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Deadwood Decay in a Burnt Mediterranean Pine Reforestation

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Academic Editor: Raffaele Spinelli
Received: 6 March 2017; Accepted: 26 April 2017; Published: 8 May 2017

Abstract: Dead wood remaining after wildfires represents a biological legacy for forest regeneration, and its decay is both cause and consequence of a large set of ecological processes. However, the rate of wood decomposition after fires is still poorly understood, particularly for Mediterranean-type ecosystems. In this study, we analyzed deadwood decomposition following a wildfire in a Mediterranean pine plantation in the Sierra Nevada Natural and National Park (southeast Spain). Three plots were established over an elevational/species gradient spanning from 1477 to 2053 m above sea level, in which burnt logs of three species of pines were experimentally laid out and wood densities were estimated five times over ten years. The logs lost an overall 23% of their density, although this value ranged from an average 11% at the highest-elevation plot (dominated by *Pinus sylvestris*) to 32% at an intermediate elevation (with *P. nigra*). Contrary to studies in other climates, large-diameter logs decomposed faster than small-diameter logs. Our results provide one of the longest time series for wood decomposition in Mediterranean ecosystems and suggest that this process provides spatial variability in the post-fire ecosystem at the scale of stands due to variable speeds of decay. Common management practices such as salvage logging diminish burnt wood and influence the rich ecological processes related to its decay.

Keywords: deadwood management; decay rate; decomposition; density loss; Mediterranean

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1. Introduction

Deadwood decomposition is a key process for ecosystem functioning and structure. Throughout the time of decomposition, decaying wood provides shelter and habitat for a large number of organisms [1–4], guarantees nutrient availability and turnover [5–7], defines carbon residence time and sequestration [8,9], enhances soil moisture [10], and determines the vertical and horizontal physical structure of the habitat as snags or fallen logs [11–14]. All these processes, both singly and in synergic combination, deeply influence other ecosystem processes, ranging from the performance of individual plants to landscape-scale biodiversity and even biogeochemical cycles [15–20]. Knowledge of the factors that determine the rate of wood decomposition is therefore relevant for understanding the residence time of logs, with broad implications for numerous ecosystem functions and services [20–22].

The rate of wood decomposition is also of paramount importance for forest management and planning, particularly after severe disturbances that create large amounts of dead wood, such as fires, pest outbreaks, or windstorms [1,23]. Particularly in the case of burnt forests, the rapid loss of economic value of the wood due to decomposition and the difficulties that it imposes for transit and management are often-claimed arguments for the quick implementation of post-fire management [24–27]. In this sense, extensive post-fire salvage logging—i.e., the removal of the logs, usually accompanied with the in situ elimination of the rest of coarse woody debris—is a widely implemented post-fire management action that seeks to recover part of the capital of the forest as well as to prepare the terrain for post-fire restoration [25,26]. However, post-fire salvage logging may impact ecosystem functioning and the capacity for natural regeneration through a variety of processes, such as reducing nutrient and moisture availability, decreasing the necessary substrate for saproxylic organisms, diminishing advance regeneration, or increasing soil erosion, among others [25,28–32]. Understanding the rate of wood decomposition after a fire is thus of great relevance to properly balance the economic benefit of quick salvage operations against the potential benefits for conservation and natural regeneration of nonintervention approaches. However, studies on wood decomposition are scarce and mostly concentrated in certain types of ecosystems such as boreal forests [33,34]. In particular, studies in Mediterranean-type ecosystems are very scarce [34], except for some that have focused on the decomposition of standing snags [35,36].

Wood decomposition is affected by abiotic and biotic factors, as well as the interactions and feedbacks between them. The speed of decomposition depends on moisture and temperature [1,22,37,38], and hence it can be expected to vary across environmental gradients where these factors gradually change, such as elevational or latitudinal gradients [1,21,39]. Decomposition rates may also be affected by species identity and log diameter, as these factors determine the proportion between heartwood and sapwood [9], and heartwood resists decay for longer than sapwood [40].Trunk diameter can also determine the identity of detritivorous species that colonize the log, and these may, in turn, affect the species assemblages of decomposers [5,41,42]. In short, decomposition is a complex process whose understanding requires proper control of the starting conditions and stand characteristics.

