Post-Fire Management Impact on Natural Forest Regeneration through Altered Microsite Conditions

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Abstract: High severity stand-replacing wildfires can deeply affect forest ecosystems whose composition includes plant species lacking fire-related traits and specific adaptations. Land managers and policymakers need to be aware of the importance of properly managing these ecosystems, adopting post-disturbance interventions designed to reach management goals, and restoring the required ecosystem services. Recent research frequently found that post-fire salvage logging negatively affects natural regeneration dynamics, thereby altering successional pathways due to a detrimental interaction with the preceding disturbance. In this study, we compared the effects of salvage logging and other post-disturbance interventions (adopting different deadwood management strategies) to test their impact on microclimatic conditions, which potentially affect tree regeneration establishment and survival. After one of the largest and most severe wildfires in the Western Alps that affected stand-replacing behavior (100% tree mortality), a mountain forest dominated by *Pinus sylvestris* L., three post-fire interventions were adopted (SL-Salvage Logging, logging of all snags; CR-Cut and Release, cutting snags and releasing all deadwood on the ground; NI-No Intervention, all snags left standing). The differences among interventions concerning microclimatic conditions (albedo, surface roughness, solar radiation, soil moisture, soil temperature) were analyzed at different spatial scales (site, microsite). The management interventions influenced the presence and density of safe sites for regeneration. Salvage logging contributed to the harsh post-fire microsite environment by increasing soil temperature and reducing soil moisture. The presence of deadwood, instead, played a facilitative role in ameliorating microclimatic conditions for seedlings. The CR intervention had the highest soil moisture and the lowest soil temperature, which could be crucial for seedling survival in the first post-fire years. Due to its negative impact on microclimatic conditions affecting the availability of preferential microsites for regeneration recruitment, salvage logging should not be considered as the only intervention to be applied in post-fire environments. In the absence of threats or hazards requiring specific management actions (e.g., public safety, physical hazards for facilities), in the investigated ecosystems, no intervention, leaving all deadwood on site, could result in better microclimatic conditions for seedling establishment. A preferred strategy to speed-up natural processes and further increase safe sites for regeneration could be felling standing dead trees whilst releasing deadwood (at least partially) on the ground.

Keywords: microclimate; soil temperature; post-fire management; *Pinus sylvestris*; salvage logging; restoration ecology; forest regeneration

1. Introduction

After highly severe disturbance, forest recovery can be impeded by harsh microclimatic conditions arising from the event [1]. In the absence of specific plant traits related to the occurrence of disturbances and in the aftermath of a stand-replacing wildfire, the conditions may become particularly adverse, strongly limiting the establishment and survival of tree regeneration. In these circumstances, if the disturbance is followed by management practices that affect the abundance, quality, and spatial pattern of biological legacies, forest regeneration processes can be further hampered and altered in terms of both timing and seedling density.

Post-fire management practices vary from passive management, allowing natural recovery to occur, to undertaking different levels of intervention. Salvage logging is by far the most widespread intervention [2]. Its consequences on forest ecosystems have been investigated by several studies in the last few decades [3–6] by looking at the different effects on living components of forest ecosystems, like avian communities [7], arthropods assemblage [8], mammals [9], bryophytes [10], and tree species [4]. Furthermore, salvage logging has been found to modify the abiotic environment, triggering surface erosion and runoff [11], and promoting snow-mass movements [12]. As recently underlined [13], the interactions are expected to be between the natural disturbance and subsequent logging, with effects that could be hard to foresee. Felling and removing affected trees, both dead and damaged, can act as a further disturbance, with possible unwanted implications on several ecosystem processes [6].

Successful seedling establishment is based on microclimatic requirements that are usually more restrictive than those required for adult plant survival [14]. During ontogenetic stages, trees develop structures allowing limiting factors to be overcome (i.e., a deep or large root system able to reach water deeper in the soil).

The soil temperature and moisture environment, which deeply influences seedling growth and survival, can be substantially affected by the management practices adopted after a high-severity wildfire [15–17]. Stand regeneration can, thus, be impaired by the resulting changes in irradiance and albedo at the soil surface, reduced soil insulation, or physical properties alteration.

