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# Post-fire salvage logging increases restoration costs in a Mediterranean mountain ecosystem

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**Abstract** Post-fire salvage logging (i.e. felling and removing burnt trees, often eliminating the remaining woody debris) is a practice routinely performed by forest managers worldwide. In Mediterranean-type ecosystems, salvage logging is considered a measure to reduce future reforestation costs, but this assumption remains largely untested. We made a cost analysis of different management schemes, addressing the immediate post-fire burnt-wood management as well as the costs and success of subsequent reforestation efforts. Two experimental 25-ha plots were established in a burnt pine reforestation of SE Spain, in which three replicates of three post-fire treatments were applied: non-intervention (NI), partial cut plus lopping (PCL; felling and lopping off the branches from most of the trees, leaving all biomass in situ), and salvage logging (SL). After 4 years, a mechanised reforestation was undertaken, and seedling mortality was monitored for 2 years. The cost of all management operations was recorded in situ, and the cost of re-planting the dead seedlings was estimated according to the expenses of previous reforestation. Initial cost of wood management was greatest in SL and zero in NI. Reforestation cost was highest in NI and lowest in SL, and seedling-mortality rates proved lowest in PCL (43 % vs. 51 % and 52 % in SL and NI, respectively). Considering all the post-fire management operations, salvage logging did not provide particular economic advantages for forest restoration, and had an overall cost of 3,436 ± 340 €/ha. By contrast, NI and PCL reduced total restoration costs by 50 and 35 %, respectively, and PCL indeed promoted restoration success. We suggest that the full cost of management operations needs to be considered when evaluating the economic implications of post-fire salvage logging.

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**Keywords** Forest economics · Nurse objects · Post-fire restoration · Salvage logging

## Introduction

Fire is a common disturbance in many forests, deeply affecting ecosystems and human societies around the world (FAO 2007; Bowman et al. 2009; Thompson et al. 2009). After fire, human intervention is common in order to restore the forest, as natural regeneration of tree species may be slow or even hampered for different reasons [e.g. seedbed limitations (Mallik et al. 2010), post-fire environmental conditions (Tercero-Bucardo et al. 2007), or seed and seedling predation (Ordóñez and Retana 2004; Denham 2008; Puerta-Piñero et al. 2010)]. In many cases, the final action to restore the forest is the direct planting of tree seedlings (Savill et al. 1997; Zhang et al. 2008; Ahtikoski et al. 2009; Moreira et al. 2012). Before reforestation is undertaken, other management measures are typically implemented, with post-fire manipulation of the burnt wood particularly common (McIver and Starr 2000; Lindenmayer et al. 2008; Castro et al. 2011). Very often, the logs are cut and removed, and the remaining coarse woody debris (e.g. branches and log remnants) is eliminated by chopping, mastication, or fire (Bautista et al. 2004; Castro et al. 2011). Such operations are called post-fire salvage logging (McIver and Starr 2000; Lindenmayer et al. 2008).

Salvage logging is extensively implemented worldwide (McIver and Starr 2000; Lindenmayer et al. 2008; Castro et al. 2011), with several reasons commonly presented to support such actions. In certain regions the main motivation is economic, as timber may still provide commercial benefits after the fire, hence the term "salvage logging" (salvaging part of the capital in the burnt area; McIver and Starr 2000; Lindenmayer et al. 2008). However, in many cases burnt wood is not a profitable resource, e.g. due to small size of the affected timber stand, low quality of the wood, high costs of wood extraction due to landscape features, or regional lack of a timber-production industry. The unprofitable nature of SL is a common situation in mountain forests of the Mediterranean basin (Bautista et al. 2004; Castro et al. 2011). In such cases, the purposes of salvage logging are mainly silvicultural (McIver and Starr 2000; Castro et al. 2010a, 2011), the preparation of the ground for subsequent reforestation being one of the main reasons (Castro et al. 2009). It is assumed that reforesting the area through direct planting will be less costly and more efficient if the reforestation is conducted in an open (salvaged) area than in a place covered by burnt logs and branches (Bautista et al. 2004). The underlying logic assumes that the economic balance of conducting salvage logging is positive when considering reduced reforestation efforts and costs.

