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Pinus sylvestris forest regeneration under different post-fire restoration practices in NW Italian Alps

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Abstract
It is frequently believed that a post-fire environment requires immediate actions in order to be restored. Salvage logging followed by plantation are common post-fire restoration practices in many forests of North-western Italian Alps.
The objectives of this study were to assess the impact of active and passive management techniques on the restoration of a burned area of the Aosta Valley and to determine which approach is the most suitable for enhancing *Pinus sylvestris* regeneration after stand replacing wildfires.
The influence of five management options (no intervention; salvage logging; broadleaves plantation; *Larix decidua* plantation; *P. sylvestris* or *Pseudotsuga menziesii* plantation) and environmental variables on natural regeneration structure and composition was evaluated through direct gradient analysis.
P. sylvestris and *Populus tremula* were the dominant tree species (40% and 29% respectively) in the regeneration layer. Density, size, and structural diversity of natural regeneration were higher in the no intervention area. The proximity to forest edge was found to be the most important environmental variable.
This study provided evidence that taking advantage of natural restoration processes may be a suitable alternative strategy to the active restoration practices adopted according to the Aosta Valley policy of post-fire management.

Keywords
Post-fire management, Natural regeneration, Stand-replacing fire, Salvage logging, *Pinus sylvestris* L., Aosta Valley

1. Introduction

The post-fire restoration of burned areas is a major task for national and regional governments and for forest managers. Concern about this topic is likely to intensify since fire regimes are widely expected to be altered worldwide by an increase in frequency, extent and/or intensity of wildfire events due to ongoing climate changes (Dale et al., 2001; Cary, 2002; Flannigan et al., 2005; Westerling et al., 2006).
The importance of natural disturbances as fundamental ecosystem processes in creating habitats and resources vital to biodiversity has been increasingly recognized by scientists (e.g. Sousa, 1984; Parr and Andersen, 2006). Early successional forests resulting from natural disturbances are considered among the most biologically diverse of all forest conditions (Dellasala et al., 2006; Noss et al., 2006). Biological legacies (Franklin et al., 2000) remaining following natural disturbances at the stand and landscape levels significantly influence through their type, number and spatial arrangements the patterns of recovery of a post-disturbance ecosystems (Lindenmayer and Franklin, 2002).

Nevertheless, a forest affected by a disturbance is often perceived negatively as a destroyed or damaged landscape. Consequently, it is frequently believed that a post-fire environment requires immediate actions in order to be restored (Beschta et al., 2004), with the logical consequence to promote an active approach as necessary and beneficial.

A common practice is salvage logging, defined as the harvesting of dead or damaged trees from sites after natural or human-caused disturbance events (Lindenmayer and Noss, 2006; Lindenmayer et al., 2008). Its ecological consequences are debated in many parts of the world and its application is still controversial (for a comprehensive review see McIver and Starr, 2000; Lindenmayer et al., 2008; Peterson et al., 2009). Post-disturbance logging is frequently motivated by the pervasive belief that any high severity disturbance destroys forest ecosystems and should thus be avoided or remediated (Foster and Orwig, 2006). Despite its many justifications, from economics to public safety, salvage logging is often associated with a lack of aesthetic appreciation for disturbed vegetation and a limited understanding of the ecological role of natural disturbances (Noss and Lindenmayer, 2006).

Effects of post-disturbance interventions on forest ecosystems can many times be more severe than those produced by the initial disturbance (Noss and Lindenmayer, 2006). In addition, the combined impact of natural and human disturbances still has to be clarified (Lang et al., 2009), with a particular focus on its potential to create new ecological conditions, as already suggested by a few authors (Donato et al., 2006; Lindenmayer and Ough, 2006), possibly altering forest recovery. Salvage logging could thus impair ecosystem restoration (Lindenmayer et al., 2004), particularly when followed by deliberate plantings to restore tree cover (Lindenmayer and Noss, 2006).

Ecologically sound criteria should provide a basis for the definition of effective policies and practices to be promoted and supported in post-disturbance management of forests (Motta et al., 2009). In particular there is a need for the development of regional strategies for post-fire management designed according to the specific requirements and characteristics of regions. Unfortunately there is still a lack of knowledge on the best management techniques to use, even concerning wildfire (Moreira et al., 2009), by far the dominant disturbance type in the existing literature on post-disturbance conditions and management (Lindenmayer et al., 2008).

Restoration activities after major wildfire events in Italy are strongly subject to budget constraints. A greater emphasis is still devoted to suppression rather than restoration, with a consequent unbalanced allocation of resources and priorities.

Current post-fire management activities commonly involve salvage logging operations, sometimes followed by plantation. Erosion stabilization measures are also adopted when necessary. Salvage logging is not applied as a way of minimizing the economic impact of forest fires, since this harvesting activity has usually no or little economic revenue, given the low merchantability of salvaged wood, complex topography and reduced accessibility of burned forests.

In this paper we analysed the impact of different post-fire management activities aiming at restoring a *Pinus sylvestris* L. stand in Aosta Valley, NW Italy. Our objective was to determine which approach, passive or active restoration, is the most suitable for successful regeneration of *P. sylvestris* forests following a high severity wildfire in NW Italian Alps. The study addressed the following questions: (1) what are the natural restoration dynamics of these forests after a stand replacing fire? (2) what is the combined effect of natural disturbance and human intervention on tree regeneration? (3) how effective are current restoration practices and what are their ecological consequences?