Deadwood can play a critical role in determining regeneration patterns. Its presence may increase the availability of suitable sites for seedling establishment and survival, acting as a shelter or shield against multiple limiting factors. This may become very important immediately after a stand replacing fire, in the absence of other facilitation mechanisms provided by neighboring mature plants or shrubs [4]. Particularly when lying on the ground, deadwood elements can influence heat transfer at the soil surface level, affecting diurnal and seasonal soil temperature, and moisture patterns.

The role of biological legacies (sensu [18]) has been widely recognized by forest ecologists and scientists. However, after severe disturbances in the forestry sector, the prevailing management strategy, is still frequently to salvage the economic value of timber by extracting the dead or affected trees, often by public demand [5]. Few researches have focused on this topic in the Alps, mainly in post-windthrow areas, or insect outbreaks [19,20]. Concerning post-fire management in these ecosystems, only a few studies compared salvage logging and other post-disturbance silvicultural interventions [4,21]. Their results pointed out that salvage logging delayed obligate-seeder species regeneration, leading to lower biodiversity (in both species richness and structure). These patterns were linked to the lack of site amelioration provided by deadwood, but no direct evidence was presented.

In this study, we wanted to test whether different post-fire management interventions altered the microsite at temperature and water availability levels, with our main hypothesis being that salvage logging creates harsher conditions, especially on the most sun-exposed (south-facing) slopes.

2. Materials and Methods

2.1. Study Area

The Bourra study site (45°46′21′′ N, 7°29′55′′ E) is located in the Aosta Valley (NW Italy), within the municipality of Verrayes. The area, characterized by an almost pure Scots pine (*Pinus sylvestris* L.)

forest, was severely affected by a stand replacing fire in March 2005. The wildfire, one of the biggest and most severe in the region, burned 257 ha, of which almost 160 ha had stand replacing behavior (100% mortality). The elevation ranges between 1650 and 1800 m a.s.l., and the south-facing slope has an average inclination of 25°. The bedrock is ophiolite and schist, and the soils are entisols (Soil Taxonomy USDA). Mean annual temperature is 5.6 °C and mean annual precipitation is approximately 750 mm (less than 250 mm from June to August), with the driest month being February (Nus-Saint Barthélemy meteorological station, 1650 m a.s.l., 1931–2012 period), coinciding with the main peak of the fire season. On average, there are less than 100 rainy days per year, seldom in February, and recurrent water deficit in summer. Snow falls are usually distributed in November-December and March-April, reaching an average annual amount of 150 cm, with fast melting dynamics due to its southern aspect. The tree vegetation comprised a dense even-aged *P. sylvestris* forest with sporadic *Larix decidua* Miller, *Picea abies* L. Karst, *Quercus pubescens* Will., *Populus tremula* L. and *Betula pendula* Roth. The stand was the result of a secondary succession dating back to 60–80 years ago on abandoned pastures and fields. Prior to the fire it had a mean density of 720 trees ha^{-1} (dbh > 12.5 cm), with a basal area of 26 m^2 ha^{-1} and a standing volume of 160 m^3 ha^{-1}.

2.2. Experimental Design

A post-fire salvage logging project was approved in December 2005; Salvage Logging (SL) operations began during the autumn of 2007, according to the conventional post-fire management activities adopted in the Aosta Valley Region (Figure 1a) [21]. An area of 5 ha was instead used to test alternative management solutions, namely Cut and Release of deadwood (CR; 2 ha; Figure 1b) and No Intervention (NI—Passive management; 3 ha; Figure 1c). Our experimental design, included three treatments (SL, CR, NI), which was applied to adjoining areas, characterized by similar pre-fire conditions and fire severity (complete stand mortality). In the SL area, all trees were felled, trunks and large branches removed, and the slash stacked in piles. In the CR all trees were felled and all the detritus was left on the ground, whereas the NI area was not treated at all. Our experimental design followed two different approaches in order to capture the effects of post-fire management at different spatial scales (site and microsite). At the site scale, we used remote sensing data (satellite images and LiDAR data) to calculate the surface albedo and surface roughness, and at the microsite scale we collected the field data to assess near-ground solar radiation, soil temperature, and soil moisture values.

