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Severity, Logging and Microsite Influence Post-Fire Regeneration of Maritime Pine

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Abstract: We investigated the influence of fire severity, logging of burnt wood, local ecological factors and their interaction on the natural regeneration, survival and growth of maritime pine (*Pinus pinaster* Ait.), following a fire that took place in 2005. During the period 2006–2020, a sample of 1900 seedlings were monitored, in which three post-fire treatments were applied: (1) Early logging (before seedling emergence); (2) Delayed logging (after emergence); and (3) No management. Multivariate semi-parametric and non-parametric techniques were used to model seedling survival, estimated density and growth of natural pine regeneration. Seedling survival was 31% with a mean density of more than 2000 seedlings/ha at the end of the study period. Logging before seedling emergence was positively related with pine survival and density. Delayed logging resulted in the lowest seedling density and regeneration. Fire severity had a negative influence on regeneration density. The findings indicate that site conditions and fire severity have a stronger influence on natural regeneration of maritime pine than subsequent post-fire management treatments. In order to ensure the presence of maritime pine in pure or mixed stands, silvicultural work is required to control competition from other species and reduce the risk of new wildfires.

Keywords: competition index; fire severity; local ecological factors; maritime pine; pine–shrub interactions; post-fire management; post-fire regeneration; salvage logging

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1. Introduction

Post-fire regeneration is one of the biggest environmental challenges in the Mediterranean Basin. Ecosystem conservation requires enhancing forest resilience, reducing vulnerability and promoting the regeneration of burned areas. At the global level, the United Nations is focusing on forest restoration for ecosystem conservation in the period 2021–2023 (https://www.decadeonrestoration.org, accessed on 13 April 2023). Although wildfires occur naturally in many forest environments around the world [1], fire burns about 5% of land in the world per year [2], and loss of forest cover due to forest fires has increased across the globe in the past decade [3]. In the Mediterranean Basin, wildfires are considered a major agent in landscape dynamics [4]. However, fire recurrence and intensity are influenced by climate change [5] and anthropogenic actions [6]. Proof of this is the abandonment of rural areas since the second half of the 20th century, which has led to an increase in available biomass and forest continuity [7,8]. The increase in forest cover and in the number of extreme drought events [9] represent two of the main drivers of the increased occurrence of large fires [10].

The recovery of vegetation communities after forest fires is affected by alterations to the soil, which in turn are strongly influenced by fire severity and climatic suitability, mainly the rainfall regime in the first and second year after the fire [11]. In addition, the post-fire recovery will vary according to the type of plant community, biotic factors, the fire prevention strategies used and/or the intensity of anthropogenic pressure [12]. In non-resprouting plants, post-fire recovery of root systems is much slower than in resprouter communities, and recovery will be particularly slow in cases of high fire severity with significant erosion [12].

Fire severity is one of the most influential factors in the post-fire regeneration process [13,14]. High levels of fire severity strongly affect the biological and physical–chemical degradation of the forest floor [1,15–17], soil permeability [18], level of erodibility [19,20] and the partial or total ignition of the soil surface layer. The consequent variation in microclimatic conditions affects the regeneration potential of different species [21] and influences the variability in post-fire vegetation recovery dynamics; however, it is difficult to generalize the results of the different studies and translate them into recommendations for managing forest or shrub communities [22]. In stressed dryland environments with low regeneration survival [23], the regeneration strategies of different species, annual climatic variations and stochastic processes (e.g., microsite niche conditions [24] and seed banks [25]) can be important in relation to seedling recruitment [26,27].

Post-fire restoration treatments are applied worldwide to mitigate or reverse the negative impacts of fire, facilitating the regeneration of vegetation [28–30] and restoring ecosystem functioning, including the use of prescribed fire in the post-fire medium term [31] to reduce fuel in the event of a potential fire recurrence. Forest restoration in the Mediterranean Basin includes actions aimed at protecting the soil, as well as management of burned trees and the use of active or passive techniques [32]. In Spain, restoration actions in burnt areas have traditionally been led by active silvicultural management [33,34]. In areas where standing dead wood has a high market value, the trees are usually removed quickly, which can generate erosion-related problems in the autumn after the fire, especially in areas with high rainfall [20]. With the aim of slowing run-off and reducing erosion after felling of burned trees, one of the most common post-fire management practices in Spain makes use of the non-commercial remains of dead timber (trunks and branches), which are placed parallel to the contour and fixed to the ground with wooden stakes [35]. For example, Lucas-Borja et al. [36] found that erosion barriers constructed with logging debris had positive effects on the regeneration of Spanish black pine (*Pinus nigra* Arn. ssp. *salzmannii*). Erosion barriers are usually accompanied by monitoring natural regeneration and by active support, where appropriate, through replanting or shrub clearing and thinning to reduce competition, favouring species of interest, whether ecological or commercial, while reducing the vulnerability of the area to new forest fires [37].

Evidence of climate change (global warming, altered precipitation regimes and increased recurrence and intensity of natural disturbances) has led some authors to rethink alternative post-fire restoration strategies such as using dead wood to help protect natural regeneration. Thus, Thorn et al. [38,39] found that salvage logging had negative effects on the richness of some taxonomic groups such as saproxylic beetles, wood-inhabiting fungi and birds, and they recommended leaving some dead wood on site to reduce the impact of salvage logging on biodiversity. Leverkus et al. [40] recommended extracting wood from stands judged to be most susceptible to future wildfires while retaining dead wood in more ecologically sensitive sites. Following the same line, Juan-Ovejero et al. [41] reported that dead wood can act as a reservoir of carbon and nutrients in the long term and thus protect the soil, since they found that carbon and nutrient concentrations were higher in sites where the wood was scattered on the ground during a decade of post-fire and salvage logging. In addition, Castro et al. [42] considered that the permanence of burned wood does not increase the risk of fire, since the part that could act as the source of ignition decomposes in a relatively short period. By contrast, in other study systems, Peterson et al. [43] and Stevens-Rumann et al. [44] have found that coarse woody debris can remain for decades post-fire without decomposing, which would contribute to the severity of fires in high wildfire frequency scenarios and thus hinder subsequent stand regeneration.