2. Methods

2.1. Study area

Aosta Valley is a mountainous autonomous region located in the north-western part of Italy. The region is characterized by a complex geology and abrupt environmental gradients; the mean altitude is about 2100 m a.s.l. and only 20% of the surface is below 1500 m. The main valley axis is

prevalently west-east oriented. The fire regime is characterized by a winter-early spring fire season, with low severity surface fires (average size 7.6 ha; Bovio et al., 2005). An increase in size and intensity of wildfires has been observed over the last decades, with a higher number of large, severe crown fires. These fires usually spread within *P. sylvestris* forests, located in south-facing slopes.
Because the Aosta Valley is a renowned tourist area, the regional policy of post-disturbance management quite often adopts salvage logging followed by planting, as the most appropriate response to a stand replacing fire.
The research was carried out in the main valley of the Aosta Region, in the municipalities of Verrayes and Saint-Denis (45°46'21''N, 7°33'16''E). The altitude of the area ranges between 1135 m and 1480 m a.s.l. and the soils are classified as entisols (Soil Taxonomy USDA). The mean annual precipitation is approximately 600 mm and the mean annual temperature 10 °C.
The tree vegetation consists almost solely of dense even-aged *P. sylvestris* stands, with a sporadic presence of *Larix decidua* Miller, *Picea abies* L. Karst, *Quercus pubescens* Will., *Populus tremula* L., *Betula pendula* Roth. The understory is dominated by *Rosa canina* L., *Rubus fruticosus* L., *Ligustrum vulgare* L., *Berberis vulgaris* L., *Clematis vitalba* L., *Hippophaë rhamnoides* L., *Arctostaphylos uva-ursi* (L.) Spreng., *Thymus vulgaris* L. and *Juniperus communis* L.
The area was severely affected by a wildfire in September 1995. The fire was a wind-driven stand replacing fire, quite unusual in terms of type, intensity and season of occurrence from the typical fire event in Aosta Valley. Within the fire perimeter 28 ha of the stands were completely killed, 8 ha experienced partial mortality and 16 ha were not covered by forest.
Immediately after the fire, the regional administration approved an experimental reforestation project for the burned area, consisting in salvage logging, site preparation and planting. Both conifers (*P. sylvestris*, *L. decidua*, *Pseudotsuga menziesii* Mirbel) and three different combinations of broadleaves (including *Fraxinus excelsior* L., *Acer pseudoplatanus* L., *Sorbus aucuparia* L., *Sorbus aria* L., and *Prunus avium* L.) were planted.

2.2. Sampling design
Sample plots of 10 x 10 m (0.01 ha) were randomly positioned using the *Random point generator* (ArcGis 8.2 ESRI) and located on the ground with a GPS unit. A total of 92 plots were established.
Plots were grouped according to a gradient of increasing post-disturbance management severity produced by different management options (MO, Table 1) on natural restoration processes in terms of soil compaction and erosion, competition, removal of biological legacies: MO1 - no intervention; MO2 - salvage logging; MO3 - salvage logging followed by broadleaves plantation (*broadleaves*); MO4 - salvage logging followed by *L. decidua* plantation (*larch*); MO5 - salvage logging followed by *P. sylvestris* or *P. menziesii* plantation (*conifers*).

2.3. Data collection
The field work was carried out in summer 2007. In each plot all saplings (regeneration taller than 10 cm and with diameter at 130 cm above ground (DBH) lower than 7.5 cm were identified to species and classified as natural or artificially regenerated. For each sapling the diameters at 130 cm above ground, at 50 cm and at ground level (root collar diameter or RCD) were measured to the nearest 0.1 cm. Sapling height (to the nearest cm) and location (x, y) were also recorded. Game damage within the study area was assessed by counting the number of saplings presenting signs of browsing or fraying. In order to define the mortality rate of the artificial regeneration seven years after the plantation, we recorded the number of dead and missing plants.
To better analyse natural restoration processes the floristic composition was assessed in the no intervention plots using the vertical point-quadrat method (Daget and Poissonet, 1971; Jonasson, 1988) along transects located on both plot diagonals (n=66). In the transects, at each 50-cm interval, shrub and herb species touching a steel needle were identified and recorded.

2.4. Regeneration descriptors

Both classical stand structure measures (basal area of natural regeneration=BA-n, density=De) and structural diversity indices were used to describe natural regeneration characteristics. The distribution pattern of species was explored through the Brillouin index (HB) (Brillouin, 1956; Magurran, 2004) and the relative dominance of *P. sylvestris* and *P. tremula* (the two most abundant species among natural saplings). The size differentiation between trees was assessed with the tree height diversity (THD) index (Kuuluvainen et al., 1996), adopting 25-cm-deep horizontal layers, and the tree diameter diversity (TDD) index (Rouvinen and Kuuluvainen, 2005) applied to 1 cm RCD classes.

2.5. Environmental parameters

In order to analyse the effect of environmental parameters on natural regeneration we considered topographic variables, distance to seed source, and ground cover for each plots through 7 descriptors obtained both from field survey collection and GIS-derived data.

Elevation and slope steepness were derived from a 10-m resolution digital elevation model. Geographic coordinates of forest patches were derived using a recent aerial orthophotograph (Regione Valle d'Aosta, 2001) and proximities to forest edges and green islands of surviving trees were calculated in ArcGIS using Euclidean distances. Herb, shrub and bare soil cover were measured by visually estimating their percent cover within each plot.

2.6 Data analysis

Multivariate ordination and grouping methods as well as ANOVA were combined to assess the impact of post-disturbance management and environmental variables on natural regeneration of tree species.

90 out of 92 plots were considered for the investigation after performing an outlier analysis.

To address effects produced by the different restoration practices, basal area, RCD, and height of natural tree saplings were evaluated among the 5 MOs through Multi-response Permutation Procedure (MRPP) and one-way ANOVA tests respectively. MRPP permitted to test differences between and homogeneity within MOs (Zimmerman et al., 1985). Differences in mean RCD and height of natural *P. sylvestris* and *P. tremula* among MOs were tested by one-way ANOVA (SPSS® version 16.0). When the expectations for parametric statistical tests about normal distribution and equivalence of variances were not fulfilled, logarithmic transformation ($\log_{10}$) was carried out for height and diameter. In the case of significant effect ($p < 0.05$), post-hoc comparisons were made using the Ryan-Einot-Gabriel-Welsch (REGW) F test.