The economic balance of conducting salvage logging for reforestation purposes will depend, however, on trade-offs among various factors related to the difficulty of working and operating machinery. For example, the time needed for natural treefall and wood decomposition, or structural characteristics of the stand such as tree size or density, should determine the difficulty of reforestation in unsalvaged areas (Catry et al. 2012), and consequently its cost. Post-fire non-intervention measures may increase the costs of reforestation according to the above-mentioned factors, yet the costs of burnt-wood management would be nil. Moreover, in areas with low accessibility (e.g. remote or roadless areas, or rugged terrain with steep slopes) the removal of burnt logs might not be possible, and hence any reforestation would need to be conducted in the presence of the burnt wood. In summary, less intense post-fire management strategies than salvage logging might raise the costs of future reforestation, but the full economic balance is not clear when considering the lower initial wood-management costs of these alternatives. In this line, economical motivations for any kind of post-fire management should be based on its economic efficiency considering all the steps of management (Mavsar et al. 2012). However, the economics of post-fire management are still one of the unresolved questions regarding fires (Barbati et al. 2010).

In addition to economic issues, post-fire salvage logging may have ecological implications relative to the naturally or artificially established vegetation. For example, the remaining coarse woody debris may act as a nurse structure that provides improved microclimatic conditions (Castro et al. 2011), protection against herbivores or seed predators (Ripple and Larsen 2001; Puerta-Piñero et al. 2010), and enhanced nutrient availability (Brown et al. 2003; Lindenmayer et al. 2008; Marañón-Jiménez 2011). These improved conditions could lead to higher plant survival and growth rates in places where salvage logging is not practised (e.g. Donato et al. 2006; Castro et al. 2011), and thus boost the success of restoration efforts, with economic returns. Contrarily, if salvage logging leads to a greater proportion of reforested trees to die, this could reduce the economic benefits of a less costly initial reforestation under this treatment.

In this study, we analyse the costs of first conducting three different post-fire wood management treatments and then of reforestation. These treatments included Non-Intervention (NI, no action taken), Partial Cut plus Lopping (PCL, an intermediate level of intervention), and Salvage Logging (SL, removal of burnt logs). Reforestation was performed in all the treatments, and mortality of the planted trees was monitored for 2 years. The costs of all the actions (Fig. 1) were monitored, and the cost of subsequent re-planting efforts depending on the mortality rates of the planted seedlings was also calculated. We hypothesise that costs and success of reforestation will depend on previous burnt-wood management, and that the overall cost of restoration will derive from the trade-offs among the differential difficulty of management operations under the three treatments. No analogous studies are available explicitly addressing the full cost analysis of different management schemes for post-fire forest restoration. Few studies are available tackling the economics of stand establishment (Ahtikoski et al. 2009), let alone in combination with post-fire wood management.

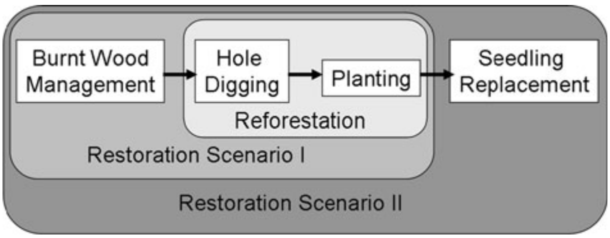


**Fig. 1** Conceptual diagram of the steps involved in the post-fire restoration works, with the nomenclature employed throughout the manuscript. "Burnt-Wood Management" was the first step taken after the fire; it involved cutting the burnt trees (in the SL and PCL treatments) as well as the mastication of the remaining coarse woody debris (in SL only); by definition, none of these actions were taken in NI. "Hole Digging" and "Planting" were performed in all replicates of all treatments, and both these steps are what we call "Reforestation". "Burnt-Wood Management" and "Reforestation" are experimental actions, which we called "Restoration Scenario I". "Seedling Replacement" consists of the reposition of dead seedlings, in our case counted after two growing seasons (this step was not carried out in the field, but the cost was still calculated). The sum of the four steps is "Restoration Scenario II". Treatments are Non-Intervention (NI), Partial Cut plus Lopping (PCL), and Salvage Logging (SL)

## Methods

### Study site and experimental design

The study site is located in the Sierra Nevada Natural and National Park (SE Spain), where in September 2005 a fire burned 1,300 ha of pine reforestations. Two plots of ca. 25 ha were established after the fire at different altitudes. The first plot was located at 1,698 m a.s.l. (Low Plot, hereafter), and the second plot at 2,053 m a.s.l. (High Plot). They were similar in terms of orientation (SW), slope (30.1 ± 1.2 %; throughout the paper, values are mean ± 1 SE of the mean), bedrock type (micaschists) and parameters related to tree characteristics (Table 1). Before the fire, the pine species present in each plot differed according to their ecological requirements along this elevational/moisture gradient. Black pine (*Pinus nigra*) dominated in the Low Plot, and Scots pine (*Pinus sylvestris*) in the High Plot. Both species are native in the region, although they were extensively planted in the area some 40 years earlier for forestry purposes. The plantations were carried out using terraces established with bulldozers, previously a common reforestation practice on hillsides in Spain. Each terrace stairstep is composed of a steep backslope, approx. 1 m high, and bed ca. 3 m wide.

