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RESEARCH ARTICLE

# Salvage Logging Versus the Use of Burnt Wood as a Nurse Object to Promote Post-Fire Tree Seedling Establishment

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## Abstract

**Intense debate surrounds the effects of post-fire salvage logging (SL) versus nonintervention policies on forest regeneration, but scant support is available from experimental studies. We analyze the effect of three post-fire management treatments on the recruitment of a serotinous pine (*Pinus pinaster*) at a Mediterranean mountain. Treatments were applied 7 months after the fire and differ in the degree of intervention, ranging from "no intervention" (NI, all trees left standing) to "partial cut plus lopping" (PCL, felling most of the trees, cutting the main branches, and leaving all the biomass in situ without mastication), and "SL" (felling and piling the logs, and masticating the woody debris). Seedling survival after 3 years was the highest in PCL (47.3% versus 38.7% in SL). This was associated with the amelioration of microclimatic conditions under the scattered branches, which reduced radiation and soil temperature while increasing soil moisture. Seedling density after 2 years was approximately 5.5 times higher in PCL than in SL, as in SL a large fraction of seedlings was lost as a consequence of mechanized mastication. The NI treatment showed the lowest seedling survival (17.3%). Nevertheless, seedling density was similar to SL. Seedling growth scarcely differed among treatments. Our results show that branches left onsite acted as nurse objects that improved key microclimatic conditions for seedling recruitment. This creates a facilitative interaction ideal for seedling establishment in moisture-deficient ecosystems, as it provides the benefit of a shading overstory but without underground competition.**

**Key words: facilitation, nurse structures, *Pinus pinaster* regeneration, post-fire restoration, salvage harvesting.**

## Introduction

A current controversial issue among restoration ecologists and forest managers is the appropriate management of dead burnt trees after fire. Post-fire salvage logging (SL) (i.e., the felling and removal of the burnt tree trunks, also often eliminating the remaining woody debris [branches, logs, and snags] by chipping, mastication, fire, etc.) has historically been routinely and widely practiced by forest administrations around the world (McIver & Starr 2000; Bautista et al. 2004; Beschta et al. 2004; Spanos et al. 2005; Lindenmayer & Noss 2006), particularly in the case of burnt conifer forests. However, there is currently an intense debate about the suitability of this approach. Several recent studies show that the felling and removal of burnt trees using ground-based yarding techniques may hamper the regeneration of the plant community by increasing soil erosion and compaction, reducing nutrient availability, damaging the seedling bank, or reducing species richness and diversity (McIver & Starr 2000, 2001; Beschta et al. 2004; Donato et al. 2006; Lindenmayer & Noss 2006). As a result, there are increasing calls to implement less aggressive post-fire treatment policies and actions, including nonintervention, associated with evidence that snags and decaying burnt wood are important components of natural systems that promote ecosystem recovery and diversity (Beschta et al. 2004; Lindenmayer et al. 2004; DellaSala et al. 2006; Hutto 2006).

The reasons commonly invoked to justify post-fire SL may be summarized into five core rationales: (1) recover economic returns from burnt logs; (2) reduce subsequent fire risk; (3) improve site conditions for managed reforestation work in the future (e.g., tree planting); (4) decrease risk of insect pests provoked by burnt wood; and (5) reduce risk of accidents to humans from treefall (Ne'eman et al. 1995; Martínez-Sánchez et al. 1999; McIver & Starr 2000; Bautista et al. 2004; Spanos et al. 2005). These potential reasons to support post-fire SL, however, depend on the characteristics