Three data sets were used in the ordination analyses: i) natural regeneration structure (7 variables x 90 plots); ii) environmental variables (7 variables x 90 plots); iii) herb and shrub layer composition (48 species x 33 plots).

The variability of natural regeneration structure in relation to management type and environmental factors was analyzed through redundancy analysis (RDA) (Rao, 1964; ter Braak and Prentice, 1988). This direct gradient analysis is a constrained ordination method that was used to investigate the variability explained by the explanatory variables and their correlation with regeneration structure variation.

Separate multivariate analyses on a reduced number of plots (n = 33, MO1 "no intervention") were performed using the herb and shrub layer cover as response data and the environmental variables and the regeneration composition as explanatory variables. The Canonical Correspondence Analysis (CCA) was used to explore the community structure related to the measured environmental variables, in order to understand the importance of underlying gradients determining the distribution of herb and shrub vegetation. The variability of natural regeneration in relation to the herb and shrub layer was then assessed through RDA.

Redundancy analyses were performed using Canoco® (Ter Braak and Smilauer, 1998), while MRPP and CCA multivariate analyses were performed using the PC-ORD statistical package (McCune and Mefford, 1999). The statistical significance of all ordination analyses was tested by the Monte Carlo permutation method based on 10000 runs with randomized data. Outlier analysis was also performed using PC-ORD.

To characterize the spatial pattern of natural regeneration within the plots, Point Pattern Analysis techniques were applied by means of Ripley's *K(t)* (Ripley, 1977). Since the cumulative *K*-function confounds effects at larger distances with effects at shorter distances (Getis and Franklin, 1987), the *O-ring* function (Wiegand et al,. 1998) was adopted as complementary analysis. The software PROGRAMITA (Wiegand and Moloney, 2004) was used for both Ripley's and *O-ring* functions.
The analyses were only realized for plots having more than 10 saplings, applying a 0.25 cm lag distance and not exceeding half side (5 m) of the study area in order to limit the influence of the margin effects (Haase, 1995). Complete spatial randomness (CSR) was adopted as null model.

3. Results

3.1. Composition and density of tree saplings

Natural regeneration mean density was 1551 saplings · ha^{-1} and it was particularly abundant in MO1 (no intervention), MO3 (plantation with broadleaves) and MO4 (plantation with *L. decidua*).
P. sylvestris and *P. tremula* saplings accounted for the greatest part of the natural regeneration with 621 and 458 saplings · ha^{-1} respectively. The highest density of these species was found in MO1 and MO3 (Table 2).
Planted broadleaved species and larch emerged as having a very high mortality rate (36% and 32% respectively), while evergreen conifers showed a lower mortality (4%).
Wildlife pressure was very low since damages were found only on 3.4% and 2.1% of artificial and natural regeneration respectively.
Basal area of natural saplings varied significantly among MOs considering the overall species (MRPP: T = -4.645, p < 0.001). The MRPP pairwise comparisons between MOs identified MO1 as being significantly different from all the others.
Diameter and height of natural *P. sylvestris* saplings varied significantly among MOs (ANOVA, F = 11,24 p < 0.0001 and F = 12,96 p < 0.0001 respectively, Fig. 1).
P. sylvestris mean height ranged from 44 cm (MO3 and MO5) to 108 cm (MO1) and mean diameter varied from 1.17 cm (MO5) to 3.40 cm (MO1). *P. tremula* did not show significant differences between MOs. Mean height varied from 121 cm (MO1) to 185 cm (MO4) whereas mean diameter ranged from 1.74 cm (MO1) to 2.53 cm (MO4).

3.2. Natural regeneration structure

The influence of MO and environmental factors on the structure of natural regeneration of tree species was analyzed through direct gradient analysis (Table 3).
Redundancy analysis of natural regeneration structure related to the examined management options and basal area of artificial regeneration is shown in Fig. 2. The first and second axes accounted for 18.3% and 1.7% of the total variation respectively. A clear separation between artificial and natural regeneration emerged from the ordination graph. The MO1 was positively associated to density (BA-n, De) and diversity (THD, TDD, HB) of tree seedlings. *P. sylvestris* presence was positively correlated to plots managed with broadleaves plantation.
The relationships between natural regeneration structure and environmental variables were analyzed through redundancy analysis and emerged as significant (Table 3, Fig. 3). The first and second axes accounted for 18.0% and 2.7% of the total variation respectively. *P. sylvestris* saplings were positively associated to harsh site conditions (steep slope and bare soil), shrub cover (e.g. *Arctostaphylos uva-ursi* (L.) Spreng and *Juniperus communis* subsp. *communis* L.) and negatively

to herbs cover. High values in density and diversity of tree saplings were found in higher elevation plots which were also located close to the forest edge.
Ripley's *K(t)* for natural regeneration (conducted in 65 out of 92 plots) revealed a clumped distribution of saplings (data not shown) in the great majority of plots (75%). The tendency toward aggregation was confirmed at short distances by the *O-ring* analysis.