In this study, we seek to determine the rate of wood decomposition in a burnt pine reforestation under Mediterranean conditions. Three experimental plots were distributed across an elevational gradient spanning some 800 m, and logs with a standardized length but variable diameter were marked, spread on the ground, and sampled over 10 years. Given the marked differences in climatic conditions and the change in species across the elevational gradient, we hypothesized that decomposition rate would vary across elevations (hypothesis 1). Furthermore, the proportion of hartwood to sapwood tends to increase with log diameter [43], so we hypothesized that decomposition would be faster in logs with smaller diameters (hypothesis 2). Given the large amount of conditions that may affect decomposition rates and their variability across time, we expected potential interactions between elevation and diameter to affect decomposition rates (hypothesis 3). Overall, we expect this study to contribute to the understanding of the speed of wood decomposition in Mediterranean-type ecosystems, which should ultimately provide input to make informed post-fire decision-making.

2. Methods

2.1. Study Site

The study was conducted in the Sierra Nevada Natural and National Park (southeast Spain), in an area that burned in September 2005 (the Lanjarón fire). The fire burned around 1300 ha of 35 to 45 year-old reforested pine stands on a southwest-oriented mountainside. It was a high-intensity crown fire that consumed all the leaves, twigs, and litter and charred the bark of the trunks [30]. After the fire, the Forest Service established three plots across an elevational gradient within the context of a long-term research program devoted to study the effect of salvage logging with respect to other post-fire burnt wood management alternatives on ecosystem restoration and regeneration ([17,26,44]; Table 1). The three plots were similar in terms of pre-fire tree density (1000–1500 trees ha^{-1}), fire intensity (high), bedrock (micaschist), aspect (southwest), soil type (haplic phaeozems), and other soil characteristics ([30,45]; Table 1). However, the plots differed in climatic conditions, as expected from the increasing elevational gradient: mean rainfall increased and temperature decreased with elevation.

This influenced the species of pine that had been planted at each site (Table 1). For this study, we made use of areas in which 90% of the burnt trees were felled, the trunks were separated from their main branches and cut in pieces of ca. 2 m, and all the wood was left on the ground [46]. The climate is Mediterranean, with rainfall concentrated in spring and autumn, alternating with hot, dry summers. Snow is common during the winter, persisting up to 2 months at the highest elevation.

Table 1. Location and characteristics of the study plots.

	Plot		
	1	**2**	**3**
Coordinates [1]	36°57′12.1″ N 03°29′36.3″ W	36°58′11.9″ N 03°30′1.7″ W	36°58′6.5″ N 03°28′49.1″ W
Elevation (m above sea level [1]	1477	1698	2053
Mean daily minimum temp. (°C) [2]	6.8 ± 0.2	5.6 ± 0.2	3.4 ± 0.2
Mean daily maximum temp. (°C) [2]	17.1 ± 0.2	16.2 ± 0.2	13.4 ± 0.2
Mean ann. precip. (mm) [2]	536 ± 41	550 ± 40	630 ± 42
Dominant species	*Pinus pinaster*	*P. nigra*	*P. sylvestris*
Mean log diameter (cm) [3]	12.6 ± 0.4	12.8 ± 0.3	10.0 ± 0.2

[1] Measured at the centroid of each plot. [2] Data obtained from interpolated maps of Sierra Nevada (1981–2010) generated at the Centro Andaluz de Medio Ambiente (CEAMA). [3] Estimated from the logs that were used in this study, mean ± 1 SE.

2.2. Sampling Design

Six months after the fire (March to April 2006), 50 sampling points were randomly established within an area of 2 ha at each elevation to monitor wood decomposition. The sampling points were sufficiently away from standing trees so as to avoid their collapse over the point. At each of the sampling points, five logs were cut with a chainsaw to a standardized length of 75 cm (experimental logs, hereafter) and spread over an area of ca. 1 × 1 m, resulting in 250 experimental logs per elevation (Figure 1). All the logs had the bark charred to a similar extent as a result of the even-aged and even-spaced nature of the stands, and they were only superficially affected by the fire (Figure 1). The experimental logs belonged to *Pinus pinaster* in plot 1 (lower elevation), *P. nigra* in plot 2 (intermediate elevation), and *P. sylvestris* in plot 3 (higher elevation), which were the main pine species at each elevation according to their climatic requirements. This variation in species is a normal situation in reforested (and natural) pine stands across marked elevational gradients. Although such sampling design does not allow the effect of pine species and elevation on decay rates to be separated, it does provide the opportunity to measure wood decomposition under three realistic forest scenarios. Each experimental log came from a different tree and was cut from a random height along the tree trunk. Therefore, the logs constitute a representative sample of trunk characteristics in the study site in terms of diameter and sectional origin along the trunks. At the same time, we cut one wood disc of 6–8 cm height from each of 50 logs that were randomly selected at each elevation (initial discs, hereafter). These discs were brought to the laboratory, and their volume was estimated after measuring two perpendicular diameters from both sides and four heights. The discs were then oven-dried at 40 °C to constant weight. The initial density of the wood was estimated from the known volume and weight of these discs, which did not present any sign of decay.