Research findings, particularly in the context of global change, confirm that restoration actions should be more flexible [45,46] and that site characteristics (physical, biological, social, economic, etc.), as well as the level of fire severity, should be taken into account [1]. Findings also indicate that active and passive management strategies should be adopted to promote biodiversity [47] and that active management strategies [33,34] should be used to control competition and reduce the vulnerability of the area to wildfires [37]. Fire should also be considered an ecosystem process [48] within a scenario of fire recurrence. It has been observed that 15 years post-fire, a proportion of snags and woody debris is not decomposed, thus affecting the available fuel load [43,44]. Maritime pine (*Pinus pinaster* Ait.) is widely distributed across the western Mediterranean Basin, and fire is a key factor in the regeneration of natural stands [49]. This species can only regenerate from the seed [50,51], and it displays high phenotypic plasticity [52]. Maritime pine has evolutionary adaptations that help it to perpetuate in fire-prone environments [49], but studies in provenance regions in Spain indicate reduced or no serotiny in many provenances in central Spain [25,52]. Together with a scarce aerial bank [53], the low serotiny could become a limiting factor for post-fire regeneration [54] and affect the survival of pine forests in these areas, in favour of other resprouting taxa such as *Quercus pyrenaica* Willd. [46,55]. Several studies have considered the regeneration and survival of maritime pine and the influence of post-fire treatments on these parameters in the short and medium term [13,42,56–58]. Nevertheless, medium- and long-term monitoring studies involving this species are scarce. Long-term monitoring of post-fire regeneration of maritime pine should also be conducted in order to further scientific knowledge, to reduce vulnerability of the sites and to enhance the capacity of the species to adapt to future impacts of climate change [48,59].

The research hypotheses of the present study are as follows: (1) logging of wood before the emergence of seedlings favours post-fire regeneration of maritime pine; (2) fire severity and its interaction with post-fire management techniques influence the regeneration of maritime pine; (3) erosion barriers constructed with logging standing dead trees positively affect regeneration of maritime state; (4) local ecological factors (slope and stoniness) could positively influence the success of maritime pine regeneration. Therefore, our aims in this study were to evaluate the influence of fire severity, logging of burnt wood with erosion barriers constructed with logging debris (relative to no intervention post fire), interaction effects and effects of local ecological conditions (site conditions for density and growth analysis at stand-level and microsite for individual-level survival analysis) on the post-fire regeneration, survival and development (height, diameter) of maritime pine seedlings. For these purposes, we monitored the regeneration of maritime pine in El Rodenal de Guadalajara over a period of 15 years (2006–2020) since the occurrence of a fire in the site in 2005.

2. Materials and Methods

2.1. Study Area

In July 2005, a forest fire occurred in the northeast of the province of Guadalajara (Central-Eastern Spain, located between coordinates 40.77° and 41.10° N latitude and −1.87° and −2.66° W longitude). The large fire affected an area of 12,874 ha. The substrate is characterized by Buntsandstein red sandstones, secondary limestones and siliceous sediments. The elevational range varies between 1200 m.a.s.l. and 1370 m.a.s.l., with steep, stony relief and open, gently sloping areas. The mean annual temperature in the area is 10.5 °C and the mean annual precipitation, 468 mm (https://sig.mapama.gob.es/siga/ accessed on 1 April 2023). Before the fire, the area was dominated by mature stands of maritime pine aged 80–90 years old and young stands of age 30–40 years [60]. Other tree species dominated some areas inside the fire perimeter, including oaks spp. (*Quercus pyrenaica* Willd., *Q. faginea* Lam. and *Q. ilex* subsp. *ballota* (Desf.) Samp.) and *Juniper* spp. (*Juniperus thurifera* L. and *J. oxycedrus* L.). The shrub layer predominantly consists of rock rose species (particularly *Cistus laurifolius* L., *C. populifolius* L. and *C. ladanifer* L.). Pinewood of the natural provenance Rodenales de Molina [61] was managed until the beginning of the 1980s, when resin production was abandoned. Since then, a low level of management has been implemented.

2.2. Experimental Design and Field Sampling

In the burned area, we selected nine sites along a transect following the direction of the fire (northwest–southeast), in order to achieve a representative and balanced design according to physiographic criteria and supporting characteristics (Figure 1). In the spring of 2006, the Junta de Comunidades de Castilla-La Mancha (Spain) installed paired plots (each 40 m × 40 m) for application of two contrasting post-fire management treatments in eight of the nine sites: (1) Early logging of wood before emergence of pine seedlings (autumn 2005), with logging of burnt wood and erosion barriers generated from logging debris (ELogg); (2) No post-fire management, in which during the first years, the dead wood was formed by snags until they began to fall, changing to coarse woody debris (BNa, Burn No action or control). In two of the nine sites, the forest service felled the remaining trees in autumn 2006 (after emergence of pine seedlings). This gave us the opportunity to include an additional treatment (3) Delayed logging of wood, consisting of logging burnt trees after emergence of pine seedlings (autumn 2006) with logging of burnt wood and erosion barriers constructed with the logging debris (DLogg). This treatment was not planned in the original experimental design, and we considered it randomly applied in two of the nine sites. Due to the delayed logging in two of the plots that were initially meant to be an additional control, the forest service installed a new plot in one of these sites, so we kept the paired design of the control and early logging treatments in 8 of the 9 sites. Finally, the study included eight control plots, nine early logging plots and two delayed logging plots. We therefore generated a new post hoc unbalanced design with the 3 treatments and 19 plots (Table 1).

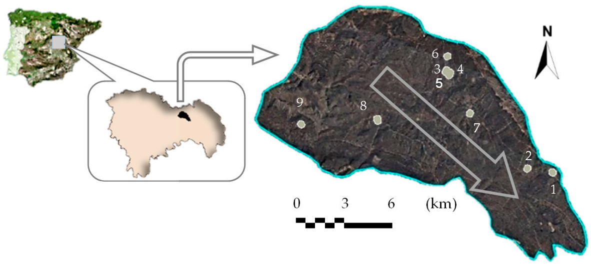


Figure 1. Geographical location in the northeast of the province of Guadalajara (Central-Eastern Spain) of the study area. The fire affected an area of 12,874 ha. The map on the right shows the fire perimeter. The arrow indicates fire direction (northwest–southeast). The points show the location of the nine measurement sites.

We identified two levels of fire severity according to the degree of damage of crown [15,62], distinguishing plots affected by moderate fire severity with totally crown scorched (foliage is killed but not consumed during the fire, Scor) and plots affected by extreme fire severity with totally combusted crown (foliage, buds and fine branches are either consumed during flaming combustion or charred during the fire, Cons). The degree of fire severity was the same in plots in the same site.

