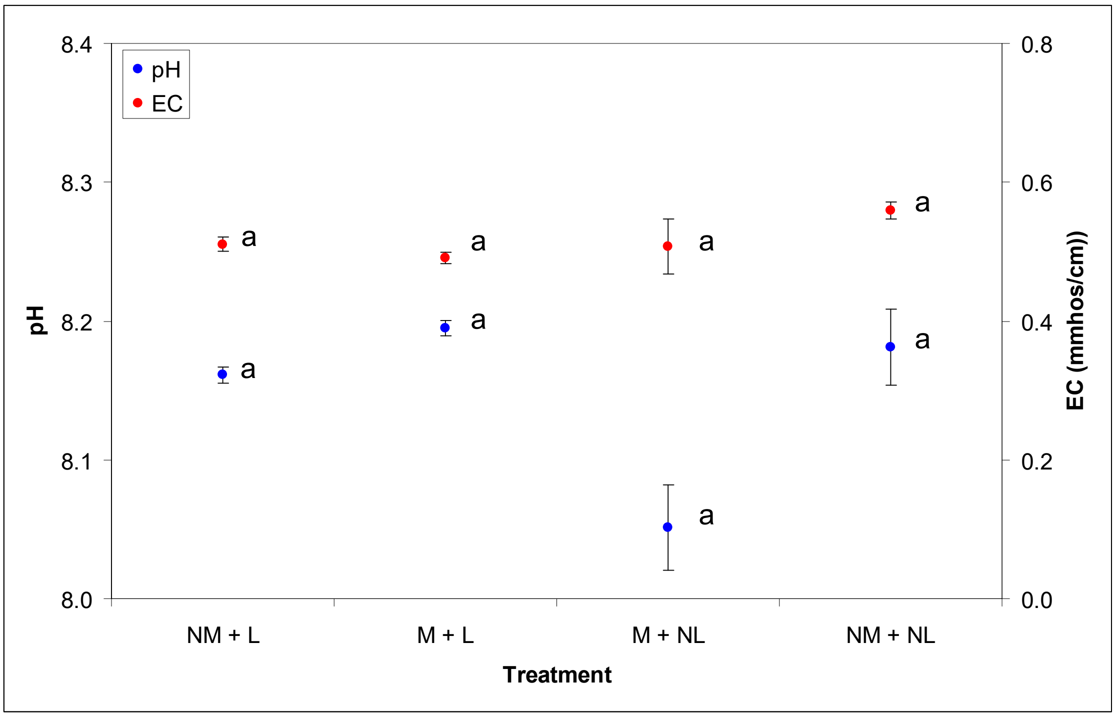


(**e**)