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of the stand affected and the restoration objectives for the area. First, not all burnt areas are economically profitable to salvage log, as exemplified by forests of the Mediterranean region, where typically the removal of the burnt logs implies additional cost given the low quality and economic value of the wood (Bautista et al. 2004). A common problem with rationale #2 is that post-fire woody fuel loads can be less important for determining fire risk and severity than traditionally assumed (Passovoy & Fulé 2006), particularly in humanized landscapes (Mortiz et al. 2004; Salvador et al. 2005), whereas other factors such as topography, microclimate, or human population may be stronger drivers. Third, the need for access to the area for future restoration may also depend on the capacity for natural regeneration and the management objectives for the area. For example, if the management objectives are focused on preserving ecosystem function and structure (as is the case in national parks and other preserves), it might be desirable to leave the burnt wood in situ as an ecosystem component essential for habitat structure and nutrient cycling (Brown et al. 2003). Fourth, the potential risk of pests originating from burnt wood is also controversial, and the available results suggest a more complex picture depending on fire severity and specific pests (Martikainen et al. 2006; Jenkins et al. 2008). In summary, the overall impacts of SL remain unclear, and these effects need to be rigorously evaluated to establish management guidelines that optimize regeneration and minimize impacts in an area intended for restoration.

Despite the discrepancy between the pros and cons of SL and its relevance for forest economies and restoration, there are surprisingly few studies that address its effect on forest regeneration under controlled experimental conditions. In addition, most of these experimental studies have been polarized between SL versus no intervention (Pérez & Moreno 1998; Martínez-Sánchez et al. 1999; Spanos et al. 2005), despite the fact that there are a plethora of intermediate management possibilities that may bridge restoration, silvicultural, and economic objectives. Furthermore, the few available studies do not explicitly address the mechanisms that underlie the positive or negative effects that different post-fire management strategies have on plant survival and growth, making it difficult to put the results into the context of ecological theories and understanding.

We conducted an experimental study on the effects of three post-fire management treatments on the regeneration of a serotinous pine species, the cluster pine (*Pinus pinaster* Aiton). The silvicultural treatments differ in the degree of ecosystem intervention, ranging from no intervention and partial cutting with lopped branches to the conventional SL with mastication carried out the by local Forest Service. Two questions were posed: (1) What is the effect of post-fire wood management on microclimatic characteristics? and (2) What is the effect of post-fire wood management on seedling survival, growth, and density?

## Methods

### Study Site and Species

The study site is located in Sierra Nevada Natural Park (SE Spain), in an area that burned in September 2005 in the Lanjarón Fire. The fire burned Circa 1,300 ha of pine forests of different species, distributed along an elevational/moisture gradient according to their ecological requirements. The burnt *Pinus pinaster* stand was of approximately 40 ha, and was located around 1,400 m a.s.l., in appropriate local environmental conditions for this species (Table 1). The stand was created by a reforestation Circa 50 years ago to reestablish tree cover on long-deforested hillslopes, using terraces made with bulldozers, previously a common reforestation practice on hillsides in Spain. Each terrace stairstep is composed of a steep cutslope or "backslope" (approximately 90 cm high), and the nearly flat area of the terrace ("terrace" hereafter) of approximately 3 m in width. Initial seedling density was very low on backslopes (data not shown), and thus growth and survival was monitored only for seedlings located on the flat terrace areas. The climate of the area is Mediterranean, with rainfall (mean annual of 487 $\mathrm{L\,m^{-2}}$) concentrated in spring and autumn. Originally, a conventional SL had been planned for the whole stand by the local Forest Service, consisting of the felling of all burnt trees, removal of the logs with a log-forwarder, and elimination of branches and other woody debris by onsite mechanical mastication with a tractor.

*Pinus pinaster* Aiton grows in the western Mediterranean basin and Atlantic area of the Iberian peninsula and southern France, from sea level to 1,700 m a.s.l. (Franco 1986). It is a fast growing species that has been widely used in reforestation plantings, thus increasing its distribution area in the Mediterranean basin throughout the twentieth century. It produces serotinous cones (Tapias et al. 2001) that protect the seeds from intense heat (Reyes & Casal 2002). Seeds may still be viable after short heat pulses of above 100°C (Martínez-Sánchez et al. 1995; Herrero et al. 2007), and the regeneration of the species after fires relies mostly on the aerial seed bank.