Figure 1. Wood samples used in the study. **Left**: standardized 75 cm length experimental logs that were spread through the three elevations (plots) since the beginning of the experiment (March–April 2006); a metal tag can be observed in one of the logs. **Center**: Wood disc from an experimental log after some years (two in this case) of decomposition. **Right**: a highly decomposed wood disc after 10 years; when discs showed a high degree of fragmentation, as in this case, we used the two longest available arcs of the circle to find the perpendicular bisectors and the center of the disk at their intersection, from which the diameter was measured.

2.3. Wood Decomposition

Wood decomposition was estimated by cutting one random subsample of each of 20 randomly-chosen experimental logs per elevation in June 2008, 2010, 2014, and 2016, thus at 2, 4, 8, and 10 years after the experimental setup. The experimental logs were brought to the laboratory, and afterwards a disc of 6–8 cm length was obtained from the central part of each log by using a manual saw. Log dimensions and dry mass were measured as indicated above for the initial discs. As decay progresses, dead wood pieces become more elliptical. This is why we used the conic-parabolic formula proposed by Fraver and colleagues [47] to estimate the volume of the logs. Wood density (g cm^{-3}) was then calculated by dividing wood dry weight by its volume for each disc sample.

2.4. Statistical Analyses

We analyzed wood density with mixed models in R version 3.3.1 [48], with the "nlme" package [49]. We initially fitted a model with Plot (a categorical factor with three levels), Year, and Log Diameter, as well as all the possible interactions between these factors, as fixed effects, and we included plot as a random effect to account for pseudoreplication [50]. The response variable was wood density. Model simplification was carried out by sequentially eliminating interaction terms from the model and performing likelihood ratio tests (LRTs) to assess their significance [50]. Heteroscedasticity was assessed with the varIdent function, with the use of LRTs [51]. Assumption checking through plotting of residuals and random effects was carried out as suggested by Pinheiro and Bates [51].

As our response variable was wood density measured at a specific point in time but we were interested in assessing the factors that changed the speed at which density was reduced, in the Results we mainly focus on the factors that changed the effect of Year on wood density (i.e., we interpreted an interaction between Year and another factor as an effect of that factor on the speed of decomposition).

3. Results

Wood density showed an initial decline from an average of 0.482 ± 0.004 g cm^{-3} (mean ± 1 standard error (SE)) in 2006 to 0.420 ± 0.007 g cm^{-3} in 2008. Density then increased slightly until 0.445 ± 0.007 g cm^{-3} in 2010, and then dropped again to 0.415 ± 0.008 g cm^{-3} in 2014 and 0.370 ± 0.013 g cm^{-3} in 2016 (all plots pooled). Our results show that wood density was affected by three interactions between the studied factors. First, there was an effect of plot on wood decomposition rates (i.e., Plot × Year interaction affecting wood density; Table 2): the wood decomposed slower at the highest-elevation plot than at the other plots (Figure 2). Second, the temporal change in wood density was also modified by the size of the log (i.e., significant Year × Diameter interaction; Table 2): larger logs decomposed faster than smaller logs (Figure 3). Third, there was a Diameter × Plot interaction, indicating different effects of log diameter on wood density across plots when years are pooled (Table 2).

The Year × Diameter × Plot interaction was not significant, indicating that diameter and plot affected the speed of decomposition independently. Note that the Plot factor includes differences in elevation and species.

Table 2. Results from linear mixed effects models on the effect of year, log diameter, and plot (defined by the elevation/species gradient) on wood density.

Term Removed from Model	Likelihood Ratio	*p*-Value
Year × Diameter × Plot [1]	1.63	0.44
Year × Diameter [2]	8.26	<0.01
Year × Plot [2]	6.48	<0.05
Diameter × Plot [2]	10.78	<0.01

[1] Tested by removal from the model containing all possible interactions among factors. [2] Tested by removal from the model containing all two-way interactions between the factors.