Within each plot, three replicates of three burnt-wood management treatments were implemented in a random spatial distribution: (1) Non-Intervention (NI), where no action was taken. (2) Partial Cut plus Lopping (PCL), where ca. 90 % of burnt trees were cut and felled, with the main branches lopped off but leaving all the biomass in situ. (3) Salvage Logging (SL), where trees were cut and the trunks cleared of branches with chainsaws. Trunks were manually piled in groups of 10–12, and the woody debris was chopped using a tractor with a mechanical masticator. The removal of trunks was planned, but this was eventually cancelled by the Forestry Service due to technical difficulties arising from the spatial arrangement of the plots. However, in the rest of the affected area this step was

**Table 1** Summary of the main characteristics of the study plots

| | Low plot | High plot |
|---|---|---|
| UTM coordinates (*x*,*y*)[a] | 455449; 4091728 | 457244; 4091551 |
| Area (hectares) | 23.9 | 31.7 |
| Altitude (m a.s.l.)[a] | 1,698 | 2,053 |
| Slope (%)[b] | 28.7 | 31.4 |
| Tree density (units/ha)[c] | 1,064 ± 67 | 1,051 ± 42 |
| Basal trunk diameter (cm)[d] | 18.3 ± 0.1 | 15.7 ± 0.1 |
| Dominant species | *P. nigra* | *P. sylvestris* |
| Plant cover (%)[e] | 69.1 ± 1.7 | 72.9 ± 1.6 |

[a] Measured at the centroid of the plot

[b] Average of the nine replicates for each plot

[c] Sampled after the fire by counting the trees in four randomly placed 25 × 25 m quadrates per replicate; values are Mean ± 1 SE

[d] Measured after the fire for 30 random trees per quadrat (120 trees per replicate)

[e] Sampled 2 years after the fire (July 2007) in 8 randomly established 25 m-long linear transects per replicate. The nature of the contact (soil or vegetation) was noted every 50 cm along the transect in the central position and at 1 m to both sides of the transect (150 points per transect, 1,200 per replicate). See Castro et al. 2010a for further details

undertaken. The burnt trees fell naturally, so that 0.0 % had fallen by February 2006 and 2007, 13.3 ± 0.3 % by 2008, 83.5 ± 4.0 % by 2009, and 98.3 ± 1.0 by 2010 (Castro et al. 2010a). Thus, by the time of reforestation (2010; see below), there were nearly no standing trees in any treatment.

The size of the resulting 18 experimental replicates averaged 3.09 ± 0.20 ha, with no significant differences among treatments (Kruskal–Wallis test; $p = 0.24$). There were no differences among treatments (within each plot) in terms of slope, tree density, basal trunk diameter, or tree height (Kruskal–Wallis tests; $p > 0.05$). All post-fire management treatments were implemented between March and May 2006 (about 7 months after the fire). The fire was moderate to high in severity, consuming or totally scorching most of the tree crown. Grasses and forbs dominated the understory during the years of study. Kruskal–Wallis tests showed no differences in plant cover between plots (Table 1; sampled 2 years after the fire), but cover slightly differed among treatments, being 73.9 ± 1.8 % in NI, 71.5 ± 2.0 in PCL, and 67.6 ± 2.2 % in SL (both plots pooled; $F = 2.55$, $df = 2$, $p = 0.052$; see Table 1 for methodology).

Climate in the area is Mediterranean, with hot, dry summers and wet, mild winters. Mean annual rainfall recorded by a nearby meteorological station placed at 1,465 m a.s.l. is 470 ± 50 mm (1988–2008 period). Mean temperature according to another meteorological station placed at 1,652 m a.s.l. is 12.3 ± 0.4 °C, ranging from a minimum yearly average of 7.6 ± 0.5 °C to a maximum of 16.2 ± 0.6 °C (1994–2008 period).