Within each 40 m × 40 m plot, the regional forest service systematically distributed 25 subplots (1.5 m × 1.5 m) within each plot (see Supplementary Material, Figure S1), in which we assessed the success of regeneration (estimated density) and stand characteristics such as stoniness, determined as an average of the values assigned to each of the 25 subplots for each plot. In 2006, we randomly selected and labelled 100 pine seedlings within each plot, yielding an overall sample of 1900 seedlings. We also recorded the height and basal diameter of each of the maritime pine seedlings. In addition, when we detected interference from other species with pine seedlings, we proposed a proxy of the competition indices dependent on distance according to research by other authors [63–66]. And we assumed the existence of interference or competitive interaction when overlapping crowns and proximity between plants assured that there would at least be competition for light, we recorded the height of the vegetation and the type of plant: *Oak* spp., *Shrub* spp. (mainly *Cistaceae*), herbaceous or intraspecific interaction.

Table 1. Main characteristics of the nine sites of the paired plots.

Site	Z (m.a.s.l.)	H_o (m)	$Dens_o$ (Trees ha^{-1})	Exp. (°)	Slope (%)	Ston. (%)	Depth (cm)	Sev.	Initial Emergence (Seedlings ha^{-1})		
									ELogg	BNa	DLogg
1	1368	9.0	587	270	33	89	26	Cons	4978	3911	NA
2	1205	8.9	612	290	6	25	38	Scor	68,622	43,022	NA
3	1238	8.7	933	88	33	33	44	Cons	1422	1422	NA
4	1238	12.7	1146	225	15	19	32	Scor	3022	1067	NA
5	1243	16.0	363	163	6	4	71	Scor	32,533	NA	20,978
6	1267	16.4	219	248	11	5	51	Scor	12,089	3378	NA
7	1248	16.0	62	130	2	5	51	Scor	8711	8355	NA
8	1244	16.2	512	76	32	68	48	Cons	533	3733	3200
9	1227	12.7	575	198	17	42	50	Scor	3022	20,800	NA

Z = altitude (m.a.s.l.); H_o = dominant pre-fire stand height; $Dens_o$. = pre-fire stand density; Exp. = slope exposure; Ston. = estimated stoniness; Depth = soil depth; Sev. = estimated fire severity according to the type of fire with scorched crown (moderate severity, Scor) or consumed crown by fire (extreme severity, Cons); Initial emergence = Estimated mean density of regeneration in July 2006 for the treatments (ELogg = Early logging of wood; DLogg = Delayed logging of wood; BNa = Burn No action); NA = not applicable.

Although we did not ultimately include them in the analysis, we measured other site features of the site in each stand, including altitude (with a Global Positioning System, GPS), exposure (with a Suunto® compass, Vantaa, Finland) and the depth of the mineral soil (with a manual auger).

2.3. Data Analysis

We assessed the regenerative seedling growth by measuring the morphological variable total height of the seedling (m) and basal diameter of the seedling (cm). We measured the seedling height with a flexometer (accuracy, 0.5 cm) or, for seedlings taller than 2 m, with a VERTEX IV® hypsometer (accuracy, 10 cm). We recorded the basal diameter with a gauge or, for basal diameters greater than 15 cm, with a caliper (both with an accuracy of 0.1 cm). Our sampling effort was greater during the first years after germination that are a critical period for seedling establishment or death. During the first three years (2006–2008), two annual measurements (spring–summer and autumn campaigns) were carried out. Subsequently, we made at least one annual measurement, in autumn, until 2014, and then, we made two further measurements in autumn in 2017 and 2020, i.e., at the end of the study period, when pine mortality was very low (Table S1). We carried out the survival analysis of maritime pine considering the initial sample of 1900 seedlings. The unbalanced post hoc design and the small number of plots indicated the need to use non-parametric statistical methods.

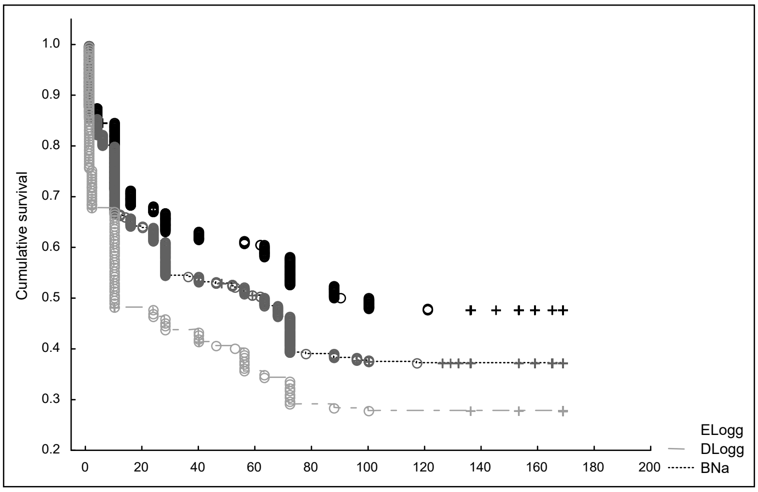
To describe seedling survival as a function of post-fire management treatment and fire severity and the interaction between them, we used non-parametric survival functions obtained using the Kaplan–Meier product-limit method [67], and we compared the functions using the Wilcoxon test and Chi-square test or Z test, by applying a 95% significance level ($p < 0.05$). Also, we adjusted each survival function to an exponential function ($S(t) = e^{\alpha t}$) in order to compare with the Kaplan–Meier product-limit method, where, $S(t)$ is the survival function, α the scale coefficient of the distribution exponential and t the time. In addition, we analysed survival data using a hazard index approach [68], relating maritime pine survival (dependent variable) to influencing factors (predictors) at different times throughout the study period (2007, 2009, 2011, 2014, 2017 and 2020). We used, for hypothesis testing, χ^2 and Wald test statistics (p-value < 0.05), and we fitted risk coefficients for each of the explanatory variables. These models included six explanatory variables to test their effects on survival. We included two continuous variables that represent local conditions (percentage of slope, measured with a hypsometer VERTEX® (Långsele, Sweden), and estimated stoniness per plot). Despite being nested within the burned wood logging treatments, we included in the analysis a dummy variable representing the presence or absence of woody debris generated during construction of erosion barriers from the burnt trees felled at the beginning of the study in 2006 (seedling emergence and growing inside or outside the woody debris). Determining whether or not the seedlings germinated close to log erosion barriers enables evaluation of the effect at microsite level of the dead wood on survival and could provide valuable information for post-fire management. Finally, we considered three variables related to effects or interference: intraspecific competition (dummy variable, yes/no nearest neighbour method); interspecific competition from oaks, shrubs or herbaceous plants (dummy variable, yes/no); and competition index (CI) (adimensional, calculated as the ratio between the height of the inter or intra-specific competitors and the height of the maritime pine seedling). We determined interference to have occurred when the seedling and competitor showed crown tangency, pine seedling growing under the competitor and/or the distance between the seedling and the stem competitor was not greater than 50 cm. From estimated density in the field in 2006 and the survival data for the period 2006–2020 (decrease proportional to the number of seedlings that had died since the last census period), we estimated the reduction in density of regenerated trees in the successive monitoring until 2020 (response variable).