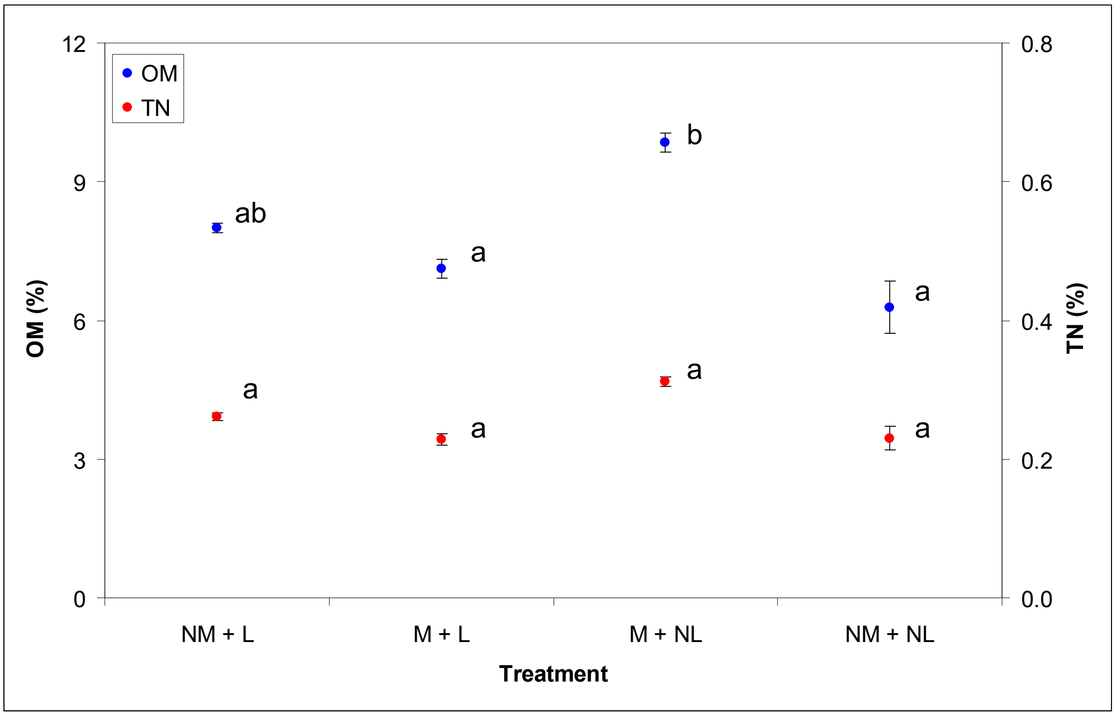
Figure 4. Morphometric characteristics of seedlings (mean ± standard deviation) of *Pinus halepensis* Mill. growing in plots subjected to four treatments in Sierra de Los Donceles forest (Liétor, Castilla La Mancha, Spain). Length of aerial part (**a**), length of roots (**b**), dry weight of aerial part (**c**), dry weight of roots (**d**), dry weight of needles (**e**). Different letters indicate significant differences among treatments according to the LSD test ($p < 0.05$). Legend: M + L = Mulching + Logging; NM + L = No Mulching + Logging; NM + NL = No Mulching + No Logging; M + NL = Mulching + No Logging.

3.3. Main Chemical Properties of Soils

Among the studied soil parameters, ANOVA revealed that only the differences in the OM content of soil were significant among the four treatments (F = 5.623; $p < 0.01$), while the other parameters (pH, EC and TN) were not significantly different (F = 2.463, $p = 0.113$ for pH; F = 0.716, $p = 0.561$, and F = 3.438, $p = 0.052$ for TN) (Table 2). In more detail, soil pH was in the range 8.05 ± 0.03 (M + NL plots) to 8.20 ± 0.01 (M + L), while the EC was the lowest in the M + L plots (0.49 ± 0.01 mmhos/cm) and the highest in the NM + NL soils (0.56 ± 0.01 mmhos/cm) (Figure 5a). The latter plots showed the minimum content of OM (6.29% ± 0.57%), while the maximum value was measured in the M + NL soil (9.85% ± 0.2%). This value was significantly different compared to NM + NL and M + L plots, but similar as the NM + L plots. A very similar pattern was noticed for the TN content of soils. The M + L and NM + NL plots showed the lowest value (0.23% ± 0.01% and 0.23% ± 0.02%, respectively), while the lowest content was observed in the M + NL soils (0.31% ± 0.01%) (Figure 5b).



(**a**)



(**b**)

Figure 5. Main chemical properties of soils (mean ± standard deviation) supporting growth of *Pinus halepensis* Mill. in plots subjected to four treatments in Sierra de Los Donceles forest (Liétor, Castilla La Mancha, Spain). pH (**a**) and OM (**b**). Different letters indicate significant differences among treatments according to the LSD test ($p < 0.05$). Legend: M + L = Mulching + Logging; NM + L = No Mulching + Logging; NM + NL = No Mulching + No Logging; M + NL = Mulching + No Logging; EC = electrical conductivity; OM = organic matter; TN = total nitrogen.