## Site reforestation

Reforestation was carried out by the local Forestry Service (Andalusian Regional Environment Ministry) between March and April 2010 (4 years after burnt-wood management) in all replicates of both plots. A surface of ca. 1.5 hectares was used in each replicate. Around 600 holes of 60 × 60 × 60 cm were made with a mini-tracked excavator 51/70 HP, resulting in an average planting density of 400 seedlings per hectare. Holes were made in terrace beds. The excavator dug the soil, broke it up, and returned it to the hole, leaving a worked soil bulk that could easily be dug by hand. Forestry employees manually planted seedlings from trays after digging the machine-worked soil with a pick. The seedlings, 1–2 years old by the time of planting, were potted in a volume of ca. 300 $cm^3$. The species used were *Crataegus monogyna*, *Berberis hispanica*, *Quercus pyrenaica*, and *Quercus ilex*, all naturally present in the area. 150 seedlings per species were planted in each experimental replicate, totalling 10,800 planted seedlings. The species were planted in a mixed order, thus distributed all across the reforested area. Afterwards, a random subsample of 75 plants per species were tagged and monitored for mortality after two growing seasons (in September 2011). A few seedlings were lost, and therefore eliminated from subsequent analysis. In the end, a total of 4,950 seedlings were monitored for mortality.

## Economic assessment of management operations

Management operation costs were calculated for all the steps described in Fig. 1. The forestry staff registered the resources (man and machine hours, materials) spent for each replicate in every management step in order to calculate these costs. The cost of Burnt-Wood Management operations was calculated considering the hours of machine, workers, and foremen needed. Reforestation costs were similarly calculated, considering the different steps involved and the time employed by employees and machinery, as well as the price of tree seedlings. All costs were later transformed to a one-hectare basis for each treatment. See "Appendix" for cost calculation details.

The total sum of all the steps is here termed "Restoration". For this, we considered two scenarios (Fig. 1). For Restoration Scenario I, we assumed that there was no replacement of dead seedlings. This is a realistic scenario for the local Forestry Service, as very often, due to logistic and economic reasons, the seedlings that do not survive are not replaced (Mavsar et al. 2012). For Restoration Scenario II, we assumed that there was Seedling Replacement. In this case, the number of seedlings being re-planted would be the same as the number of seedlings that died in each replicate. This is also a realistic scenario, as seedling replacement is usually done taking advantage of the holes made in the original Reforestation. As Seedling Replacement was not performed under field conditions, we estimated the Planting costs per seedling as being the same as during Reforestation, multiplying this by the number of dead seedlings per hectare in each experimental replicate (thus excluding the costs of Hole Digging). The costs were estimated at the time when each management step was completed using real costs at that time. All costs are presented in Euros (€).

The Forestry Service sold the wood to a sawmill located 177 km from the burnt site, with a sell price of 30 € per tonne. Costs of wood extraction to the log-loading area with the log-forwarder were 2.5 € per tonne, and the cost of wood transport by truck to the sawmill was 26 € per tonne [a value similar to the cost estimated for wood transport in Spain calculated by Velasco and Hernández (2012)]. As a result, the benefit of wood selling roughly covered the cost of wood extraction plus transport (Direction of the National and Natural Park of Sierra Nevada, personal comm.). We did not consider these variables in our analyses because they added no relevant modification in the global economic balance and, as the potential benefits of salvage logging depend on timber quality, distance from roads, market conditions, and forest ownership (Vallejo et al. 2012), analyzing the cost of extraction and the benefit from the sale would have reduced the portability of our results to other burnt areas.

## Data analyses

The mortality of seedlings was analysed using a generalized linear model (glm) with binomial errors (corrected for overdispersion by using quasibinomial errors) and logit as link function. A full model with plot, treatment, and species was created and simplified, beginning with the highest-order interactions present in the model and hierarchically moving on to the single factors. Significance of the effect of factors and interactions on seedling mortality was checked by performing likelihood ratio tests on the models with and without that specific factor or interaction (Crawley 2007). Significant increases in deviance with model simplification indicated a significant effect of the interaction or factor being removed. The minimal adequate model (MAM) was the one where all non-significant factors or interactions had been removed. To check for *ad hoc* differences among factor levels, the levels were pairwise merged into a single level of the same factor. Significant changes in deviance among the MAM and the model with the new factor, given by likelihood ratio tests, indicated that the merged factor levels significantly differed from one another (Crawley 2007).