We used the SIMPLS algorithm General Partial Least Squares Model [69] for partial least squares regression (Partial Least Squares PLS) to produce multiple linear models relating maritime pine regeneration density (dependent variable) to influencing factors at different times (2007, 2009, 2011, 2014, 2017 and 2020). PLS enables model fitting with strong correlation between predictors. These models included eight explanatory variables: post-fire management treatment applied to each plot (categorical: ELogg, DLogg and BNa), fire severity (categorical: Scor, Cons), percentage of slope, estimated stoniness, presence or absence of woody debris generated during construction of erosion barriers, intraspecific competition, interspecific competition and competition index (CI). Finally, we used the same explanatory variables for simultaneous fitting of multiple linear PLS models (SIMPLS algorithm) for dependent height and basal diameter variables, as a measure of the success of maritime pine regeneration. We used the cross-validation method to determine the optimal number of components in the PLS model using the Stone-Geiser Q^2 statistic. We evaluated the relative contribution of each independent variable in the model according to the value of the scaled coefficients, selecting those with the highest absolute value and biological meaning in each case. The R^2Y statistic is an indicator of the model fit (similar to Adjusted R^2 for general linear model), and R^2X provides information about the correlations between predictors. We conducted the statistical analyses using STATISTICA 10® and IBM SPSS Statistics 20®.

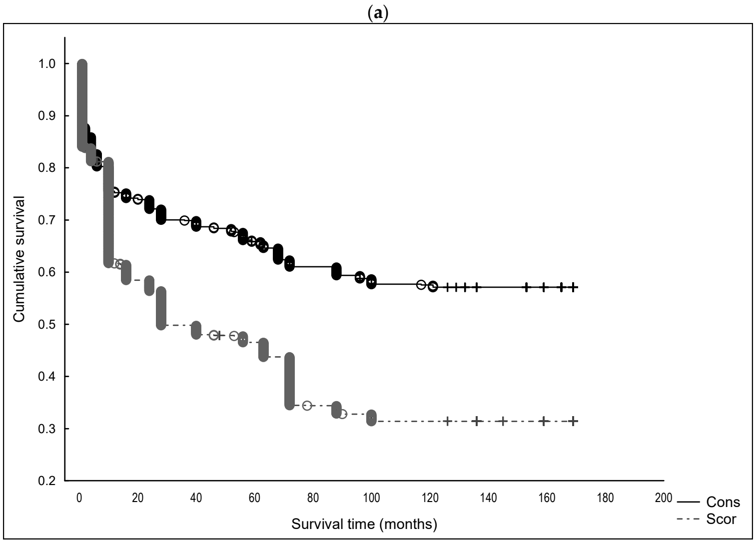
3. Results

3.1. Factors Influencing the Survival of Maritime Pine Seedlings: Stand and Microsite Scale

The initial regeneration success (May 2006) varied widely between plots (Table 1). In 2020, 31% of the initially labelled individuals survived. The minimum survival time (i.e., the lifetime of the seedlings until death months or minimum lifetime if the seedlings survive until the end of the study period) of the stands in the study period (Kaplan–Meier method) differed significantly between treatments ($\chi^2 = 46.28$, $p < 0.01$; Wilcoxon test, $p < 0.01$), with higher cumulative survival (2006–2020) and longer survival times in the early logging treatment than in the delayed logging treatment and in the burn no action treatment (Figure 2a). Although the regeneration success was higher in plots characterised by moderate burn severity (scorched), survival functions were different ($Z = 8.41$, $p < 0.01$; Wilcoxon test, $p < 0.01$), with higher survival in plots characterised by extreme burn severity (consumed) (Figure 2b).



(**a**)



(**b**)

Figure 2. Graphical output for survival analysis using the Kaplan–Meier product-limit method (**a**) as a function of post-fire management treatment (ELogg, Early wood logging; DLogg, delayed wood logging; BNa, Burn no action) and (**b**) as a function of fire severity (Cons, consumed or extreme fire severity; Scor, scorched or moderate fire severity). Circles or ellipses indicate the survival decrease between measurements.

The combined analysis of the three treatments (Burn no action, early and delayed logging) and the two levels of fire severity (moderate and extreme) indicated differences (χ^2 = 131.71, $p < 0.01$; Wilcoxon test, $p < 0.01$) overall, as well as in the pairwise comparison of the groups, with $p < 0.05$ in all cases, except for delayed wood logging–extreme fire severity versus early wood logging–moderate fire severity (p = 0.23) and for delayed wood logging–extreme fire severity versus control treatment–moderate fire severity (p = 0.52) interactions. The early wood logging–extreme fire severity interaction showed the highest cumulative survival values at the end of the study period (Table 2 and Figure S2). The adjustment of the $S(t)$ functions to an exponential function presented high R^2 fit values, in general, and showed a trend very similar to the functions obtained by the Kaplan–Meier method (Figure 3). The value of α coefficient provided an estimate of the monthly mortality risk rate. In the case of both treatment and severity, as well as in its combined analysis, the value of α was less than 1%.

Table 2. Survival analysis (Kaplan–Meier product-limit method) for the interactions between post-fire management treatment and fire severity.