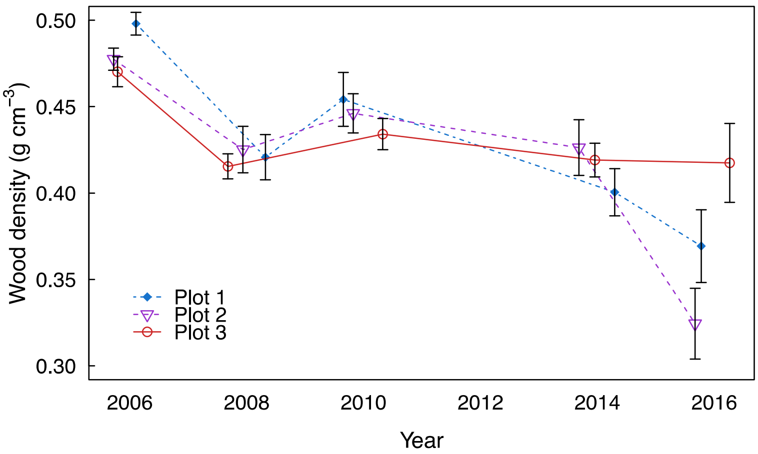

Figure 2. Temporal changes in wood density across the three study elevations (plots). Plot 1 was located at an elevation of 1477 m, Plot 2 at 1698 m, and Plot 3 at 2053 m (note that tree species varied across elevations too; Table 1). Plot did not significantly affect wood density in 2016 according to ANCOVA ($F_{2,66}$ = 0.74, p = 0.48), but log diameter did (see Figure 3). Error bars indicate ± 1 SE of the mean.

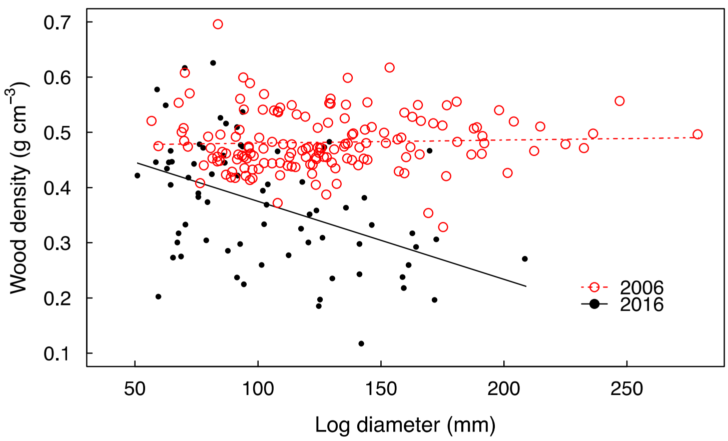

Figure 3. Effect of log diameter on wood decomposition. The density of wood was independent of diameter in 2006 (ANCOVA; $F_{1,70}$ = 0.28, p = 0.6). In 2016, the average density was lower than in 2006 for all the ranges of diameters considered in the study and negatively affected by log diameter (ANCOVA; $F_{1,70}$ = 18.4, p < 0.001), indicating that larger-diameter logs decomposed faster than smaller logs. The figure shows the measured values of each log and simple linear regression lines for each year.

4. Discussion

We found that the burnt wood lost nearly one-fourth of its mass after 10 years of decomposition. The rate of decomposition was lowest at the greatest elevation and for small-diameter logs. The differences across elevations might be related to several interacting factors that we cannot rule out, such as differences in climatic conditions and species, or even to an indirect effect of log diameters, which were lowest at the highest elevation (Table 1). This is, in any case, a normal situation under natural conditions, where variability in forest conditions across elevational gradients exists even within even-aged stands. Overall, our study provides novel results concerning burnt wood decomposition in Mediterranean mountains, and it represents one of the longest wood decomposition time-series available for a Mediterranean-type ecosystem.

Despite the overall decline in wood density, the rate of this process changed over time—and even reversed from the second to the fourth year. This has also been observed in previous studies of wood decomposition (e.g., [52]), and it might be related to the often-reported peak in colonization and nutrient immobilization by detritivorous organisms and decomposers in substrates with high carbon to nutrient ratios at the initial stages of decomposition [4,53]. On the other hand, our final values of wood density loss are clearly lower than those reported for other ecosystem types with higher rainfall. For example, Olajuyigbe and colleagues [23] found 50% of decomposition for *Picea sitchensis* after 12 years in Ireland, Mackensen and Bauhus [54] found a 71% decomposition for *Pinus radiata* after 10 years in southeastern Australia, Brown and colleagues [55] reported 25% of decomposition for *Pinus pinaster* after 5 years in places of Western Australia with average rainfall around 1000 L m^{-2} $year^{-1}$, and Yang and colleagues [56] found density losses greater than 50% after 9 years for three species in an old-growth tropical forest. The lower decomposition rate in our study might be explained by the uncoupling between moisture and temperature during the characteristic summer drought in Mediterranean-type ecosystems [57]. Still, the wood lost up to 26% and 32% of its mass in plots 1 and 2 (lowest and intermediate elevations, respectively) after 10 years, which supports that decomposition, despite being slower than in other temperate ecosystems, remains fast enough to ensure nutrient turnover, increase soil fertility, and reduce the fuel potential of the burnt logs [24,30,31]. Although the logs laid out for this study likely decomposed faster than the remaining wood due to their direct contact with the soil, the decomposition of the standing snags was likely not much slower, as all of them had collapsed and were mostly touching the ground 5.5 years after the fire [46].