### Experimental Design

The study was conducted in three plots averaging approximately 2 ha in area (Table 1), where the local Forest Service implemented the required treatments as part of the conventional SL conducted across the entire burnt area. The three plots adjoined each other in an area of the stand composed pre-fire of pure *P. pinaster* and devoid of any remaining live trees. Differing post-fire management of the burnt trees was applied to each of these plots, resulting in three treatments:

1. "Non-Intervention" (NI), leaving all of the burnt trees standing.
2. "Partial Cut plus Lopping" (PCL), approximately 90% of burned trees were felled by sawyers with chainsaws, with the main branches also manually lopped off, leaving all the cut biomass randomly in situ on the ground. Logs

**Table 1.** Characteristics of the study plots.

| | *Treatment* | | |
|---|---|---|---|
| | *NI* | *PCL* | *SL* |
| Centroid coordinates (x; y) | 456,152;<br>4,089,694 | 455,967;<br>4,089,635 | 456,266;<br>4,089,764 |
| Area ($m^2$) | 18,798 | 14,586 | 26,157 |
| Altitude* (m a.s.l.) | 1,486 | 1,432 | 1,516 |
| Slope (%) | 26.8 | 23.9 | 23.1 |
| Pre-treatment tree density (individuals/hectare) | 1,304 ± 95 | 1,236 ± 73 | 1,316 ± 88 |
| Pre-treatment mean basal tree diameter* (cm) | 18.6 ± 0.6 | 18.9 ± 0.6 | 18.6 ± 0.5 |
| Post-treatment woody debris cover* (%) | | | |
| 0–10 cm from ground level | — | 45 | 32 |
| 11–50 cm from ground level | — | 61 | 11 |
| 100 cm form ground level | — | 9 | 0 |

* Altitude at the centroid position. Pre-treatment tree density was sampled by counting the trees in four 25 × 25 m randomly placed quadrats per treatment. Basal trunk diameter was estimated for 30 random trees per quadrat (thus 120 trees per treatment). Post-treatment burnt woody debris cover was sampled in June 2006 using 100 random points per treatment and counting the number of contacts of burnt wood with a vertical needle at 0–10, 11–50, and 51–100 cm from the ground (performed only in PCL and SL treatments). There were no differences for tree density ($p = 0.34$; Kruskal–Wallis test) or for trunk diameter ($p = 0.86$; one-way ANOVA) among treatments. NI = no intervention; PCL = partial cut plus lopping; SL = salvage logging.

and branches diffusely covered approximately 45% of the surface at ground level (Table 1).

(3) "SL," all trees were manually cut and the trunks cleaned of branches with chainsaws. Trunks were manually piled (groups of about 10–15 logs) and the woody debris was masticated by a tractor. The Forest Service had planned to extract the trunks with a log-forwarder, but the foresters eventually cancelled this step (only in the experimental plots) due to difficulties in precisely operating machinery within the spatial arrangement of the plots. Masticated woody material (Circa 2–5 cm in diameter) covered 32% of the surface.

There is only a single replicate per treatment. Additional replication for this study of *P. pinaster* recruitment was not possible because the local Forest Service could only provide these three designated plots for experimental research on *P. pinaster*. The replicates of each treatment were similarly sized within a homogenous landscape setting, presenting identical pre-treatment conditions in terms of bedrock (micaschist), slope, aspect (southwest exposure), high fire severity, and stand tree characteristics (Table 1). In order to reduce potential spatial bias for statistical inference, we monitored a large number of seedlings (150) per treatment that were randomly distributed through the surface of the replicates.

All post-fire management treatments were implemented from 21 April 2006 to 10 May 2006 (about 7 months after the fire). From late February 2006 onward, we observed the onset of emergence of *P. pinaster* seedlings. This means that management treatments were performed during the spring period of seed germination and seedling emergence and initial growth (a common situation under actual post-fire operational conditions in this region), thus the success of seedling establishment is subjected to potential alteration by implementation of treatment practices (see Discussion).