Paired Interaction (A versus B)				Z Test	*p*-Value
(Treatment × Severity) A		(Treatment × Severity) B			
Early logging	Consumed	Burn No action	Consumed	2.46	0.01
Early logging	Consumed	Delayed logging	Consumed	4.21	0.00
Early logging	Scorched	Early logging	Consumed	6.21	0.00
Burn No action	Scorched	Early logging	Consumed	8.92	0.00
Delayed logging	Scorched	Early logging	Consumed	8.34	0.00
Delayed logging	Consumed	Burn No action	Consumed	2.98	0.00
Early logging	Scorched	Burn No action	Consumed	3.25	0.00
Burn No action	Consumed	Burn No action	Scorched	6.18	0.00
Burn No action	Consumed	Delayed logging	Scorched	6.98	0.00
Early logging	Scorched	Delayed logging	Consumed	−1.2	0.23
Burn No action	Scorched	Delayed logging	Consumed	0.65	0.52
Delayed logging	Scorched	Delayed logging	Consumed	2.94	0.00
Early logging	Scorched	Burn No action	Scorched	3.79	0.00
Delayed logging	Scorched	Early logging	Scorched	6.07	0.00
Burn No action	Scorched	Delayed logging	Scorched	4.3	0.00

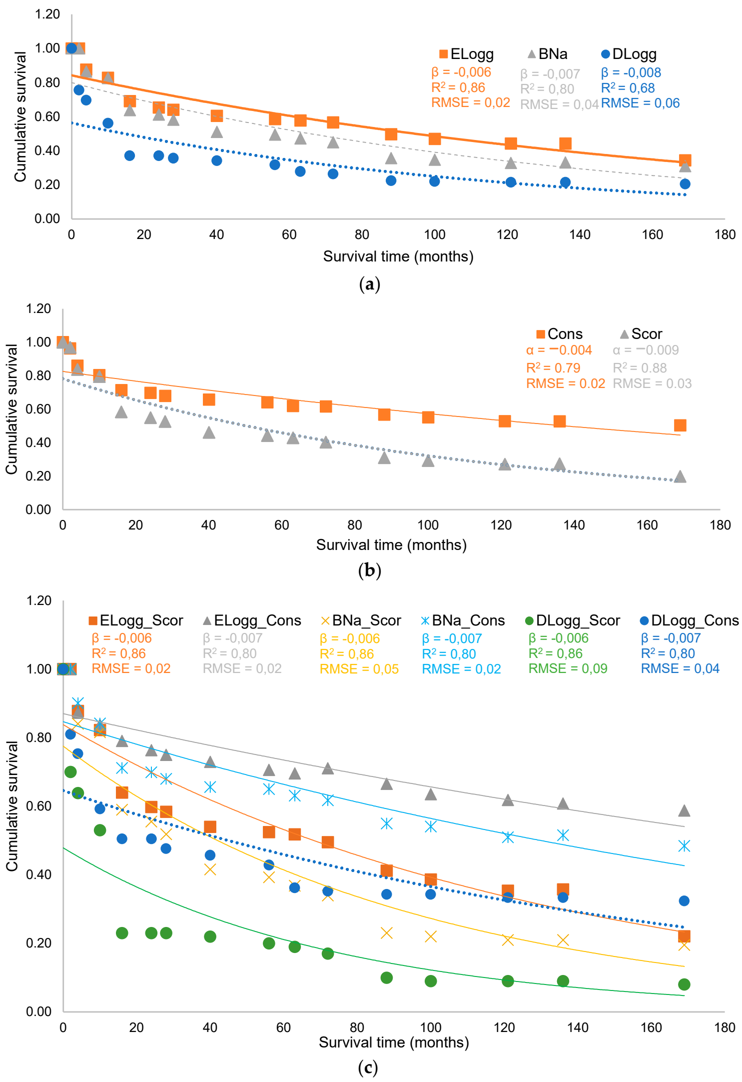


Figure 3. Survival functions adjusted to an exponential function ($S(t) = e^{\alpha t}$) throughout the study period for (**a**) different treatments (ELogg, Early wood logging; DLogg, delayed wood logging; BNa, Burn no action);

(**b**) as a function of fire severity (Cons, consumed or extreme fire severity; Scorc, scorched or moderate fire severity); and (**c**) the combination of both. The value of the coefficient α indicates the risk rate of monthly mortality. R^2 shows the fit, and RMSE indicates the root mean square error.

In survival analysis using proportional hazard models, we performed a step-by-step regression and obtained the best combination of variables and best fits (χ^2 = 114.44, p = 0.000, Figure S3). The explanatory variables selected were slope percentage, stoniness, interspecific competition (in 2009), intraspecific competition (in 2011), competition index (in 2011) and presence of woody debris (Table 3). Stoniness was statistically significant, and the hazard coefficient was very low (p = 0.000, hazard coefficient Exp (B) = 0.050). Intraspecific competition in 2011 (p = 0.028, Exp (B) = 0.642) was positively related to maritime pine survival. By contrast, the presence of interspecific competition in 2009 (p = 0.049, Exp (B) = 1.603) was related to a higher risk of cumulative mortality during maritime pine regeneration. The slope (p = 0.342) and the competition index in 2011 (p = 0.351) were not significant in the combined predictive model. The presence/absence of woody debris was not a significant factor (p = 0.496).

Table 3. Output for each of the explanatory variables of the survival model using hazard analysis.

Variable	[4] B	[5] SE	[6] Wald	[7] Sig.	[8] Exp (B)	95.0% Confidence Interval for Exp (B)	
						Lower	Upper
Woody debris	−0.244	0.358	0.464	0.496	0.784	0.389	1.580
[1] Inter_comp_09	0.472	0.239	3.883	0.049	1.603	1.003	2.563
[2] Intra_comp_11	−0.444	0.202	4.836	0.028	0.642	0.432	0.953
[3] CI_11	0.040	0.043	0.871	0.351	1.041	0.957	1.132
Slope (%)	−0.010	0.010	0.903	0.342	0.990	0.971	1.010
Stoniness	−2.987	0.509	34.446	0.000	0.050	0.019	0.137

[1] Inter_comp_09 = interspecific competition in 2009 (adimensional); [2] Intra_comp_11 = intraspecific competition in 2011 (adimensional); [3] CI_11 = competition index in 2011, ratio between the height of the competitors and the height of the maritime pine (adimensional); [4] B = individual coefficient; [5] SE = standard error; [6] Wald = Wald test; [7] Sig. = significance, p-value; [8] Exp (B) = hazard coefficient.