Differences in management costs among treatments were analysed for each management operation independently (Burnt-Wood Management, Hole Digging, Planting, and Seedling Replacement), as well as for Reforestation (Hole Digging + Planting), Restoration Scenario I (Burnt-Wood Management + Reforestation), and Restoration Scenario II (all steps added; Fig. 1), using non-parametric Kruskal–Wallis tests. Given that both plots are similar in terms of tree density, tree size, slope, etc. (see Table 1), we assumed that plot is not a factor that determined the costs of the different management steps. We thus pooled plot for these analyses, resulting in a sample size of 6 replicates per treatment. Where treatment had a significant effect, differences among treatment levels were evaluated by a non-parametric multiple comparison test for balanced data (Nemenyi test; Zar 1996).

For analyses, we used R, version 2.12.0 (R Development Core Team 2010).

## Results

Seedling mortality differed among treatments, the lowest value being recorded in PCL (43 %), followed by SL (51 %), and NI (52 %, all replicates of each treatment pooled; Fig. 2, Table 2). Mortality was lower in the High Plot, and also differed among species, although the pattern was consistent across treatments and plots, as reflected by the lack of interactions among factors (Table 2; overall mortality: *Q. ilex*, 40 %; *C. monogyna*, 41 %; *Q. pyrenaica*, 51 %; *B. hispanica*, 60 %).

The cost of Burnt-Wood Management significantly differed among treatments ($\chi^2 = 15.30$, $df = 2$, $p = 0.0005$), being zero in NI and highest in SL (Fig. 3a). The cost of Hole Digging differed slightly among treatments ($\chi^2 = 5.77$, $df = 2$, $p = 0.06$), being lowest in SL (407 ± 23 €/ha), followed by PCL (545 ± 57 €/ha), and NI (559 ± 32 €/ha; all costs of reforestation actions correspond to 1 ha planted with 400 plants). The cost of Planting did not differ among treatments ($p = 0.45$), averaging 504 ± 48 €/ha. The Reforestation cost (adding Hole Digging and Planting) significantly varied with treatment ($\chi^2 = 7.05$, $df = 2$, $p = 0.03$; Fig. 3b), with the highest value in NI and the lowest in SL. Seedling Replacement costs did not differ among treatments (Kruskal–Wallis test,

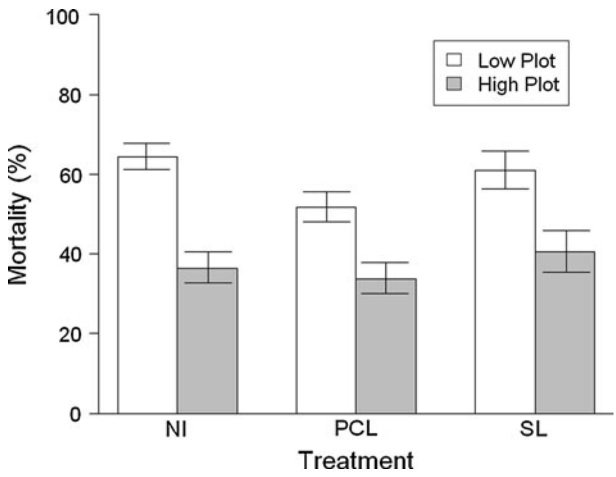


**Fig. 2** Seedling mortality after 2 years according to the burnt-wood management treatment in both plots. Treatments are Non-Intervention (NI), Partial Cut plus Lopping (PCL), and Salvage Logging (SL). Among treatments, only NI and SL did not have significantly different mortality rates ($p = 0.96$). *Error bars* indicate ± 1 SE of the mean

**Table 2** Generalized linear model for seedling mortality

| Factor/interaction | *df* | Δ Deviance | *p* value (*F* test) |
|---|---|---|---|
| Species | 3 | 140.87 | **<0.0001** |
| Plot | 1 | 257.13 | **<0.0001** |
| Treatment | 2 | 37.00 | **0.02** |
| Species × treatment | 6 | 6.08 | 0.97 |
| Species × plot | 3 | 3.00 | 0.90 |
| Treatment × plot | 2 | 4.67 | 0.63 |
| Species × treatment × plot | 6 | 15.42 | 0.82 |