### Microclimatic Conditions

Soil moisture at 0–5 cm depth was determined using the gravimetric method on 29 August 2006 (the period of strongest drought stress). Samples were collected with a 5-cm diameter core from 10 replicates per treatment. Soil moisture was estimated as the loss of weight after oven-drying each sample to constant weight (80°C for 48 hours); calculations were performed after sieving the soil through a 2-mm sieve to discard stones. Soil moisture was also estimated on 9 June 2007 with a TDR system at 0–12 cm depth (20 samples per treatment). Soil temperature at 3 cm in depth was recorded from 22 to 25 August 2006 by using HOBO temperature data loggers (Onset Computer Corporation, MA, U.S.A.). We used 5–6 data loggers per treatment, with temperature recorded every 10 minutes. The quantity of PAR radiation received at 25 cm from the soil was measured on 11 July 2007, a clear day with no clouds, by using an EMS7 canopy transmission meter (PP-system, U.K.). Sampling was performed from 8:00 hours to 16:00 hours solar time. Twenty-five measurements per treatment (at 25 random points) were made at every hour, starting at the exact hour and randomizing the order of the treatments in any hourly cycle. A whole cycle of 75 measurements was completed in 15–20 minutes.

### Seedling Survival, Growth, and Density

For each of the experimental treatments, we randomly chose 150 seedlings from 1 to 5 June 2006 (450 seedlings in total) that were mapped and marked with a wooden stick. Pine survival was sampled in August 2006 and September 2006 (first year survival), September 2007 (second year survival), May 2008 and September 2008 (third year survival). Growth parameters were monitored in September 2006, 2007, and 2008 (thus at the end of each growing season), considering trunk diameter, plant height, number of shoots, and number of dead shoots. Patterns were similar across years; thus for simplicity, only data after 3 years are reported. Damage by ungulate herbivores in the three study years was less than 1% and therefore not further analyzed.

The density of seedlings was sampled in September 2007 (2 years post-fire) in eight randomly established belt transects (25-m long × 2-m wide) per treatment, placed perpendicular to the slope, in which all pines present were counted.

### Data Analyses

Soil moisture, growth parameters of seedlings, and seedling density were assessed with an analysis of variance (ANOVA). Soil temperature and PAR radiation were analyzed with a repeated-measures ANOVA. Seedling survival was evaluated with a failure-time approach, measuring the time to failure (death) of each individual (Fox 2001). We used the Cox's Proportional Hazards semiparametric model, which produces estimates of regression models with censored survival data using maximum partial likelihood as the estimation method (Fox 2001; Allison 1995). In addition, cumulative survival at the end of the study was compared among treatments with a contingency analysis in order to explore the final result without the influence of the shape of the survival curve. For ANOVAs and rmANOVAs, data were log or arcsin-transformed when required to improve normality and homocedasticity (Zar 1996). Statistical analyses were performed with JMP 7.0 software (SAS Institute, Cary, NC, U.S.A.). Throughout the paper, values are mean ± 1 SE. When present, different letters after mean values indicate differences among treatments according to Tukey HSD post hoc test.

## Results

### Microclimatic Conditions

Soil moisture percentage measured in August 2006 was the highest in PCL (2.8 ± 0.4a%), followed by SL (1.8 ± 0.3ab) and NI (1.0 ± 0.1b; $F = 9.72$; $df = 2,27$; $p = 0.0007$). Soil moisture measured in June 2007 was also the highest in PCL (7.9 ± 0.6a), with similar lower values in SL (5.2 ± 0.6b) and NI (5.8 ± 0.6b; $F = 10.10$; $df = 2,57$; $p = 0.0002$). Soil temperature also differed among treatments, with a time (hour) × treatment interaction (Table 2), which resulted in contrasting patterns from daytime to nighttime. During late morning hours, soil temperature reached higher values in SL relative to NI and PCL, with a difference of about 10°C during the hottest hours of the day (Fig. 1). By contrast, the soil temperature at night reached the lowest values in SL (Fig. 1). PAR radiation received at 25 cm from ground level also differed among treatments (Table 2), being around 30% lower in NI and PCL treatments than in SL (Fig. 2).