The overall mean density at the end of the period (2020), estimated from the survival values and the initial density (2006), was 2913 seedling ha^{-1} (Figure S4).

The mean height of the regenerated pine trees, fifteen years after the fire, was 1.11 ± 0.64 m (average ± standard error). In 2020, the overall mean basal diameter was 3.3 ± 2.5 cm. Interference effects occurred in 93% of the maritime pine trees (2020). Interspecific competition was observed in 83% of the trees in 2020. Nevertheless, intraspecific competition was lower than competition with other species, reaching 33% in 2020 (Table 4). The ratio between the height of competitors and regenerated pine increased during the period 2007–2009, with a maximum index of more than three times the height in 2009, after which it has gradually decreased, reaching a value of 1.4 m in 2020 (Table 4).

Table 4. Mean values of height and diameter of maritime pine, and relative to competitive interactions.

Year	[1] h (m)	[2] bd (cm)	[3] Gral_comp	[4] h_comp (m)	[5] Inter_comp	[6] Intra_comp	[7] CI
2007	0.14 (±0.08)	0.4 (±0.6)	0.58 (±0.49)	0.21 (±0.24)	0.56 (±0.49)	0.03 (±0.18)	1.19 (±2.10)
2009	0.27 (±0.16)	0.7 (±0.9)	0.73 (±0.44)	0.72 (±0.47)	0.68 (±0.46)	0.08 (±0.26)	3.25 (±2.89)
2011	0.39 (±0.22)	0.9 (±0.6)	0.77 (±0.42)	0.77 (±0.47)	0.71 (±0.45)	0.20 (±0.40)	2.30 (±1.70)
2014	0.54 (±0.33)	1.5 (±1.1)	0.81 (±0.39)	0.99 (±0.52)	0.73 (±0.44)	0.23 (±0.42)	2.23 (±1.71)
2017	0.82 (±0.52)	2.2 (±1.8)	0.88 (±0.32)	1.13 (±0.59)	0.74 (±0.43)	0.29 (±0.45)	1.65 (±1.13)
2020	1.11 (±0.64)	3.3 (±2.5)	0.93 (±0.25)	1.26 (±0.58)	0.83 (±0.37)	0.33 (±0.46)	1.40 (±1.04)

[1] h = height (metres); [2] bd = basal diameter (centimetres); [3] Gral_comp. = general apparent competence, inter-, apparent intraspecific competitive effect, or both, detected (adimensional); [4] h_comp. = height of apparent competition (meters);

[5] Inter_comp. = apparent interspecific competition (adimensional); [6] Intra_comp. = apparent intraspecific competition (adimensional); [7] CI = apparent competition index, ratio between the height of the competitors and the height of the maritime pine (adimensional). The standard deviation is indicated in brackets.

3.2. Factors Influencing the Regeneration Process: Stand Scale

The PLS models constructed to estimate the density (dependent variable) with the SIMPLS algorithm showed a stable fit throughout the study period (0.57–0.74) and autocorrelation of predictors close to 0.5 (Table 4). The variables that yielded the highest scaled coefficients (highest relative importance explaining the response variable density) were intraspecific (+) and interspecific competition (−) (Figure 4). On the one hand, the negative influence of interspecific competition on density tended to increase its importance with higher scaled coefficients over time. On the other hand, areas with a higher density of maritime pine seedlings were related to a higher level of intraspecific competition. The competition index was inversely related to seedling density after 2007. Finally, higher percentages of slope, stoniness (except for 2020) and presence of woody debris were negatively related to pine density.

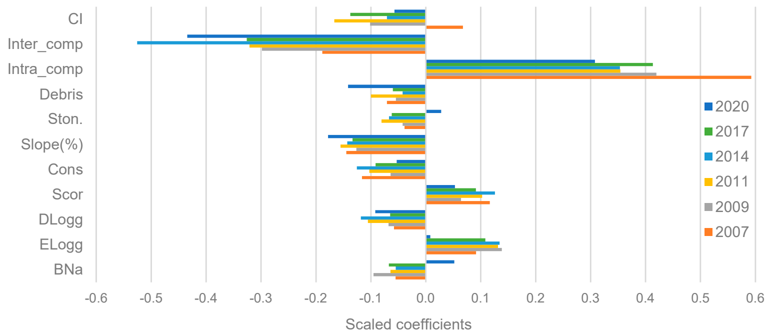


Figure 4. Scaled coefficients in PLS SIMPLS analysis of dependent variable 'density' for different years of measurement (CI = competition index; Inter_comp = interspecific competition; Intra_comp = intraspecific competition; Ston. = stoniness; Cons = consumed or extreme fire severity; Scor = scorched or moderate fire severity; DLogg = delayed wood logging; ELogg = early wood logging; BNa = burn no action).

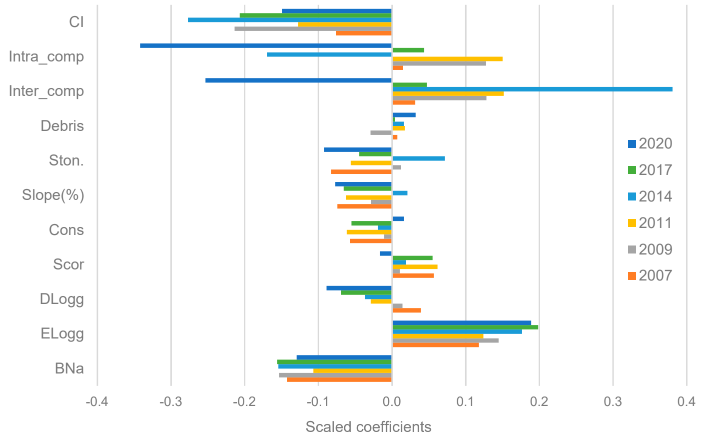
The results showed a positive effect of early logging of wood and moderate fire severity on pine seedling density. By contrast, for greater fire severity, lower seedling densities were associated with delayed logging of wood and no-management sites.

In the simultaneous fitting of PLS models to estimate height and diameter of pine seedlings, the models yielded an R^2Y of between 0.2 and 0.43 (Table 4). The scaled coefficients (Figure 5a,b) showed that during the two years after seedling emergence, the control (no-management) treatment had a negative influence on seedling vigour (lower height and diameter). Between 2009 and 2017, lower interaction indices indicated more vigorous growth of pine seedlings (higher height and diameter, Table 5).