3.3 Herb and shrub composition

Herb and shrub species-environment relationships were evaluated by using Canonical Correspondence Analysis (CCA) direct gradient analysis (Fig. 4). The first axis (eigenvalue = 0.197) was positively correlated to elevation and negatively with bare soil. Many species, closely related to sub-continental grassland (Schawabe and Kratochwil, 2004), were mostly located at relative high elevation with low bare soil percentage (e.g. *Festuca valesiaca, Koeleria valesiaca, Hippocrepis comosa,* and *Thesium linophyllum*). In very steep sites, where topography amplifies dry soil condition and disturbance by erosion, many xerophilous chamaephytes growing in open and rocky habitats were found (e.g. *Arctostaphylos uva-ursi* and *Fumana procumbens*). The second axis (eigenvalue = 0.084) was strongly correlated to proximity to forest edges, where mesophilous grasses (e.g. *Trisetum flavescens, Festuca rubra,* and *Poa pratensis*) and species related to fringe communities (e.g. *Rubus fruticosus* and *Epilobium angustifolium*) were dominant. Green islands of woody plants did not emerge as having an important influence on species composition.
Species composition of the herb and shrub layer was significantly related to the tree regeneration composition (Table 3). The first and second RDA axes accounted for 21.1% and 7.6% of the total variation respectively. *P. sylvestris* and *Q. pubescens* saplings were associated to xeric species from rocky habitats and debris (e.g. *Arctostaphylos uva-ursi, Fumana procumbens, Scutellaria alpina,* and *Astragalus monspessulanus*) (Fig. 5). At the opposite, *Salix caprea* and *P. tremula* were mostly related to moderately less xerophytic species from grass-dominated ecosystems (e.g. *Festuca valesiaca, Koeleria valesiaca, Hippocrepis comosa,* and *Thesium linophyllum*).

4. Discussion

Information on the spontaneous development of natural *P. sylvestris* forests in Aosta Valley after high severity wildfires is still fragmented and incomplete since burned stands are immediately subjected to the traditional forest management practice of logging and removing dead and damaged trees.
Natural regeneration in our study area was more abundant where no post-fire intervention was realized. High values in sapling density were also found among plots planted with broadleaves and *L. decidua*. These two MOs, both characterized by deciduous light crowns, experienced very high mortality of artificial saplings, thus resulting in reduced competition with natural regeneration. On the contrary planted *P. sylvestris* showed the highest growth rate among artificial saplings and appeared to hinder the establishment and development of natural origin individuals.
Salvage logged, non planted areas presented a very low natural regeneration density, associated with a dense herb layer. One of the first consequences of salvage logging within the first few years after wildfire is killing many recently germinated or recovering plants through mechanical disturbance (Lindenmayer and Ough, 2006). Moreover human intervention after the fire may have caused delay in succession because of soil compaction and competition with the artificial plantation. Post-fire treatments such as salvage logging and/or plantation with non native species can alter succession dynamics and delay restoration by removing biological legacies or by accentuating damage to soil and water resources (Beschta et al., 2004; Silins et al., 2009).
Our results are consistent with other studies (e.g. Donato et al., 2006; Greene et al., 2006) highlighting that natural regeneration of conifers after a high-severity fire was more abundant in unsalvaged stands, compared to salvaged areas where regeneration was considerably reduced.
Natural regeneration structure was significantly influenced by post-fire restoration activities. The highest values in structural diversity and abundance in natural regeneration were found in the

passive management sites, particularly those close to the forest edge and at higher elevations. A higher heterogeneity in site conditions, resulting for instance from a variable light environment, the wind shield effect or the presence of biological legacies (Murcia, 1995; Gunter et al., 1997; Coop et al., 2010; Yamagawa et al., 2010) provides a possible explanation for their greater diversity in natural regeneration.

A high number of saplings close to the unburned canopy edge can be explained by the coincidence of both high seed availability and environmental conditions conducive to seedling-establishment success (Bonnet et al., 2005).

The abundance of downed deadwood in unsalvaged areas may have contributed to providing favorable sites for regeneration establishment, given the characteristics of high insolation and low precipitation of the studied area. Fallen trees and uprooted stumps most likely resulted in the creation of microsites where more shade and moisture were available for seedlings, stabilizing microclimatic conditions. This facilitation effect could have enhanced regeneration and affected the spatial distribution of saplings (Kuuluvainen and Rouvinen, 2000).

The clumped structure of natural regeneration highlighted in our study appears to be a common pattern in many mountain forests (e.g. Taylor and Halpern, 1991; Lingua et al., 2008; Pardos et al., 2008). The regular spacing in the artificial plantation resulted in an altered structure, not suitable for the restoration of a natural system.

The main species in the natural regeneration layer within the burned area were all light demanding pioneer species, able to thrive in the new conditions originated by the fire (e.g. increased light availability, exposed mineral soil, favorable seedbeds). Except for MO5 plots, *P. sylvestris* was the most abundant species. Steep slopes, mostly near the forest edge, characterized by bare soil or shrub cover emerged to be favorite sites for this conifer. The presence of *P. sylvestris* regeneration proved to be related to the absence of a dense herb cover, associated with xeric species typical of open areas with skeletal soils. The herb layer could in fact be a problem for the recruitment of this pioneer species, both in the establishment phase and for subsequent competition. *P. sylvestris*, even without being a real pyrophyte, behaves like an opportunistic species germinating well in the absence of strong competitors (Nuñez et al., 2003). It was also the only species able to take advantage of the high mortality of the planted broadleaves.

The most critical stage in *P. sylvestris* recruitment is germination and establishment of contact to a stable soil moisture regime since the young seedling is highly dependent on a sufficient water supply (Hille and den Ouden, 2004). The species could thus probably take advantage of the shelter effect provided by the numerous biological legacies left in the unsalvaged area.

The regeneration of *P. sylvestris* seems to be favored by forest fires of medium intensity, which remove organic material maintaining seed trees (Hille and den Ouden, 2004). Although our study area experienced a stand replacing fire front with a very few green islands, the proximity to forest border guaranteed a sufficient seed source. Green islands of woody plants did not emerge as having an important influence on seedling establishment and species composition, probably due to their small surface area and the relative proximity of the forest edge.