The results also show an effect of log diameter on the speed of decomposition. The effect reported for the diameter in the literature is variable. For instance, several studies found no relationship between diameter and decay rate [52,58,59], and other studies found that decomposition rate declined with increasing log diameter because of reduced surface-to-volume ratios [59–61]. Interestingly, our results show the opposite trend. Although we did not study the mechanism behind this diameter effect, we consider that it was likely mediated by an effect of diameter on the deadwood-inhabiting organisms involved in the decay process. In particular, we observed larger holes produced by the larvae of xylophagous insects in the thicker logs (Figure 1). In fact, it is well known that the larvae of larger species tend to inhabit logs of greater diameter [42]. The galleries they create increase bole fragmentation and respiration and can be used by other detritivorous organisms and decomposers that further accelerate decay [4,62]. Logs with a larger diameter also retain more humidity, which is especially beneficial for the colonization of microbial fungi during drought periods [4,63] and thus accelerates decomposition [64]. Another explanation lies in the phenomenon known as "case-hardening", which refers to solar radiation heating and hardening the outer wood layers [65,66], so that a larger surface-to-volume ratio would induce a greater loss of moisture rather than enhanced decomposer colonization [64]. Under Mediterranean climate, characterized by a long, hot, and dry summer, the retention of moisture inside large logs may represent an important factor speeding up wood decomposition. Our results thus support that log size may accelerate decay under Mediterranean climate, and they highlight the need to carefully control log diameter to correctly interpret the speed of decay across environmental gradients.

Salvage logging is a common silvicultural practice after fires in Mediterranean pine reforestations, as well as other parts of the world [25,26,29]. The most obvious consequence of this approach is the subsequent large-scale absence of decomposing wood. While ecosystems and the species that constitute them are resilient to historical disturbance regimes, this resilience hinges on the existence of material legacies of the previous ecosystem that set the scene for regeneration; changes in the post-disturbance environmental conditions compared to those under which the ecosystem historically regenerated can seriously undermine resilience [67]. The present study documents relatively fast and heterogeneous decay rates in burned pine plantations under Mediterranean-type conditions, a process that involves myriads of species ranging from fungi to mammals and that virtually disappears after post-fire logging. The final decision concerning burnt wood should ultimately depend on the balance between the economic value of the wood, the cost of wood removal, the risks posed by the presence of decaying logs, and the ecological processes that dominate post-fire ecosystems under different management scenarios.

5. Conclusions

Our study shows that burnt wood decay in Mediterranean mountains is slower than in other temperate ecosystems, but still fast enough to be considered a process that may support nutrient cycling and ecosystem regeneration. Wood decay changed across an altitudinal gradient, a fact that is likely linked to changes in both abiotic (climatic conditions) and biotic (wood characteristics, decomposer and detritivorous communities) factors. Overall, we conclude that burnt wood is a biological legacy that should be partially or totally kept in situ after fires.

Acknowledgments: We thank the Consejería de Medio Ambiente, Junta de Andalucía, and the Direction of the Natural and National Park of Sierra Nevada for fieldwork permission, constant support, and facilities. This study was supported by Project 10/2005 from the Organismo Autónomo de Parques Nacionales (Spanish Government), CGL2008-01671 from the Spanish Ministerio de Ciencia e Innovación, and P12-RNM-2705 from Junta de Andalucía. A.B.L. acknowledges funding from Juan de la Cierva grant by Ministerio de Economía y Competitividad (FJCI-2015-23687). C.R.M-G. had a Ph.D. grant from the National University of Asunción (Paraguay) and Carolina Foundation (Spain). We are grateful to S. Marañón-Jiménez, who performed valuable fieldwork. Also, we thank Sergio Cortés-Merino and Fernando Bravo for their help in field work.

Author Contributions: J.C. conceived and designed the experiment; C.R.M-G. and J.C. performed the fieldwork; C.R.M-G., A.B.L., and J.C. analyzed the data; C.R.M-G., A.B.L., and J.C. wrote and edited the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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