Figure 1. Post-fire interventions in the Bourra study site. (**a**) Salvage Logging (SL; all trees were felled, trunks and large branches removed and the slash stacked in piles); (**b**) Cut and Release of deadwood (CR; all trees were felled and all the detritus was left on the ground); (**c**) No intervention (NI).

2.3. Site Scale

Surface albedo and slope surface roughness in the three treatments (SL, CR, and NI) were derived by using a remote sensing approach, in order to acquire information about the energy balance at ground level [22–24]. Four mid-summer Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images, covering the 2009–2012 period, were used to assess short-term differences in short-wave albedo [25] among treatments, starting from the first growing season following the

interventions. The database comprised cloud-free images (cloud cover <5%), acquired from Glovis USGS website(https://glovis.usgs.gov/; accessed on 15 November 2012) (Table 1).

Table 1. Acquisition dates and details of the Landsat 5 TM and Landsat 7 ETM+ images used in this study. GSD = Ground Spatial Distance; Pan = panchromatic; MS = multispectral.

Landsat Sensor	Acquisition Date	Path/Row	GSD Pan (m)	GSD MS (m)	Cloud Cover (%)
TM	28 July 2009	195/028	-	30	<5
TM	1 September 2010	195/028	-	30	<5
TM	2 July 2011	195/028	-	30	<5
ETM+	14 September 2012	195/028	15	30	<5

The images were pre-processed through radiometric calibration and atmospheric correction, in order to guarantee temporal homogeneity and spatial comparability of the dataset [26,27] by means of ENVI tools (ITT, Visual Information Solutions). Remote total shortwave albedo was retrieved from the Landsat TM, ETM+ satellite images by using the following formula:

$$ALBEDO = 0.356\rho_1 + 0.130\rho_3 + 0.373\rho_4 + 0.085\rho_5 + 0.072\rho_7 - 0.0018 \qquad (1)$$

where $\rho_{1\div7}$ represent the top of atmosphere (TOA) reflectance bands at both Landsat sensors, after the pre-processing procedure [25]. The average albedo values for each treatment were computed from a subset of 22 pixels extracted in the core area of each management type, resulting from an internal buffer of at least 10 m from the treatment borders. This image sub-setting was necessary to avoid the risk of overlapping between treatments. Annual blocks of albedo data values were contrasted among management types by ANOVA with Bonferroni's post-hoc test.

The slope surface roughness was computed as a proxy of microsite heterogeneity obtained through different deadwood treatments. A surface Roughness Index (RI) was calculated using a Digital Surface Model (DSM) and Digital Terrain Model (DTM), both derived from LiDAR data, and acquired in June 2011 and rasterized at 1 m spatial resolution [4,28]. RI was calculated as the standard deviation of differences between DSM and DTM, within a 3 × 3 pixels moving window, after the removal of negative and >1 m values, in order to filter out standing dead trees. Mann-Whitney test was applied to compare RI medians among management types. Furthermore, a Kolmogorov-Smirnov test was used to compare the distribution of the RI values between management types.

2.4. Microsite Scale

During the summer of 2011, near-ground solar radiation, soil temperature, and soil moisture were measured within the treated areas (SL, CR, NI). Solar radiation and soil temperature were measured in 13 sampling points (3 in SL, 6 in CR, 4 in NI). The sampling points were set randomly in the homogeneous SL area, near or under the cover of lying deadwood (trunks and large branches) in the CR area, and surrounded or protected by groups of standing dead trees in NI area.

In order to estimate near-ground solar radiation, hemispherical photographs were taken once in each of the previously described sampling points (*n* = 13) using a Nikon CoolPix 4500 digital camera (Nikon, Tokyo, Japan) with an FC-E8 fish-eye lens(Nikon, Tokyo, Japan). The camera was north-oriented and levelled on a tripod at a height of 35 cm above the ground. Hemispherical photographs were taken after sunset on a cloud-free day to avoid direct beam radiation. The obtained images were then processed by means of a Gap Light Analyzer (GLA) tool Version 2.0(Simon Fraser University, Burnaby, British Columbia) using Standard Overcast Sky (SOC) model sky-region brightness with a Clear-Sky Transmission Coefficient set to 0.65 [29]. The potential near-ground incoming solar radiation and the canopy openness ratio as Total Site Factor (TSF) were calculated. TSF ranges from 0 in a completely covered location (light absence), to 1 in a completely open one (100% light availability).