### Seedling Survival, Growth, and Density

Both survival curves (L–R $\chi^2 = 18.71$; $df = 2$; $p = 0.0001$) and cumulative final survival ($\chi^2 = 33.52$: $df = 2$; $p < 0.0001$) differed among treatments (Fig. 3), with PCL treatment having the highest survival after 3 years (47.3%), followed by SL (38.7%) and NI (17.3%).

**Table 2.** Summary of the repeated-measurement analysis of variance for soil temperature at 3 cm depth and PAR radiation at 25 cm from ground level in relation to treatment and time of the day.

| *Parameter* | *Source* | *df** | *F* | *p* |
|---|---|---|---|---|
| Soil temperature | Between-subject treatment | 2,285 | 30.44 | <0.0001 |
| | Within-subject time | 23,263 | 894.61 | <0.0001 |
| | Treatment × time | 46,526 | 31.13 | <0.0001 |
| PAR radiation | Between-subject treatment | 2,72 | 192.57 | <0.0001 |
| | Within-subject time | 8,65 | 222.63 | <0.0001 |
| | Treatment × time | 16,130 | 22.61 | <0.0001 |

Treatments are no intervention, partial cut plus lopping, and salvage logging.
* Numerator and denominator, respectively.

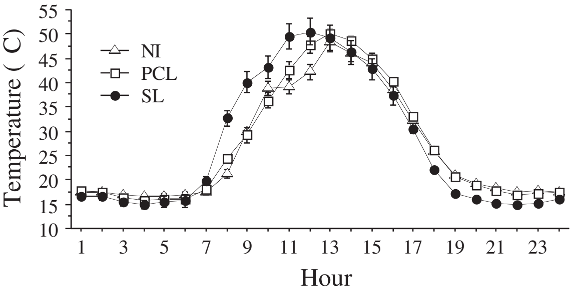

Figure 1. Soil temperature at 3 cm depth reached at hourly intervals from 22 to 25 August 2006 in the three treatments over a 24-hour period. Temperature was measured every 10 minutes, and the six records per hour were used to calculate the mean value per hour. Each point in the graph corresponds to the mean ± 1 SE per hour for the 4 days interval of measurement (4–5 data loggers used per treatment). NI = no intervention; PCL = partial cut plus lopping; SL = salvage logging. Hour is shown in solar time (local time 2 hours ahead of solar time).

Growth parameters differed among treatments after 3 years and followed a pattern likely related to radiation intensity. Thus, total height was shorter, trunk diameter larger, and number of shoots higher in saplings from SL, whereas the reverse occurred in NI, and PCL showed intermediate values (Table 3). Differences were small, however, and overall, pine seedlings reached a height of about 50 cm after 3 years. The proportion of dead branches in surviving seedlings also differed among treatments, although differences were small and the percentage was similarly low in all the treatments (lowest values in SL; Table 3).

Seedling density after 2 years was more than five times higher in the PCL treatment (31.6 ± 6.2a per 25 × 2 m transect) than in NI (5.9 ± 2.7b) or SL (5.6 ± 1.9b; $F = 13.55$; $df = 2,21$; $p = 0.0002$). This resulted in densities at the landscape level after 2 years of 6,320 seedlings per hectare for PCL treatment, 1180 for NI, and 1120 for SL.