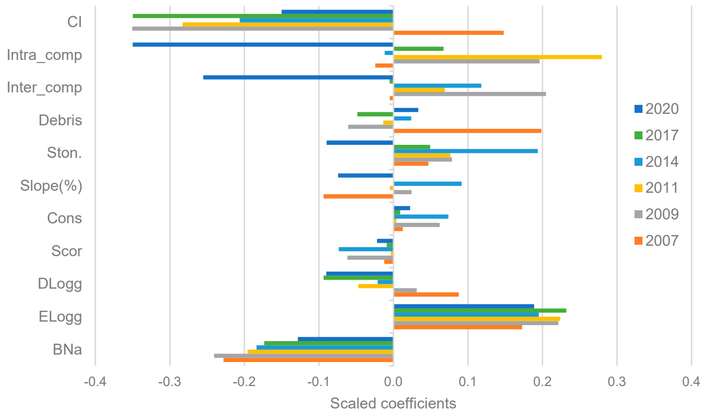
In general, the presence of competitors was positively related to the height and diameter of the maritime pine seedlings, although at the end of the study period, this trend changed, and both types of interaction (intra and interspecific) were negatively related to the height and diameter.

The absence of post-fire management was negatively related to pine height and diameter, while the removal of burnt trees was positively related to these variables. In the joint analysis of seedling height and diameter, the values of the scaling coefficients were very low for the other variables. For greater fire severity, poorer development in seedling height was observed, except at the end of the study period.

Similarly, steeper slopes also affected tree growth (lower height and diameter of seedlings in steeply sloping areas). Finally, the presence of woody remains on the surface of the soil was associated with a larger diameter of the seedlings.



(**a**)



(**b**)

Figure 5. Scaled coefficient variables in PLS analysis (**a**) of dependent variable 'height' and (**b**) of dependent variable 'basal diameter' for different years of measurement (CI = competition index; Inter_comp = interspecific competition; Intra_comp = intraspecific competition; Ston. = stoniness; Cons = consumed or extreme fire severity; Scor = scorched or moderate fire severity; DLogg = delayed wood logging; ELogg = early wood logging; BNa = burn no action).

Table 5. PLS models used to estimate the dependent variables with the SIMPLS algorithm.

Year	Dependent Variable	R^2Y cum.	R^2X cum.	RMSE	Highest Absolute Value Scaled Coefficient	
					Value	**Variable**
2007	[1] Dens	0.74	0.52	1.83	0.59	[4] Intra_comp
	[2] h	0.2	0.46	0.06	−0.14	Burn No action
	[3] Ø			0.12	−0.23	Burn No action
2009	Dens	0.6	0.49	1.28	0.42	Intra_comp
	h	0.36	0.5	0.09	−0.21	[5] CI
	Ø			0.06	−0.35	CI
2011	Dens	0.57	0.52	1.05	0.35	Intra_comp
	h	0.38	0.54	0.09	0.15	[6] Inter_comp
	Ø			0.07	−0.28	CI
2014	Dens	0.69	0.47	0.95	−0.53	Inter_comp
	h	0.43	0.48	0.04	−0.28	CI
	Ø			0.04	0.21	CI

Table 5. *Cont.*

Year	Dependent Variable	R^2Y cum.	R^2X cum.	RMSE	Highest Absolute Value Scaled Coefficient	
					Value	Variable
2017	Dens	0.68	0.49	1.54	0.41	Intra_comp
	h	0.36	0.49	0.07	−0.21	CI
	Ø			0.07	−0.35	CI
2020	Dens	0.58	0.45	0.97	−0.43	Inter_comp
	h	0.43	0.48	0.14	−0.34	Intra_comp
	Ø			0.22	−0.35	Intra_comp

[1] Dens = density (seedlings ha^{-1}); [2] h = height (m); [3] Ø = basal diameter (cm); [4] Intra_comp. = intraspecific competition; [5] CI = competition index (ratio between the height of the competitors and the height of the maritime pine); [6] Inter_comp. = interspecific competition.

4. Discussion

4.1. Factors Influencing the Survival of Maritime Pine Seedlings

Extraction of wood after the emergence of pine seedlings (autumn 2006) increased their mortality which is consistent with the results reported by other authors for the same species [13]. Notwithstanding, the results obtained for maritime pine in southern Spain [42] revealed lower survival in unmanaged plots than in the stands where two types of felling treatments were performed after the emergence of pine seedlings (felling and piling the logs and mastication of the woody debris; felling 90% of the trees and leaving the resulting biomass spread over the ground). In the present study, the differences in survival were maintained until the end of the study period (47.5% for early wood logging vs. 27.7% for delayed wood logging). Stand management may therefore be a decisive factor for survival in certain areas of the perimeter affected by the fire, because recruitment of maritime pine mainly occurs in the spring after the fire [70], up until the second autumn after fire as detected Martínez-Sánchez et al. [71] for Aleppo pine (*Pinus halepensis* Mill.). In situations with a high initial density, removal of wood after seedling emergence could reduce the need for future silvicultural work due to the reduction in the seedling density [13,24,72]. However, in areas where seedling density is not sufficiently high, this type of treatment could affect survival of the pine stand. In the plots where removal of the burnt wood was delayed, the initial density was higher than 2000 seedling ha^{-1} (year 2006) but was sufficient in both types of plots (more than 1000 seedling ha^{-1} in 2020) to guarantee regeneration of maritime pine. Thus, logging burnt wood after seedling emergence would only be advisable in sites where seedling density reaches at least 2000 seedling ha^{-1} to ensure viable regeneration [73].

Comparison of survival models (Kaplan–Meier method) showed that fire severity was an important factor regarding survival of pines in the short and medium term, as reported by Vega et al. [13] and Cansler et al. [74]. Soil organic matter depth in stands affected by high severity fire, with the crown totally consumed by fire (extreme severity), was reduced or null, as observed in other studies [1,15]. Survival of seedlings was significantly more likely than in stands affected by moderate fire severity, due to lower interference from other species. Indeed, in areas affected by moderate fire severity or scorched crown, soil degradation was lower [1,15,16] and resulted in a germination bed that favoured the recruitment of other taxa in addition to maritime pine [1,46]. Although the initial pine density was lower in areas affected by more severe fires, survival of the seedlings that managed to germinate and become established was higher. This indicates that the regeneration of other taxa was also hampered in these areas, and therefore, there was less competitive pressure for space and resources.