Soil temperature data were collected during the warmest months (Jun-Sept) every minute, using Lascar EasyLog EL-USB-2 data loggers (Lascar Electronics, Salisbury, UK), buried 5 cm beneath the soil surface.

Soil moisture was instead measured five times in 51 sampling points (9 in SL; 20 in CR; 21 in NI, including the 13 sampling points previously described) from June to September at 5 cm depth, by means of a Time Domain Reflectometry HH2 soil moisture meter and a PM300 probe (both by Delta-T Devices Ltd., Cambridge, UK), calibrated for mineral soils. The measurements were conducted at least 24 h after a major precipitation event (>10 mm), randomizing the order of the sampling point in any cycle [30].

3. Results

3.1. Site Scale

3.1.1. Albedo

Following post-fire interventions, mean values in summer albedo were always higher in SL, followed by CR and NI, with a slightly increasing trend for the 2009–2012 period. The differences between treatments were always statically significant (ANOVA with Bonferroni's post-hoc test; p-value < 0.01), except for 2012, when NI and CR values did not significantly differ (Figure 2).
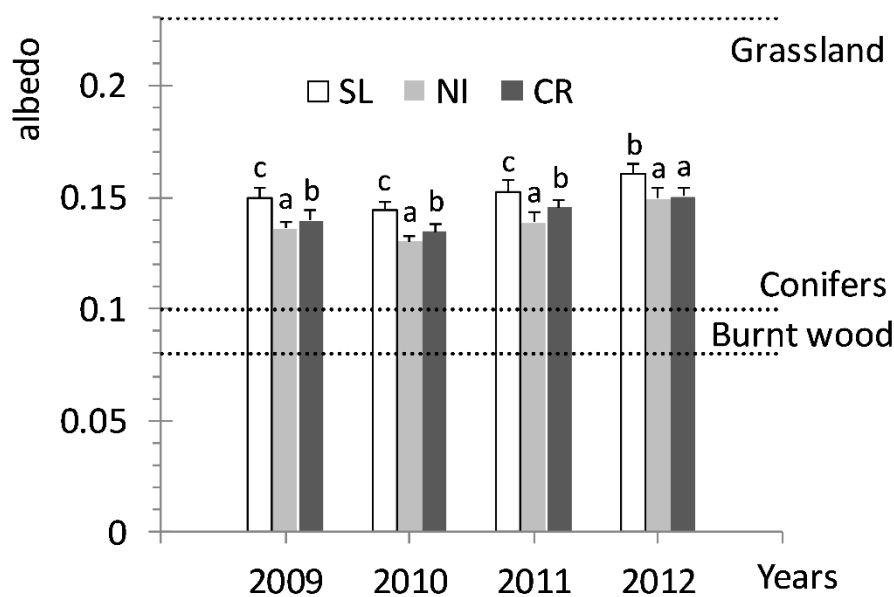

Figure 2. Temporal diagram of summer albedo values (mean values + standard deviation). Different letters highlight differences between management types (ANOVA with Bonferroni's post-hoc procedure; p-value < 0.01). Dotted horizontal lines display the average albedo values for burnt wood, closed conifer stands, and grassland for comparison [31].

3.1.2. Roughness

The highest roughness index (RI) values were found in CR (0.483) and NI (0.459) (Table 2). The CR treatment also showed the higher mean surface roughness (Mean RI = 0.18), while the SL area showed the lowest one (0.11). RI medians and distribution were always significantly different between treatments (Mann-Whitney test, $p < 0.01$; Kolmogorov-Smirnov test, $p < 0.01$). The proportional cumulated area of RI (Figure 3) shows a clear separation between SL and the other treatments, with the former having a higher homogeneity and lower surface roughness values.