Results shown for each term are those of the likelihood ratio tests among models with and without that term. For each term removed, the degrees of freedom of the interaction or factor of interest, the increase in deviance that is produced by removing it from the model, and the *p* values associated with that increase, are shown. Significant results are highlighted. *Ad hoc* analyses show that, among species, only *Q. ilex* and *C. monogyna* did not significantly differ from one another in terms of mortality ($p = 0.72$), and among treatments only NI and SL did not show significantly different mortality rates ($p = 0.96$)

$p = 0.58$; Fig. 3c). Restoration Scenario I costs significantly varied with treatment ($\chi^2 = 14.36$, $df = 2$, $p < 0.001$; Fig. 3d). Finally, Restoration Scenario II costs significantly varied with treatment ($\chi^2 = 12.12$, $df = 2$, $p < 0.005$), being greatest in SL (3,436 ± 340 €/ha), followed by PCL (2,258 ± 187 €/ha), and NI (1,707 ± 160 €/ha; Fig. 3e).

## Discussion

Our results show that the overall cost of post-fire restoration, including the cutting and extraction of the burnt wood as well as the posterior reforestation and seedling replacement actions, was clearly greater (as much as 100 %) for salvage logging than for the intermediate or non-intervention treatments. As expected, the experimental reforestation costs were lowest in SL due to the greater difficulty for hole-digging machinery, as well as for forestry staff, to work in unsalvaged areas (Catry et al. 2012). The felled logs and collapsed branches represented obstacles for post-fire forestry work that were greatly avoided when the burnt biomass was removed. In fact, this is one of the reasons for performing salvage logging in areas where it is unprofitable (Castro et al. 2009). However, while the differences in reforestation costs among treatments in our study were counted in hundreds of Euros per hectare, the differences in burnt-wood management costs were an order of magnitude greater, and thus offset the higher cost of reforestation in the non-SL treatments. In addition, seedling mortality was similar (NI treatment) or lower (PCL treatment) than in salvaged areas, with the potential to affect costs of seedling replacement whenever this step is conducted. Lower seedling mortality in PCL is consistent with results found for natural regeneration of a pine species in this burnt area (Castro et al. 2011), and it is likely promoted by the improvement of microclimatic conditions by logs and branches (acting as nurse structures; Castro et al. 2011) and by the increase in soil nutrients through decomposition in relation to both SL and NI (Marañón-Jiménez 2011). In summary, less intense post-fire management than salvage logging provided an overall reduction of restoration costs and even increased reforestation success.