Natural *P. sylvestris* saplings were taller and bigger (root collar diameter) in the passive management plots. In the first post-fire years, with a nearly intact crown structure, snags may have provided a direct sunlight exposure protection for young pine seedlings, favoring their development (Martínez-Sánchez et al., 1999).

Logging and planting operations were moreover accomplished respectively 4 and 5 years after the fire, most likely resulting in an intense and prolonged disturbance on soil and already established saplings. Post-fire management activities, despite their restoration purposes, were therefore associated with significant mortality of natural regeneration, with timing of logging certainly playing a critical role. The effects of salvage logging may be highly dependent on when and how it is conducted (Keyser et al., 2009). It is thus crucial to understand how to properly conduct post-disturbance logging to minimize negative consequences (Dellasala et al., 2006).

P. tremula was the second most abundant species in total regeneration, followed by *S. caprea*. The sprouting ability of these broadleaved species provides an explanation for their widespread presence in areas characterized by a dominance of grass species, where obligate seeder species could hardly germinate. In this study, no differences in *P. tremula* size were detected among the analyzed management options. Both gamic and agamic reproduction strategies were used by *P. tremula* for its regeneration in the post-fire environment. The main form of *P. tremula* regeneration is through vegetative reproduction, both in the absence of fire and after low intensity wildfires. Following high intensity events an abundant regeneration of *P. tremula* from seed is also detected (Zasada et al., 1983; Kay, 1993; Schimmel and Ganstrom, 1996).
The implementation of post-fire treatments should be carefully considered. They should be limited to those post-disturbance environments where a facilitation of ecosystem recovery is needed, without nevertheless interfering with natural succession processes (Karr et al., 2004). Natural regeneration is usually cost-effective and promotes a greater diversity of structure and species (Jonášová et al., 2006).
Post-fire management should promote among its priorities the minimization of activities that cause additional damage, prevent reestablishment of native species or alter microclimates (Beschta et al., 2004).
Ecologically informed policies for post-fire management should acknowledge the unique nature of burned forests as ecological communities (Nappi et al., 2004; Hutto, 2006) and the importance of biological legacies for natural development of forests (Franklin et al., 2000). Post-disturbance dynamics are particularly sensitive to conditions immediately following the disturbance event (Platt and Connell, 2003). A greater recognition should thus be achieved on the effects of human disturbances, such as salvage logging or plantation, which could be quite different from those of natural disturbances in isolation (Lindenmayer and McCarthy, 2002).
This study provided evidence that taking advantage of natural restoration processes may be a preferred strategy to salvage logging and replanting in mountain *P. sylvestris* forests of the Aosta Valley. Passive forest restoration proved to be a valid approach in this post-fire environment, where the restoration activities adopted according to the regional policy of post-disturbance management altered natural forest structure and delayed its development.

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References
Beschta, R.L., Rhodes, J.J., Kauffman, J.B., Griesswell, R.E., Minshall, G.W., Karr, J.R., Perry, D.A., Hauer, E.R., Frissell, C.A., 2004. Postfire management on forested public lands of the western United States. Conserv Biol 18, 957-967.
Bonnet, V.H., Schoettle, A.W., Shepperd, W.D., 2005. Postfire environmental conditions influence the spatial pattern of regeneration for *Pinus ponderosa*. Canadian Journal of Forest Research 35, 37-47.
Bovio, G., Camia, A., Guglielmet E., Cesti, G., 2005. Piano regionale per la programmazione delle attività di previsione, prevenzione e lotta attiva contro gli incendi boschivi. Regione Autonoma Valle d'Aosta, Assessorato Agricoltura, Risorse Naturali e Protezione civile, Dipartimento risorse naturali, Corpo forestale, Protezione civile e antincendio.
Brillouin, L., 1956. Science and information theory. Academic Press, New York.