Table 2. Summary statistics of the Roughness Index (RI) computed for each post-fire management type: Salvage Logging (SL), Cut and Release (CR) and Non-Intervention (NI). Number of pixels corresponds to surface area (m^2).

| Roughness Index Statistics	SL	CR	NI
N pixels	18,141	16,497	17,664
Mean ± SD	0.11 ± 0.06	0.18 ± 0.07	0.17 ± 0.08
Median	0.12	0.18	0.16
Minimum	0.02	0.01	0.00
Maximum	0.39	0.48	0.46
Range	0.37	0.47	0.46
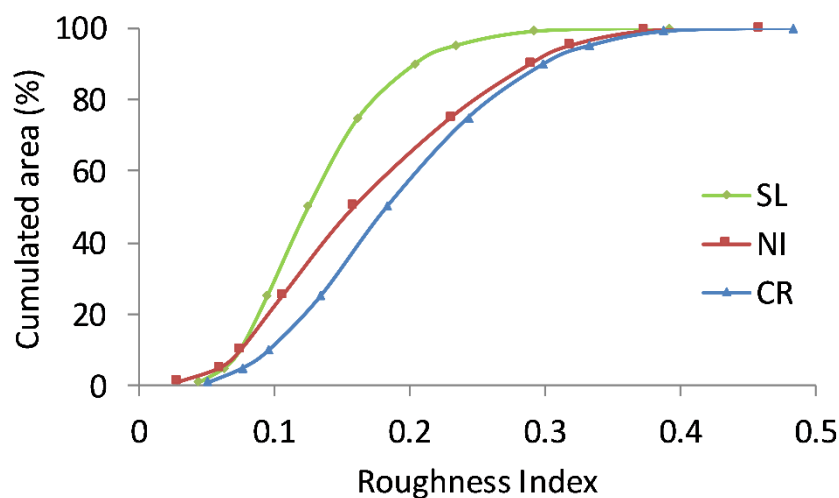
Figure 3. Quantile plot-diagram illustrating the proportion of data in each management type (SL = Salvage Logging, CR = Cut and Release, NI = No Intervention) that is below a given value of Roughness Index (RI). The distance between the plot lines indicates a difference in RI distributions among treatments. Differences in the slope of the curves indicate a difference between the standard deviations.

3.2. Microsite Scale

3.2.1. Solar Radiation

The highest potential incoming shortwave radiation, reaching the ground, was always recorded in SL (Figure 4). A similar pattern with lower values, particularly from October to February, was found in CR. NI always showed the lowest values, especially during the growing season, with the difference from the other treatments exceeding 10 MJ·m^{-2}·d^{-1} from May to July.
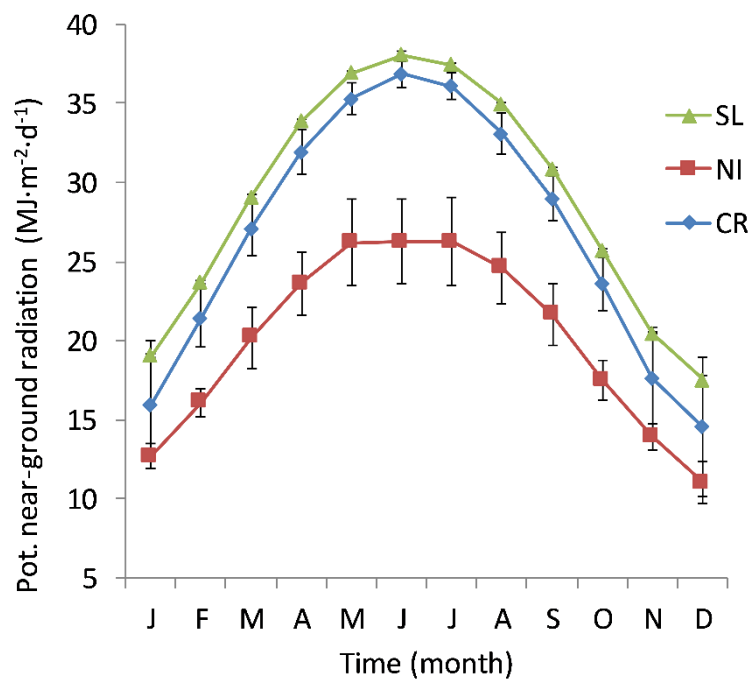
Figure 4. Potential near-ground solar radiation (± SD) estimated for each management type (SL = Salvage Logging, CR = Cut and Release, NI = No Intervention).