4. Discussion

4.1. Effects of Straw Mulching on Natural Regeneration of Pinus halepensis Mill

The monitoring of pine seedling growth throughout the 4-year observation period has revealed that post-fire mulching without logging significantly increased the number of growing plants (by 27% compared to the non-treated areas) one year after the fire. Four years after the fire, the number of seedlings was the highest in mulched and non-logged areas, and these sites showed also the highest increases in seedling diameter (+12%) and height (+25%) among the treatments. Compared to the untreated soils, mulching reduced the soil pH, which was close to the neutrality, though this treatment did not play any influence on the EC. Beneficial effects of mulching were also noticed in the OM and TN contents of soils, which were noticeably higher compared to the untreated soils. This result agrees with the findings of Lucas-Borja et al. [82], who reported higher OM content after soil mulching with straw compared to non-mulched sites. Mulching supplies organic residues that early decompose into the soil [83,84], and promotes interaction with nutrients, improving the soil structure and the OM content [35,84]. Moreover, the straw used as mulch presumably immobilized nitrogen, and this process was mainly due to the lower concentrations of recalcitrant carbon compounds, generally more easily decomposed [85]. These beneficial effects of mulching on seedling growth agree with the findings of Lucas-Borja et al. [53], who found an increased density of pine seedlings after the use of post-fire straw mulching. Dodson and Peterson [66] found increased seedling pine density after applying straw mulching with an average soil coverage below 40%. Moreover, Beggy and Fehmi [86] reported that mulch favors vegetation recovery and maximizes vegetation establishment. As shown by Calama et al. [87], natural regeneration of *Pinus halepensis* Mill. is often successful after the fire, with young plant densities between 0.1 and 10 seedlings/m^2, and this success is mainly due to its capacity to spread a large number of seeds immediately after a fire [88,89]. Therefore, a suitable time interval between mulching and logging (about three months) and the serotinous strategy of *Pinus halepensis* Mill. could support a higher recruitment of seedlings in the short term after mulching.

According to our results, mulching did not influence the temperature of soil, but it played a significant effect on its water content, which was 2-fold compared to the non-mulched soils. In contrast with our results, mulching reduces soil temperature, but, in close agreement with our study, it increases the stored water, which is useful for seedling germination and growth [90,91]. Fernández and Vega [48] reported that the straw mulching immediately after the fire can enhance plant recovery throughout a year, since the mulch maintains soil moisture. Mulching is able to create higher moisture and lower temperature in burned soils (although this effect was not observed in our study) that improves the survival of *Pinus halepensis* Mill. seedlings in an ecosystem characterized by a water stress [92]. Based on the results of Lucas-Borja et al. [53], who studied the effects of mulching on the water content and temperature of severely burned soils, the seedlings can grow in a denser composition with an increased height.

Moreover, straw is a new source of vegetal material that is easily incorporated into the soil, but this effect is highly dependent on climatic conditions [93]. Previous studies have shown that the scarce rainfall in summer should be considered the first cause of the low emergence and early death of seedlings in Mediterranean areas [94–96]. Moreover, seedling density in winter is strongly associated with variations in the average annual rainfall, indicating that water availability is an important limiting factor for plant growth [5]. Our results suggest that the number of seedlings observed over time did not follow a regular pattern. In more detail, according to the results of the study by Natan and Ne'eman [97], there are three main reasons that can explain these inconsistencies: (i) the precipitation amount in the previous months plays an important influence on *Pinus halepensis* Mill. regeneration; (ii) the annual seed production is also influenced by the climate conditions of the previous years; (iii) the quantity and timing of seed release from the cones are determined by climatic factors other than precipitation (for instance, high temperatures can favor the opening of the cones) [98,99]. In addition, short-term increases in the number of plant species in the burned pine forests of the Mediterranean Basin are very common [100,101], and this increase results from fire adaptations observed in many plants [102]. Therefore, the density of emerging seedlings is more clearly related to long-term site conditions and the resulting stand characteristics than to inter-year fluctuations in the precipitation levels [103].