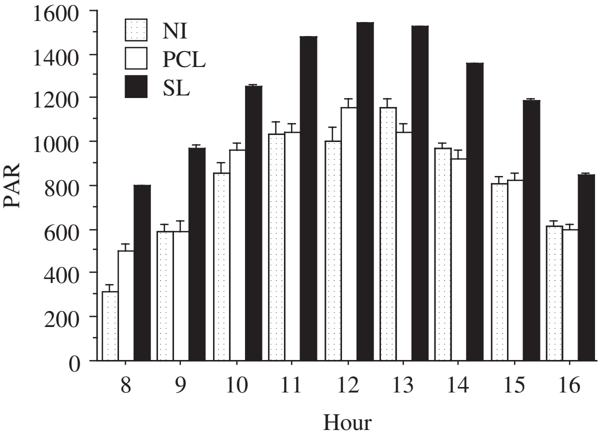

Figure 2. Photosynthetic active radiation (PAR; mmol $m^{-2}$ $s^{-1}$) measured at hourly intervals in the three treatments from 8:00 hours to 16:00 hours solar time (local time 2 hours ahead of solar time). Radiation was recorded 25 times per treatment every hour (in the first 15–20 minutes of each hour). Each point in the graph corresponds to the mean ± 1 SE per hour for the 25 records per hour. NI = no intervention; PCL = partial cut plus lopping; SL = salvage logging.

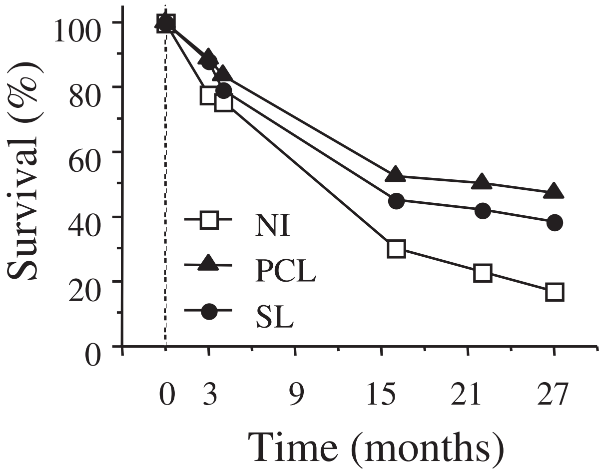

Figure 3. Survival of 150 *Pinus pinaster* seedlings for each post-fire treatment, monitored beginning in early June 2006 for three growing seasons after emergence. NI = no intervention; PCL = partial cut plus lopping; SL = salvage logging.

## Discussion

This study shows that SL did not benefit the regeneration of the native *Pinus pinaster* in the burnt area relative to other alternative treatments. Seedling density after 2 years was similar without intervention (NI treatment), and was clearly higher (about 5.5 times) in a treatment with an intermediate degree of management (cutting most trees but leaving the biomass in situ; PCL treatment). These results likely are a consequence of three complementary reasons. First, partial destruction of the pine seedling bank could have happened in the salvaged treatment due to the use of heavy machinery for the mastication operations, as the treatments were implemented after the onset of seedling emergence (see Martínez-Sánchez et al. 1999; Donato et al. 2006; Greene et al. 2006; Fernández et al. 2008 for similar results). Second, a larger fraction of pine seeds could have been released in the PCL treatment relative to nonintervention by the tree felling, driving increased seedling density (Fernández et al. 2008). In addition, tree fall and trampling by sawyers during PCL implementation may have favored the contact of seeds with the mineral soil, increasing differences in comparison to nonintervention (Martínez-Sánchez et al. 1999). Finally, seedling survival was highest in the PCL treatment, with presence of logs and branches spread over the ground. This is associated with the improvement of microclimatic conditions created by the burnt logs and branches, supporting the idea that dead wood structures could provide facilitation for post-fire tree seedling regeneration in Mediterranean-type and likely other arid ecosystems.