3.2.2. Soil Moisture

Soil moisture (Soil Water Content %; SWC) during the growing season was always significantly lower in the SL treatment (Figure 5) (ANOVA with Bonferroni's post-hoc procedure, *p*-value < 0.01), except for late September, when NI was similar to SL. CR always showed the highest soil water content, together with NI in 3 out of 5 measurements. In early August, a significant difference in soil water content was found between all the treatments.
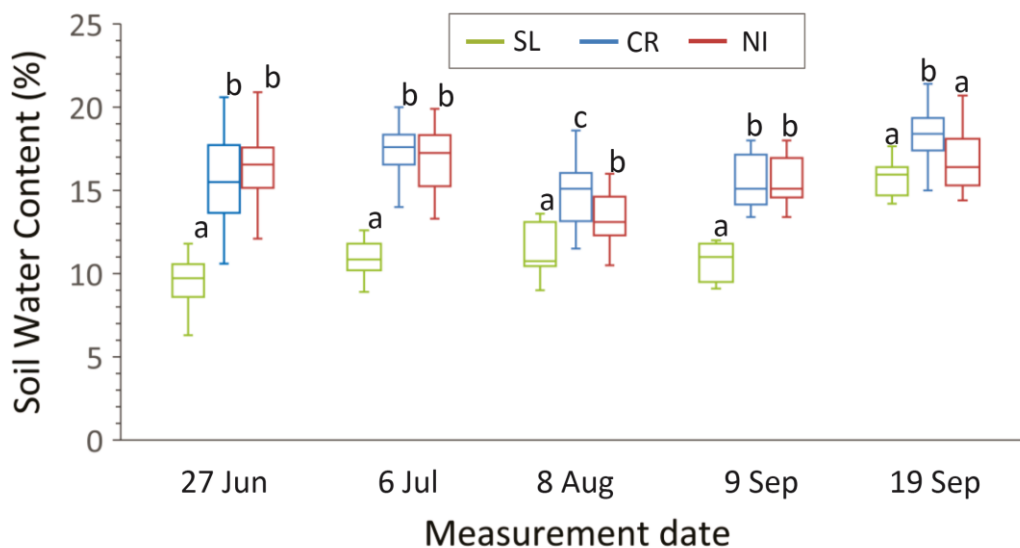
Figure 5. Soil Water Content (%; SWC) by management type (CR = Cut and Release, *n* = 20; NI = No Intervention, *n* = 21; SL = Salvage Logging, *n* = 9). Different letters highlight significant differences between management types (ANOVA with Bonferroni's post-hoc procedure, *p*-value < 0.01).

3.2.3. Soil Temperature

Mean diurnal soil temperature from June to September was higher in SL (18 °C) than in the other treatments (NI: 16 °C, CR: 14 °C). The daily temperature range was also higher in SL, with greater differences compared to the other treatments during the diurnal hours (Figure 6). A maximum soil temperature value of 40 °C was recorded in SL.
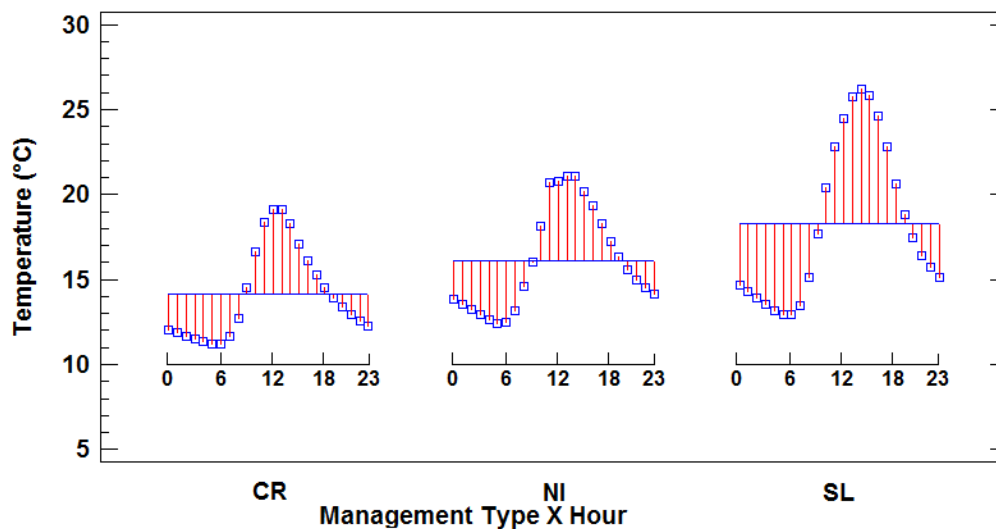
Figure 6. Mean daily soil temperature measured in each treatment from June to September (102 days). The red bars show the hourly (24 h) mean difference with the average value of the period.