4.2. Effects of Salvage Logging on Natural Regeneration of Pinus halepensis Mill

In semi-arid areas, the interaction between soil treatments and climate characteristics could include non-additive effects between natural disturbances and logging, which could lead to the recovery threshold being exceeded [104]. In Mediterranean countries, salvage logging after forest disturbances, such as the fire, is a controversial but commonplace practice that is still quite under-researched. This is due to the fact that most studies on salvage logging lack the necessary design to test interactions between natural disturbances and logging, although many studies mention interactions as a likely explanation for their results [57,104]. In our study salvage logging played a slightly detrimental effect on seedlings. This effect is shown by two factors compared to the non-treated plots: (i) the increased number of the seedling (+19%) in logged areas with mulching, against a +27% in sites without logging; (ii) the reduction (by 15%) in logged areas without mulching. Salvage logging reduces the natural recovery of vegetation and alters the composition and structure of the post-fire plant community. This negative effect increases the vulnerability of the system and prolongs the time needed to restore pre-fire functions and ecosystem services [105]. As Moya et al. [67] showed, early removal of deadwood in the first winter after the fire reduces the vigor and growth of pine seedlings, presumably because this practice increases the water stress and reduces the nutrient supply. Furthermore, the damage of forest soil due to logging can reduce seedling density when logging is postponed to early natural regeneration [106]. The negative effect of logging on the number of seedlings found in our study disappeared over time, and the mulched and logged areas showed the highest increase in seedlings (+74% after four years). However, in the mulched and non-logged areas the diameter (+12%) and height (+25%) of seedlings increased compared to the non-treated plots. In the non-mulched and logged sites we found a higher number of plants (+29%), but the diameter and height were lower both in mulched and logged plots (−34% for diameter and −15% for height) and non-mulched and logged sites (−18% and −9%, respectively). One factor that probably minimized the negative impact of logging is the permanence of mulch residues on the ground. This presumably protects the disturbed soils from rainfall and runoff, as observed by Spanos et al. [63], which used chopped woody instead of straw. This protecting effect may be due to the organic matter added to the soil with the mulch material and logging residues. Furthermore, the effects of salvage logging on soil properties were generally small, with slight decreases in OM and TN between logged and non-logged plots in mulched sites, and, in contrast, small increases in the same compounds in non-mulched areas. These low differences are in agreement with Lucas-Borja et al. [88], who found non-significant differences in TN content in burned plots (logged or non-logged) of pine forests in Central-Eastern Spain, with a soil pH that was slightly affected post-fire logging.

It is interesting to notice a significant correlation ($r^2 = 0.60$, $p < 0.05$) between OM content of soils and the number of seedlings growing on soils under different treatments. This confirms that the OM is one of the most important soil quality indicators, considering its influence on plant growth and other soil processes, such as water retention, nutrient exchange, and soil structure [107,108].

Overall, despite the variations in the number, diameter, and height of seedlings in logged areas recorded in this study, the effects of post-fire salvage logging were not significant compared to the untreated plots. These results are in close agreement with Lucas-Borja et al. [53], who reported that logging operations had no detrimental influence on pine seedling recruitment.

5. Conclusions

This study has explored the effects of salvage logging after straw mulching on the regeneration of *Pinus halepensis* Mill. throughout four years after a wildfire. Compared to the burned but non-treated areas, after four years from fire and post-fire treatments, the following results were achieved:

- Mulched and non-logged sites showed a significantly higher number of seedlings with a larger diameter and greater height;
- Logging did not significantly reduce this number, but, in mulched and logged sites, the seedlings showed significantly lower diameters and heights:
- An increase in the seedling number and decreases in the plant diameter and height were observed in the non-mulched and logged areas;
- No significant differences in the other morphometric parameters of seedlings were detected among all post-fire treatments;
- A clear gradient between the organic matter content of soils and the number of plants growing under the four treatments was evident.

These results help to confirm our first working hypothesis that the application of straw mulch without salvage logging after a wildfire increases the number and growth of *Pinus halepensis* Mill. seedlings in the mid-term in the burnt area. About the second working hypothesis that salvage logging may result in detrimental effects on the natural regeneration of *Pinus halepensis* Mill., caution should be paid when this post-fire treatment must be applied, which can result in higher recruitment but lower growth of seedlings.

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