### Burnt Logs and Branches as Nurse Objects

Summer drought is a major mortality factor for seedlings of woody species in Mediterranean environments (Rey & Alcántara 2000; Castro et al. 2004a; Boulant et al. 2008; Gómez-Aparicio et al. 2008a), and the reduction of its severity boosts seedling survival (Castro et al. 2005; Lázaro et al. 2006; Padilla & Pugnaire 2008; Mendoza et al. 2009). In this context, the standing logs and branches spread over the ground acted as structures that reduced summer drought by lowering solar radiation, soil heating, and increasing soil moisture. This ameliorates the water balance of seedlings during the growing season in Mediterranean-type and arid ecosystems, and increases seedling survival, a pattern that has been demonstrated particularly for the facilitative effect

**Table 3.** Growth parameters measured for seedlings after three growing seasons (September 2008) and results of ANOVAs for comparisons among treatments.

| | *Treatment* | | | | | |
|---|---|---|---|---|---|---|
| *Parameter* | *NI* | *PCL* | *SL* | *df* | *F* | *p* |
| Total height (cm)* | 52.9 ± 2.7a | 49.8 ± 1.6ab | 44.2 ± 1.8b | 2,150 | 4.53 | 0.0123 |
| Trunk diameter (mm) | 9.4 ± 0.8a | 10.3 ± 0.5b | 13.0 ± 0.5b | 2,150 | 8.33 | 0.0004 |
| Number of shoots | 11.9 ± 1.7a | 13.7 ± 1.0b | 21.5 ± 1.1b | 2,151 | 10.79 | <0.0001 |
| Dead branches (%) | 12.7 ± 2.9a | 13.9 ± 2.0ab | 8.7 ± 2.4b | 2,151 | 3.27 | 0.0407 |

* Measured from soil level to the tip of the sapling. Different letters indicate differences among treatments according to Tukey HSD test. NI = no intervention; PCL = partial cut plus lopping; SL = salvage logging.

that shrubs may have on the recruitment of seedlings located under their canopies (Castro et al. 2004b, 2006; Gómez-Aparicio et al. 2004; Brooker et al. 2008). Facilitation is the net effect of an interaction where benefits as well as costs (e.g., competition) are involved (Brooker et al. 2008). It has been demonstrated that the main benefit of facilitation among plants in Mediterranean environments comes from the shade provided by the canopy of the benefactor, whereas at the root level there are often costs due to competition for water or nutrients, albeit overall still with a net positive effect (Callaway 1992; Rey-Benayas 1998; Maestre et al. 2003; Gómez-Aparicio et al. 2005). In this sense, the shade of burnt logs and branches provides microclimatic amelioration but without any competitive effect, acting as nurse objects instead of nurse plants. Indeed, standing snags, logs, and branches helped hold higher soil temperatures during the night for PCL and NI compared to SL. This may be irrelevant for seedling survival during summer (when night soil temperatures do not reach damaging low values), but may affect winter seedling survival (see Breshears et al. 1998 for a similar contrasting pattern of soil temperature among seasons). In fact, the buffering of low winter temperatures by nurse shrubs also increases the survival of facilitated tree seedlings (Castro et al. 2004a; Gómez-Aparicio et al. 2008b), and thus aboveground woody structures like snags, logs, and branches might also benefit tree regeneration in areas with low winter temperatures.

There were, however, clear differences in the facilitative effect between the PCL and NI treatments. Although seedling growth was similar, survival was much higher in PCL. This suggests that microhabitat conditions were better under the branches spread over the ground than under the canopy of the burnt, standing trees. A likely explanation is the combination of differences in canopy cover and soil moisture between these treatments. Although values of PAR radiation measured at 25 cm from ground level were similar, pines reached a height approaching this threshold after 2 years, and some of their shoots were overgrowing the branches that surrounded them in the PCL treatment. After 3 years, most of the pines were outgrowing the branches. Under these circumstances, the saplings started to receive more radiation while still keeping the benefit of microclimatic amelioration at the soil level (higher soil moisture, lower soil temperature), allowing improved seedling development in relation to the denser, more homogeneous canopy of the NI treatment (see Castro et al. 2002, 2006, for a similar explanation related to nurse shrubs of different size and canopy structure). Indeed, the low shade tolerance of *P. pinaster* in relation to broad-leaved species of the area may have contributed to the observed poorest seedling performance under the NI treatment. In this sense, it is likely that the beneficial effect of nonintervention policies could be higher for more shade-demanding species, such as *Quercus* or *Acer* species, which are important components of native Mediterranean forests.