4. Discussion

Post-disturbance management through deadwood manipulation has greatly affected microclimatic conditions, modifying the availability and pattern of "safe sites" for germination. The importance of these sites, where preferential recruitment occurs, is particularly evident in climatically stressed sites and arid environments, such as our study area. The abundance and performance of seedlings are often limited by mechanisms operating at fine scales, with the probability of long-term survival being strictly related to the physical habitat surrounding a seedling [32]. Microsite amelioration can be provided by mature plants, shrubs, deadwood, or rocks, through the reduction of soil temperature, and the increase in relative humidity and soil moisture [33–35]. Low values of this latter have been generally associated with a reduced establishment, growth, and survival of tree species [36,37]. In the salvaged sites, microclimatic conditions were harsher (warmer and dryer) compared to the other treatments, in terms of both soil temperature and water content. The presence of deadwood, and especially lying logs, reduced water stress throughout the growing season. Similar results were obtained in other burned pine forests by Maranon-Jimenez et al. [16]. The role of deadwood in seedling establishment has often been addressed as seed substrate and seed trap [38], the former function being strictly related to decay status, and the latter to size and species (e.g., [39]). Deadwood can also greatly influence regeneration processes by modifying microclimatic conditions through the reduction of solar radiation (shading effect) and increasing the moisture absorption [40]. Following a severe wildfire with widespread mortality of adult trees and shrubs, the shelter effect provided by deadwood elements can protect seedlings against high radiation, temperatures, and transpiration rates, that are typical of a post-fire environments in drought-stressed or xeric ecosystems, such as the Mediterranean mountain forests. Previous studies in the same site or in similar stands of the same geographical area [4,21] highlighted a positive anisotropic relationship between seedlings (particularly Scots pine) and deadwood, with regeneration preferentially occurring in the shady sides of shelter elements that offer crucial protection against radiation in the sunniest hours. In the absence of shelter elements, the salvage logged site had

the highest near-ground solar radiation, while standing dead trees still provided enough shade to substantially reduce radiation in the untouched area.

Potential negative effects of high solar radiation on seedlings can be exacerbated by an increase in albedo, due to the exposed mineral soil in the first post-fire years, particularly where salvage logging operations removed dead trees and delayed the recovery of herb and shrub layers [4]. By contrast, the high amount of deadwood on the ground, resulting from the cut and release treatment, greatly increased surface roughness and created microhabitat heterogeneity, which counteracted the consequences of soil exposure in the disturbed areas. Soil temperature was in fact lower in treatments with deadwood release (CR and NI), as found by Castro et al. [17], confirming that deadwood elements provided enough shade to decrease the extreme temperatures. Furthermore, deadwood can play an important role in winter due to its higher absorption of shortwave radiation [15,41], speeding up snow melting, and thus, lengthening the growing period in the surrounding area [15]. Releasing deadwood on the ground leads to more heterogeneous snow cover conditions and accumulation, compared to salvaged sites, producing higher structural diversity of the established forest stand [42], as an indirect and welcome effect.

Soil moisture was always lower in the salvaged site. The absence of shelter elements reducing direct insolation led to a soil temperature increase, as observed in different salvaged sites [17,43]. Seedling establishment and survival on dry south-facing slopes greatly depend on soil water content, especially in a harsh post-fire environments. Indeed, even pioneer and drought-resistant species (i.e., *Pinus sylvestris*), at the establishment stage, need moisture to germinate [4,14].

After high severity fires, soil is generally more vulnerable to degradation, particularly on dry south-facing slopes [44] and where vegetation recovery is hampered by post-fire drought periods. Shade, provided by both standing and lying deadwood elements, can mitigate the harsh conditions, thereby reducing moisture shortage [17].

The fine-scale heterogeneity in unsalvaged stands plays a crucial role in post-fire vegetation recovery [45]. This heterogeneity was successfully measured by surface roughness as a metric of microtopographic variability. In this sense, LiDAR technology proved to be a reliable and cost-effective tool for deriving local surface complexity, especially in the presence of deadwood [46].