Cary, G.C., 2002. Importance of a changing climate for fire regimes in Australia. In: Bradstock, R.A., Williams, J.E., Gill, A.M. (Eds.), Flammable Australia: The Fire Regimes and Biodiversity of a Continent. Cambridge University Press, Melbourne, Australia, pp. 26-48.
Coop, J.D., Massatti, R.T., Schoettle, A.W., 2010. Subalpine vegetation pattern three decades after stand-replacing fire: effects of landscape context and topography on plant community composition, tree regeneration, and diversity. J Veg Sci 21, 472- 487.
Daget, P., Poissonet, J., 1971. Une métode d'analyse phytologique des prairies. Ann Agron 22, 5 - 41.
Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J., Wotton, B.M., 2001. Climate change and forest disturbances. Bioscience 51, 723-734.
Dellasala, D.A., Karr, J.R., Schoennagel, T., Perry, D., Noss, R.F., Lindenmayer, D., Beschta, R., Hutto, R.L., Swanson, M.E., Evans, J., 2006. Post-fire logging debate ignores many issues. Science 314, 51-52.
Donato, D.C., Fontaine, J.B., Campbell, J.L., Robinson, W.D., Kauffman, J.B., Law, B.E., 2006. Post-wildfire logging hinders regeneration and increases fire risk. Science 311, 352-352.
Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R., Stocks, B.J., 2005. Future area burned in Canada. Clim Change 72, 1-16.
Foster, D.R., Orwig, D.A., 2006. Preemptive and salvage harvesting of New England forests: When doing nothing is a viable alternative. Conserv Biol 20, 959-970.
Franklin, J.F., Lindenmayer, D.B., MacMahon, J.A., McKee, A., Magnuson, J., Perry, D.A., Waide, R., Foster, D., 2000. Threads of continuity: Ecosystem disturbances, biological legacies and ecosystem recovery. Conservation Biology in Practice 1, 9-16.
Getis, A., Franklin, J., 1987. Second-order neighborhood analysis of mapped point patterns. Ecology 68, 473-477.
Greene, D.F., Gauthier, S., Noel, J., Rousseau, M., Bergeron, Y., 2006. A field experiment to determine the effect of post-fire salvage on seedbeds and tree regeneration. Frontiers in Ecology and the Environment 4, 69-74.
Gunter, S., Weber, M., Erreis, R., Aguirre, N., 2007. Influence of distance to forest edges on natural regeneration of abandoned pastures: a case study in the tropical mountain rain forest of Southern Ecuador. European Journal of Forest Research 126, 67-75.
Haase, P., 1995. Spatial pattern analysis in ecology based on Ripley's *K*-function: Introduction and methods of edge correction. J Veg Sci 6, 575-582.
Hille, M., den Ouden, J., 2004. Improved recruitment and early growth of Scots pine (*Pinus sylvestris* L.) seedlings after fire and soil scarification. European Journal of Forest Research 123, 213-218.
Hutto, R.L., 2006. Toward meaningful snag-management guidelines for postfire salvage logging in North American conifer forests. Conserv Biol 20, 984-993.
Jonášová, M., van Hees, A., Prach, K., 2006. Rehabilitation of monotonous exotic coniferous plantations: A case study of spontaneous establishment of different tree species. Ecological Engineering 28, 141-148.
Jonasson, S., 1988. Evaluation of the point intercept methods for the estimation of plant biomass. Oikos 52, 101-106.
Kay, C. E., 1993. Aspen seedlings in recently burned areas of Grand Teton and Yellowstone National Parks. Northwest Science 67, 94-104.
Karr, J.R., Rhodes, J.J., Minshall, G.W., Hauer, F.R., Beschta, R.L., Frissell, C.A., Perry, D.A., 2004. The effects of postfire salvage logging on aquatic ecosystems in the American West. Bioscience 54, 1029-1033.
Keyser, T.L., Smith, F.W., Shepperd, W.D., 2009. Short-term impact of post-fire salvage logging on regeneration, hazardous fuel accumulation, and understorey development in *Ponderosa pine* forests of the Black Hills, SD, USA. Int J Wildland Fire 18, 451-458.

Kuuluvainen, T., Leinonen, K., Nygren, M., Penttinen, A., 1996. Statistical opportunities for comparing stand structural heterogeneity in managed and primeval forests: An example from boreal spruce forest in southern Finland. Silva Fenn 30, 315-328.
Kuuluvainen, T., Rouvinen, S., 2000. Understory regeneration on two sites of different fire history in a boreal *Pinus sylvestris* forest. J Veg Sci 11, 801-812.
Lang, K.D., Schulte, L.A., Guntenspergen, G.R., 2009. Windthrow and salvage logging in an old-growth hemlock-northern hardwoods forest. For Ecol Manag 259, 56-64.
Lindenmayer, D.B., Foster, D.R., Franklin, J.F., Hunter, M.L., Noss, R.F., Schmiegelow, F.A., Perry, D., 2004. Salvage harvesting policies after natural disturbance. Science 303, 1303.
Lindenmayer, D.B., Franklin, J.F., 2002. Conserving forest biodiversity: a comprehensive multiscaled approach. Island Press, Washington, D.C.
Lindenmayer, D., McCarthy, M.A., 2002. Congruence between natural and human forest disturbance: a case study from Australian montane ash forests. For Ecol Manag 155, 319-335.
Lindenmayer, D.B., Noss, R.F., 2006. Salvage logging, ecosystem processes, and biodiversity conservation. Conserv Biol 20, 949-958.
Lindenmayer, D.B., Ough, K., 2006. Salvage logging in the montane ash eucalypt forests of the Central Highlands of Victoria and its potential impacts on biodiversity. Conserv Biol 20, 1005-1015.
Lindenmayer, D.B., Burton, P.J., Franklin, J.F., 2008. Salvage logging and its ecological consequences. Island Press, Washington, DC.
Lingua, E., Cherubini, P., Motta, R., Nola, P., 2008. Spatial structure along an altitudinal gradient in the Italian central Alps suggests competition and facilitation among coniferous species. J Veg Sci 19, 425-436.
Magurran, A.E., 2004. Measuring biological diversity. Blackwell Science, Oxford.
Martínez-Sánchez, J.J., Ferrandis, P., de las Heras, J., María Herranz, J., 1999. Effect of burnt wood removal on the natural regeneration of *Pinus halepensis* after fire in a pine forest in Tus valley (SE Spain). For Ecol Manag 123, 1-10.
McCune, B., Mefford, M.J., 1999. PC-ORD. MjM Software Design, Gleneden Beach.
McIver, J.D., Starr, L., tech. eds., 2000. Environmental effects of postfire logging:
literature review and annotated bibliography. Gen. Tech. Rep. PNW-GTR-486.
Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest
Research Station. 72 p.
Moreira, F., Catry, F., Lopes, T., Bugalho, M.N., Rego, F., 2009. Comparing survival and size of resprouts and planted trees for post-fire forest restoration in central Portugal. Ecological Engineering 35, 870-873.
Motta, R., Brang, P., Carcaillet, C., 2009. Introductory remarks Natural hazards and disturbances in mountain forests. Ecoscience 16, IV-V.
Murcia, C., 1995. Edge Effects in Fragmented Forests - Implications for Conservation. Trends Ecol Evol 10, 58-62.
Nappi, A., Drapeau, P., Savard, J.P.L., 2004. Salvage logging after wildfire in the boreal forest: Is it becoming a hot issue for wildlife? For. Chron. 80, 67-74.
Noss, R.F., Franklin, J.F., Baker, W.L., Schoennagel, T., Moyle, P.B., 2006. Ecology and management of fire-prone forests of the Western United States, Society for Conservation Biology Scientific Panel on Fire in Western U.S. Forests. Society for Conservation Biology, North American Section, Arlington, Virginia. Also available from www.conbio.org/sections/namerica/napolicy.cfm
Noss, R.F., Lindenmayer, D.B., 2006. The ecological effects of salvage logging after natural disturbance - Introduction. Conserv Biol 20, 946-948.
Nũnez, M.R., Bravo, F., Calvo, L., 2003. Predicting the probability of seed germination in *Pinus sylvestris* L. and four competitor shrub species after fire. Ann For Sci 60, 75-81.