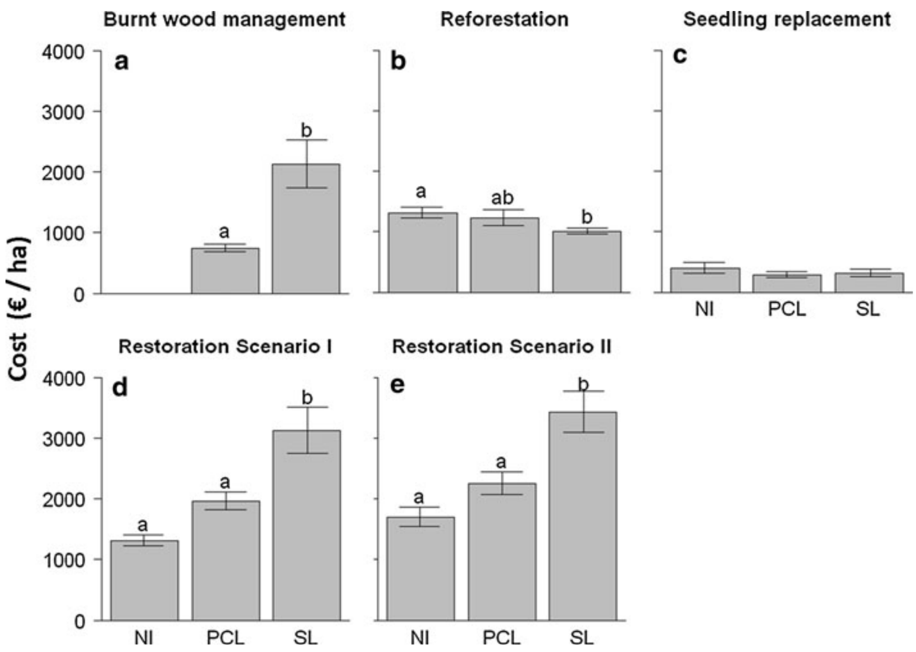


**Fig. 3** Costs of the steps involved in post-fire restoration relative to the burnt-wood management treatment. Burnt-Wood Management **a** involves the cutting of trees (carried out in PCL and SL) and the elimination of remaining coarse woody debris (only performed in SL); by definition, the cost of this in NI is nil. Reforestation **b** includes Hole Digging and seedling Planting at a density of 400 seedlings/ha. Seedling Replacement **c** takes into account the cost of re-planting the dead seedlings in each replicate, using the existing holes. Restoration Scenario I **d** includes Burnt-Wood Management and Reforestation (**a** + **b**). Restoration Scenario II **e** is the sum of these and Seedling Replacement (**a** + **b** + **c**). Values shown in the plots are means ± 1 SE (of the mean) for one hectare. Different letters show significant differences among treatments at $p = 0.1$ from *ad hoc* Nemenyi tests. For Burnt-Wood Management, as costs of NI were nil by definition, differences among PCL and SL were given by a Mann–Whitney *U* test. Treatments were: Non-Intervention (NI), Partial Cut plus Lopping (PCL), and Salvage Logging (SL)

Despite the greater restoration cost of salvage logging in this study, it is important to bear in mind that costs are context-dependent, and that a large set of management needs and decisions are based on site characteristics. For example, in many areas of the planet, the burnt wood still provides economic benefits (Van Nieuwstadt et al. 2001; Brown et al. 2003; Lindenmayer et al. 2008). Salvage logging is also performed for reasons other than to facilitate future reforestation, such as for pest and fire control, and aesthetic reasons (McIver and Starr 2000; Bautista et al. 2004; Noss and Lindenmayer 2006; Lindenmayer et al. 2008; Castro et al. 2010a). Although these reasons are controversial and recent studies are showing that the presence of burnt wood is not necessarily related to greater fire or pest risk (Ross 1997; Donato et al. 2006; Thompson et al. 2007; Jenkins et al. 2008; Toivanen et al. 2009), the overall fact is that the consequences of different post-fire burnt-wood management largely depend on the particular circumstances of the affected area. For example, in our study case the trees were relatively small (dbh ca. 13 cm), and the area is windy and snowy in the winter. All this implies that (1) trees did not provide commercial benefits (in addition to the lack of a local wood industry), (2) trees fell in a relatively short time span (4 years), and (3) the branches collapsed rapidly due to the snow load, eliminating structural elements that would have hampered reforestation. In fact, it was a surprise that the reforestation could be carried out mechanically even in the non-intervention treatment. All this added up to the higher costs of salvage logging operations with respect to the other treatments, showing that the final outcome will depend on structural particularities of the burned stand as well as on local market conditions.

In addition to the evaluation of the direct costs of management operations, the results of this study could be magnified in economic terms if other ecosystems services were considered. There is an increasing call to implement less intense post-fire management operations based on the contention that burnt wood is an essential ecosystem component that may affect a large set of ecosystem functions and processes (McIver and Starr 2000; DellaSala et al. 2006; Lindenmayer and Noss 2006; Lindenmayer et al. 2008). In fact, salvage logging has been shown to increase the levels of erosion in relation to non-salvaged areas (Inbar et al. 1997; Karr et al. 2004), degrade watersheds (Karr et al. 2004), and reduce animal diversity and species richness (Haim and Izhaki 1994; Hebblewhite et al. 2009; Castro et al. 2010b; Bros et al. 2011) as well as seed dispersal by birds (Rost et al. 2009, 2010), nutrient availability for plants (Marañón-Jiménez 2011), and carbon sequestration (Serrano-Ortiz et al. 2011). These are essential supporting and regulating ecosystem services (Millennium Ecosystem Assessment 2003; United Nations Environment Programme 2010) that may be evaluated in economic terms (Costanza et al. 1997; Heal 2000; Farber et al. 2002; Hougner et al. 2006), and if accounted for they would likely increase the economic benefit of management regimes less intense than salvage logging.

In summary, our study provides an evaluation of the costs of different management schemes addressing the immediate post-fire management of the burnt wood as well as the costs and success of subsequent reforestation efforts. The results show that, from an economic point of view, post-fire salvage logging was not the best option, and that less intensive post-fire management may lead to cost reductions and increased reforestation success. The cost-benefit output of salvage logging will depend on the socio-economic and the ecological contexts of the affected area, and it might even be economically positive in other circumstances. However, our results clearly support the contention that these kinds of trade-offs should be carefully evaluated before post-fire management actions are taken with economic aims.

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## Appendix

See Table 3.