Similar to the results observed by other authors [15,24,75–77], the hazard analysis indicates that microsite conditions are relevant to the survival of seedlings in the study area. Increased seedling survival has been associated with germination of seedlings on stony beds, as well as the location of seedlings on steeper slopes, indicating that pine growth is favoured by microenvironments with low overall vegetation density, i.e., by low initial plant interference, where growth of other taxa may also be unlikely. In addition, interspecific competition was associated with higher risk, coinciding with the findings of other authors [78], while lower mortality was observed in seedlings affected by intraspecific competition.

4.2. Factors Influencing the Regeneration Process: Stand Scale

Although the initial density of regenerating pines was higher in plots affected by moderate fire severity, survival was higher in plots characterised by extreme fire severity, as competitive effects were favoured in the short to medium term, as previously observed [14,79]. This also applied to the unmanaged plots, which together with the plots affected by moderate fire severity, included the highest proportions of competitors in 2007, although these tended to stabilize over time along with those in the other plots (early and delayed wood logging and extreme fire severity). Thus, we observed factors that favour initial seedling density but that may be detrimental to the medium-term survival of seedlings, in contrast to previous findings regarding regeneration after silvicultural treatment [45].

The results of the present study indicate that tree height is strongly affected by competitive factors, according to the results observed by other authors [14,78,79]. Successfully established trees will thus have more resources available because of the low density of individuals of other species present. In this regard, we observed that interspecific interference remained high and negatively influenced seedling density throughout the monitoring period, in line with previous findings [75]. Although intraspecific interference affected a smaller number of pine seedlings than interspecific interference in the present study, it has been shown to be a variable of great interest in explaining the evolution of the estimated density of regenerated seedlings. As expected, this variable had a positive influence on the average density of surviving regenerated seedlings per plot. In the medium term, the seedlings that grow higher than shrubs began to display problems related to intraspecific competition involving interactions with their neighbours through overlapping crowns. Thus, biomass accumulates in the fire area [7,8] and would favour the spread of fire and lead to any subsequent fires being more severe.

Overall, the presence of woody debris generated by felling burnt trees had a low explanatory power regarding the height and mean diameter of maritime pine but had a slightly positive effect on the mean diameter at the early stages of regeneration. This may suggest a protective effect that improves the microclimatic conditions for the establishment of saplings, as reported by other authors [13,39,42]. Although the presence of decomposing debris may exert a protective effect at the initial stages of development of maritime pine regeneration [39], it could also be a risk factor in a reburn scenario [80].

Stoniness and slope are important predictor variables for determining the initial density of pine regeneration [24,56,73,75,76], but they are relatively less important than facilitation and/or competition interactions in the short to medium term. However, stoniness remained an important factor throughout the study period when survival was analysed at plant level (hazard models), indicating that variables that favour germination success do not necessarily have to be the same as those determining seedling survival in the short and medium term.

5. Conclusions

The variability in seedling survival between plots was more dependent on site conditions and fire severity than on the post-fire management treatment (logging of burnt wood). However, the low survival associated with the treatment consisting of logging burnt wood after seedling emergence suggests that this treatment should be avoided in maritime pine stands with low post-fire regeneration success. Extraction of wood before seedling emergence has a neutral effect in terms of survival and growth of the pine forest and is therefore not a determining factor in decision-making regarding natural regeneration of the pine forest. However, early logging or no wood removal is recommended in areas affected by high fire severity and with low availability of an aerial seed bank, where low initial regeneration is expected. Severe fire reduces the initial regeneration (density) of pine but favours survival, largely because of reduced interference from other species. Therefore, pine forests with sufficiently large aerial seed banks are more likely to develop into pure pine forests in areas of high fire severity.

Ecological variables such as stoniness and slope, which are easy to measure and assess before and immediately after fire, and variables indicating the possible height dominance of the competing vegetation have a significant predictive value in the medium-term survival of maritime pine. Height and diameter are positively influenced by facilitation effect at early stages of seedling growth, but interaction then begins to have a negative effect on pine height and diameter a decade after the fire. Inter- and intraspecific interference were found to be the important factors determining survival and regeneration.

The state of pine regeneration 15 years after the El Rodenal does not ensure the persistence of monospecific pine forests in some of the areas affected by the fire, which will support other formations such as hardwood species (*Quercus* sp.) and shrubs (*Cistus* sp.) or mixed areas with pine forest. Based on the need for a particular forest type to be preserved or promoted (monospecific pine forest, hardwood forest, mixed forests) or not preserved, according to management criteria, one of the two types of restoration can be recommended. Passive restoration (without post-fire treatment) could be effective in some areas where the restoration does not need to be directed towards a certain type of forest and where there is a low risk of recurrence and predicted severity of a new fire (either because of the characteristics of the site itself or by a foreseeable evolution of live and dead fuel towards not high loads). However, active restoration (silvicultural treatment) is necessary to control high levels of competition and favour the growth and survival of pure stands of maritime pine, and in some areas even to maintain their representation within mixed forests.

Other factors that influence survival, such as climate, were not evaluated in this study due to the similarity of the area. Climate will be included in future research to enable analysis of the general influence of temperature and precipitation and of the specific effects of longer and more extreme periods of drought. The present study findings demonstrate the need to monitor permanent plots to obtain data to facilitate restoration planning decisions, particularly in a global context where predictions are highly uncertain and based on short-term data.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fire7040125/s1, Figure S1: Location diagram of the 25 subplots within each study plot. Measurements are given in meters [60]; Figure S2: Graphical output for survival analysis using the Kaplan–Meier product-limit method as a function of the six possible combinations between the three post-fire management treatments (Early wood logging; Delayed wood logging; Burn no action) and the two fire severity degrees studied (Consumed or extreme fire severity; Scorched or moderate fire severity); Figure S3: Hazard graphic of survival analysis model in function of slope percentage, stoniness, woody debris presence, interspecific competition in 2009, intraspecific competition in 2011 and competition index in 2011 (ratio between the height of the competitors and the height of the maritime pine); Figure S4: Evolution of overall estimated density (seedlings per hectare) at various dates over the study period (2007, 2009, 2011, 2014, 2017, 2020). Bars indicate standard error; Table S1: Measurement dates.

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