Pardos, M., Montes, F., Canellas, I., 2008. Spatial dynamics of natural regeneration in two differently managed *Pinus sylvestris* stands before and after silvicultural intervention using replicated spatial point patterns. For Sci 54, 260-272.
Parr, C.L., Andersen, A.N., 2006. Patch mosaic burning for biodiversity conservation: a critique of the pyrodiversity paradigm. Conserv Biol 20, 1610-1619.
Peterson, D.L., Agee, J.K., Aplet, G.H., Dykstra, D.P., Graham, R.T., Lehmkuhl, J.F., Pilliod, D.S., Potts, D.F., Powers, R.F., Stuart, J.D., 2009. Effects of timber harvest following wildfire in western North America. Gen. Tech. Rep. PNW-GTR-776. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest
Research Station. 51 p.
Platt, W.J., Connell, J.H., 2003. Natural disturbances and directional replacement of species. Ecol Monogr 73, 507–522.
Rao, C.R., 1964. The use and interpretation of principal components analysis in applied research. Sankhya 26, 329- 358.
Ripley, B.D., 1977. Modelling spatial patterns (with discussion). Journal of the Royal Statistical Society B 39, 172-212.
Rouvinen, S., Kuuluvainen, T., 2005. Tree diameter distributions in natural and managed old *Pinus sylvestris*-dominated forests. For Ecol Manag 208, 45-61.
Schimmel, J., Granström, A., 1996. Fire severity and vegetation response in the boreal Swedish forest. Ecology 77, 1436-1450.
Silins, U., Stone, M., Emelko, M.B., Bladon, K.D., 2009. Sediment production following severe wildfire and post-fire salvage logging in the Rocky Mountain headwaters of the Oldman River Basin, Alberta. CATENA 79, 189-197.
Sousa, W.P., 1984. The role of disturbance in natural communities. Annu Rev Ecol Syst 15, 353-391.
Taylor, A.H., Halpern, C.B., 1991. The Structure and Dynamics of Abies-Magnifica Forests in the Southern Cascade Range, USA. J Veg Sci 2, 189-200.
ter Braak, C.J.F., Prentice, I.C., 1988. A theory of gradient analysis. Advances in Ecological Research and Exploration 18, 271-317.
ter Braak, C.J.F., Smilauer, P., 1998. Reference manual and user's guide to Canoco for Windows: Software for Canonical Community Ordination (version 4). Microcomputer Power, Ithaca, NY, USA.
Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313, 940-943.
Wiegand, T., Moloney, K.A., 2004. Rings, circles, and null-models for point pattern analysis in ecology. Oikos 104, 209-229.
Wiegand, T., Moloney, K.A., Milton, S.J., 1998. Population dynamics, disturbance, and pattern evolution: identifying the fundamental scales of organization in a model ecosystem. The American Naturalist 152, 321-337.
Yamagawa, H., Ito, S., Nakao, T., 2010. Restoration of semi-natural forest after clearcutting of conifer plantations in Japan. Landsc. Ecol. Eng. 6, 109-117.
Zasada, J. C., Norum, R. A., Van Veldhuizen, R. M., Teutsch, C. E., 1983. Artificial regeneration of trees and tall shrubs in experimentally burned upland black spruce/feather moss stands in Alaska. Can J For Res13, 903-913.
Zimmerman, G.M., Goetz, H., Mielke, P.W.J., 1985. Use of an improved statistical method for group comparisons to study effects of prairie fire. Ecology 66, 606-611.

Table 1 - Description of management options analysed in the research study.

Management options (MO)	# of plots	Description	Time span since fire (years)
No intervention (MO1)	33	No post-disturbance treatment was realized, allowing natural restoration processes to take place.	/
Salvage Logging (MO2)	6	Post-disturbance logging was realized removing all dead or damaged trees from the burned area. Harvesting operation were conducted through a combination of ground-based and cable skidding, depending on slope and soil conditions. Slash chopping followed logging and erosion stabilization measures were adopted realizing contour-felled log erosion barriers. No plantation was realized.	4
Broadleaves (MO3)	25	Following salvage logging, broadleaved species (including different combinations of *Fraxinus excelsior*, *Acer pseudoplatanus*, *Sorbus aucuparia*, *Sorbus aria*, and *Prunus avium*) were planted, adopting a regular plant spacing (3 x 3 m).	5
Larch (MO4)	13	Following salvage logging, *Larix decidua* seedlings were planted with a regular plant spacing (2 x 2 m).	5
Conifers (MO5)	15	Following salvage logging, a pure plantation of *Pinus sylvestris* or *Pseudotsuga menziesii* was realized with a regular plant spacing (2 x 2 m).	5

Table 2 - Mean density (± standard error) values of artificial (live or dead) and natural regeneration, divided by species (PS - *Pinus sylvestris*; PT - *Populus tremula*; Other conifers - *Larix decidua*, *Picea abies*; Other broadleaves – *Betula pendula*, *Prunus avium*, *Prunus* spp., *Salix caprea*, *Sorbus aria*, *Quercus pubescens*), and management options (MO). MRPP test on natural regeneration density highlighted that MO1 was different from MO2 and MO3 ($p<0.05$) and from MO4 and MO5 ($p<0.001$).