**Table 3** Costs per hectare of the different management operations in the experimental replicates

| Plot | Treat | Repl | Monitored plants | Mortality (%) | Cost Burnt Wood Mgt | Cost Hole Digging | Cost Planting | Cost Seedling Replacement | Cost Restoration Scenario I | Cost Restoration Scenario II |
|---|---|---|---|---|---|---|---|---|---|---|
| Low | NI | 1 | 287 | 74.6 | 0.0 | 489.0 | 1,045.0 | 779.2 | 2,313.2 | 1,534.0 |
| Low | NI | 2 | 291 | 61.5 | 0.0 | 444.5 | 572.2 | 351.9 | 1,368.6 | 1,016.7 |
| Low | NI | 3 | 290 | 56.9 | 0.0 | 555.7 | 721.1 | 410.3 | 1,687.0 | 1,276.8 |
| Low | SL | 1 | 295 | 73.9 | 902.7 | 466.7 | 751.1 | 555.1 | 2,675.7 | 2,120.6 |
| Low | SL | 2 | 256 | 48.4 | 2,056.6 | 333.4 | 630.0 | 305.2 | 3,325.1 | 3,020.0 |
| Low | SL | 3 | 300 | 60.7 | 2,530.1 | 355.6 | 653.1 | 396.2 | 3,934.9 | 3,538.8 |
| Low | PCL | 1 | 275 | 57.1 | 708.3 | 644.6 | 591.6 | 337.8 | 2,282.3 | 1,944.5 |
| Low | PCL | 2 | 300 | 58.7 | 626.6 | 377.8 | 652.2 | 382.6 | 2,039.3 | 1,656.7 |
| Low | PCL | 3 | 272 | 39.0 | 906.7 | 355.6 | 529.0 | 206.2 | 1,997.5 | 1,791.3 |
| High | NI | 1 | 298 | 37.2 | 0.0 | 644.6 | 741.0 | 276.0 | 1,661.6 | 1,385.6 |
| High | NI | 2 | 194 | 29.4 | 0.0 | 600.1 | 498.8 | 146.5 | 1,245.4 | 1,098.9 |
| High | NI | 3 | 292 | 42.8 | 0.0 | 622.3 | 940.3 | 402.5 | 1,965.2 | 1,562.7 |
| High | SL | 1 | 300 | 38.7 | 2,155.3 | 422.3 | 539.8 | 208.7 | 3,326.1 | 3,117.4 |
| High | SL | 2 | 312 | 36.4 | 1,403.7 | 400.1 | 482.0 | 271.9 | 2,557.6 | 2,285.7 |
| High | SL | 3 | 297 | 26.6 | 3,699.7 | 466.7 | 498.8 | 132.7 | 4,797.9 | 4,665.2 |
| High | PCL | 1 | 183 | 38.8 | 848.6 | 622.3 | 1,212.7 | 470.5 | 3,154.1 | 2,683.6 |
| High | PCL | 2 | 284 | 27.5 | 500.2 | 666.8 | 587.1 | 161.2 | 1,915.4 | 1,754.1 |
| High | PCL | 3 | 224 | 33.0 | 883.0 | 600.1 | 508.5 | 168.0 | 2,159.5 | 1,991.6 |

The prices employed are standard TRAGSA (Empresa de Transformación Agraria, S.A.) prices, which at the time of the experiment were the guideline for reforestations by the local Forestry Service. For every cost column, the hours spent by the machinery and staff in each action were multiplied by the corresponding TRAGSA costs. The costs used were as follows: 14.55 €/h for workers, 15.87 €/h for foremen, 51.91 €/h for the machine used for Hole Digging, and 62.87 €/h for the machine used for woody debris mastication during Burnt-Wood Management (machines include driver). One foreman is needed for every 6 workers. The cost of one seedling was put at 0.34 €. An additional 7 % of indirect costs was added for each management step (office work, transportation, etc.). The costs of Seedling Replacement covered the replanting of seedlings that died after 2 years of plantation, using the holes initially dug by the machinery. Scenario I of Restoration includes Burnt-Wood Management, Hole Digging, and Planting, and Scenario II covers all these as well as Seedling Replacement. Data on timings were provided by EGMASA (Empresa de Gestión Medio Ambiental S.A.), who was responsible for the management operations. Costs are given as €/ha. Treatments are Non-Intervention (NI), Partial Cut plus Lopping (PCL), and Salvage Logging (SL)

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