Remote sensing analyses for post-fire monitoring are often more devoted to directly quantifying vegetation greenness recovery, comparing different post-disturbance treatments, rather than assessing the variation in the environmental drivers of these processes [47]. Integrating different data sources and spatial scales can overcome the limitations still shown by remote sensing techniques in properly quantifyed post-fire effects [48]. In this study, the combination of remote sensing data and field measurements, at microsite levels, provided a better understanding of the processes involved.

The implications of salvage logging can differ based on type and severity of natural disturbances [49,50]. For instance, following windthrows, the detrimental impact of salvaging on already established regeneration, in the short term, can sometimes be counteracted by enhanced tree species coexistence, in the long term, due to soil scarification by logging operations [51]. In the case of high severity fires the impact on the stand is not limited to canopy trees (like in insect outbreaks or windthrows). Instead, the ecosystem as a whole, including the understory and soil layers, can be deeply altered by the combustion process [44]. With the outcomes of fire directly and indirectly affecting the soil seed bed, any further alteration (e.g., salvage logging), with implications on seedling microclimatic requirements, can be detrimental for the regeneration dynamics.

Higher rates of vegetation recovery in post-fire studies have often been found in unsalvaged areas [17,21,43,52]. In our study site, an earlier inventory of natural regeneration, in salvaged and unsalvaged areas, revealed a higher seedling density in the latter five years after the fire [4]. However, treatments, that are intermediate between salvage logging and no intervention, can be adopted (e.g., CR in our study). These management options could preserve and create microsites for regeneration, accelerating, and mimicking the natural process of snag falling [53]. Releasing deadwood on the ground provides enhanced microclimatic conditions, thus, mitigating the harsh post-fire environment.

Deadwood can enhance seedling establishment also affecting seed dispersal by birds, but it can also potentially create safe sites for animals increasing post-dispersal seed predation [54]. A possible downside of unsalvaged areas is the higher fuel load, particularly from the large amount of heavy fuels, with potential consequences on fire risk in the medium term. However, contrasting results have been published on the effects of post-fire interventions (salvaging versus unsalvaging) on fuel load and characteristics (e.g., size, status, and geometry), which change over time and result in relevant fire risk modifications [3,55].

Salvage logging is often advocated to partially recover the economic value of the affected timber [56]. This can be a major incentive, together with the aim of reducing the risks arising from progressive snag fall in highly frequented areas. When the logged timber has a low value, such as in several mountain forests on the southern slopes of the Alps often affected by wildfire, salvage logging also becomes questionable from an economic point of view, due to its higher costs. In our study site, salvage logging resulted in no economic outputs, with costs five times higher than the cut and release intervention [57]. In a study comparing salvage logging and intermediate interventions in a post-fire environment in Spain, Leverkus et al. [58] obtained similar results, with higher costs and no promotion of restoration success.

The time elapsed between disturbance and salvage logging can also greatly affect its ecological responses [6,59]. In this study, logging activities started two growing seasons after the wildfire. Some studies showed that delayed interventions can reduce soil erosion, since vegetation and litter create natural mulch and protection [60]. However, the already established seedlings can suffer high mortality during salvage operations [6]. There is a need to better understand the impact of this time lag and its management implications, but comparative studies are still lacking.

5. Conclusions

Based on sound scientific evidence, it is possible to conclude that salvage logging can result in several detrimental impacts on the ecosystems where it is conducted (see for instance [6,56,61] for a review on the topic). This practice should, thus, not be considered as the only intervention to be universally applied in any post-fire environment. In the absence of threats, hazards, or societal concerns requiring specific management actions (e.g., public safety, physical hazards for facilities) in the investigated mountain Scots pine ecosystem, no intervention results in better microclimatic conditions for seedling establishment, leaving all deadwood on site. A preferred strategy to speed-up natural processes and further increasing the availability of preferential microsites for regeneration recruitment could fell standing dead trees, while releasing deadwood (at least partially) on the ground. Future research will have to demonstrate whether the potential for a higher density and better performance of natural regeneration, as already highlighted in an earlier seedling survey [4], is confirmed in the medium- and long-term.

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