## Revisiting Facilitation Theory

Facilitation increasingly is being proposed as an ecological mechanism that could help to restore ecosystems while reducing management impact and costs (Castro et al. 2002, 2006; Gómez-Aparico et al. 2004; Padilla & Pugnaire 2006; Brooker et al. 2008). However, a key point still scarcely considered is the usefulness of natural nurse objects to aid ecological restoration. Recent studies support the contention that natural nurse objects such as rocks (Smit et al. 2005; Munguía-Rosas & Sosa 2008; Peters et al. 2008) or cut branches mimicking nurse canopies (Gómez-Aparicio et al. 2005; Padilla & Pugnaire 2008) can provide more favorable microclimatic conditions, thereby playing an important role in fostering seedling establishment. In fact, artificial nurse objects are extensively used to reduce the risk of frost or water stress in reforestations (i.e., tree shelters). In this sense, the use of branches, logs or other woody debris as natural nurse objects has a high potential for the restoration of burnt sites, as they provide the benefit of a shading overstory but without underground competition. Pausas et al. (2004) also observed that post-fire regeneration success in a serotinous pine stand was related to the presence of branches spread over the ground, pointing to microclimatic amelioration. All this supports the proposition that the effect of dead branches, whether collapsed from burnt trees, left by foresters, or originating from other disturbances types, should be incorporated into facilitation theory. This offers a promising area of research, as similar post-fire treatments can be tested worldwide and across contrasting ecological conditions.

## Management Implications

In our study, cutting the trees and main branches, leaving the biomass in situ, was the option with the highest recruitment success. However, managers face a complex set of social, economic, and ecological factors in relation to post-fire management decisions. In this context, it is important to recognize that even after SL the seedling density may be high enough to guarantee regeneration (Martínez-Sánchez et al. 1999; Fernández et al. 2008). Similarly, the effects of SL may depend on the species and forest-type subject to treatment. It usually reduces seedling recruitment in seeder species (Martınez-Sánchez et al. 1999; Spanos et al. 2005; Donato et al. 2006; this study), but its impact is lower for the recruitment of resprouters (Gracia & Retana 2004; Spanos et al. 2005). The current debate, however, is commonly polarized between SL versus no intervention, which are the extremes of a set of multiple possibilities. For example, our study shows that leaving lopped branches on burnt surfaces may benefit tree regeneration in a Mediterranean ecosystem, so that mastication/chipping of the woody debris may be unnecessary and possibly undesirable even if SL is performed. We suggest that post-fire management of burnt forests should consider a variety of treatment options to help reconcile and better balance competing societal needs ranging from economic benefits to ecological restoration.

## Implications for Practice

- The burnt trees that remain after a fire may play an important role in ecosystem regeneration, structure and function. Post-fire salvage logging thus has a variety of impacts on multiple different ecosystem structural patterns and processes.
- Even when salvage logging is considered necessary or desirable (e.g., for economic reasons), options exist to mitigate environmental impacts by leaving part of the burnt wood in situ, particularly branches and other nonprofitable coarse woody debris.
- Branches left in situ reduce surface solar radiation, surface solar temperature extremes, and increase soil moisture. This may reduce water deficit for seedlings (either naturally established or planted), generating a process of facilitation with high potential to benefit vegetation restoration in water-stressed ecosystems.
- Use of branches as ground cover also offers the advantage of facilitating increased tree regeneration without adding underground root competition. Thus branches act as nurse objects that may assist forest restoration.

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