Management option (MO)	Artificial regeneration (trees/ha)		Natural regeneration (trees/ha)				
	Live	Dead	All	PS	PT	Other conifers	Other broadleaves
MO1 - No intervention	-	-	2369 (± 323)	1021 (± 253)	691 (±161)	142 (±40)	515 (±102)
MO2 - Salvage Logging	-	-	884 (± 421)	350 (±188)	117 (±75)	-	417 (±244)
MO3 - Broadleaves	480 (±53)	268 (±58)	1356 (±265)	576 (±175)	448 (±141)	20 (±8)	312 (±82)
MO4 - Larch	1792 (± 209)	838 (±292)	1100 (±353)	369 (±102)	200 (±107)	8 (±8)	523 (±164)
MO5 - Conifers	1827 (±117)	73 (±33)	734 (± 208)	140 (±49)	320 (±177)	7 (±7)	267 (±75)

Table 3 - Summary of ordination analyses (RDA and CCA) of natural regeneration structure and herb and shrub layers vegetation in relation to management (no intervention, salvage logging, broadleaves afforestation, larch afforestation, conifers afforestation), environment (elevation, forest proximity, green island proximity, herbs, shrubs), and regeneration composition. The explained variability indicates the percentage of the total variability in species data that can be explained by each group of environmental variables. The correlation of the first axis is the species-environment correlation for the first RDA or CCA axis.

Data used (plots n)	Gradient analysis	Variables tested	Explained variability (%)	Correlation 1st axis	p
Regeneration structure					
All plots (90)	RDA	Management	18.3	57.9	0.001
All plots (90)	RDA	Environment	18.0	56.1	0.001
Herb and shrub layer vegetation					
Natural plots (33)	CCA	Environment	12.9	66.7	0.001
Natural plots (33)	RDA	Regeneration	21.1	42.9	0.001

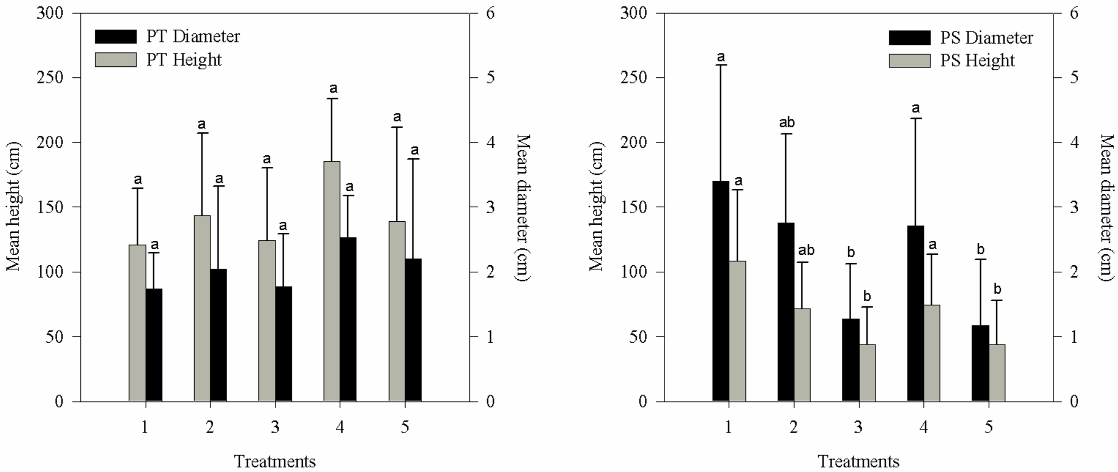

Figure 1 - Mean height and root collar diameter of *Pinus sylvestris* (PS) and *Populus tremula* (PT) saplings in the 5 treatments. Treatments without same letters were significantly different (RFGW F test, P<0.05).

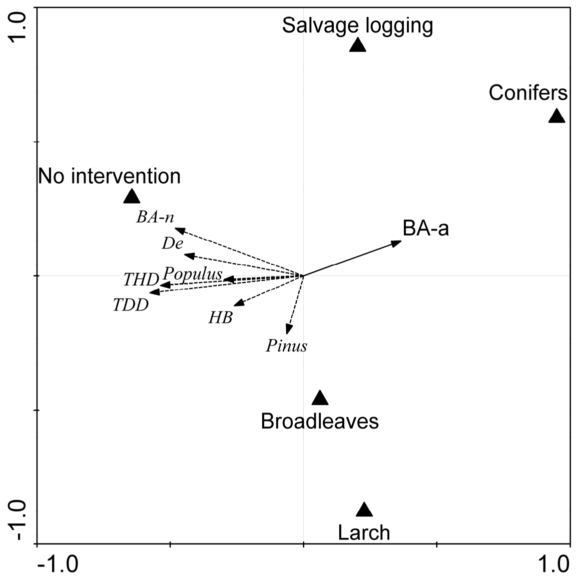

Figure 2 - Redundancy analysis (RDA of 90 plots) of natural regeneration structure in relation to management options. Dashed arrows are the natural regeneration structure variables (BA-n = basal area of natural regeneration, DBH = average DBH, THD = tree height diversity, TDD = tree diameter diversity, Div-Bril = Brillouin diversity index, Populus = relative dominance of *Populus tremula,* Pinus = relative dominance of *Pinus sylvestris*). Full line arrows represent the "biplot scores of environmental variables" (BA-a = basal area of artificial regeneration). Triangular dots are management options (No intervention - MO1 = natural restoration dynamics, Salvage – MO2 = salvage logging, Broadleaves – MO3 = broadleaves afforestation, Larix – MO4 = *Larix decidua* afforestation, Conifers – MO5 = conifers afforestation) categorical variables.

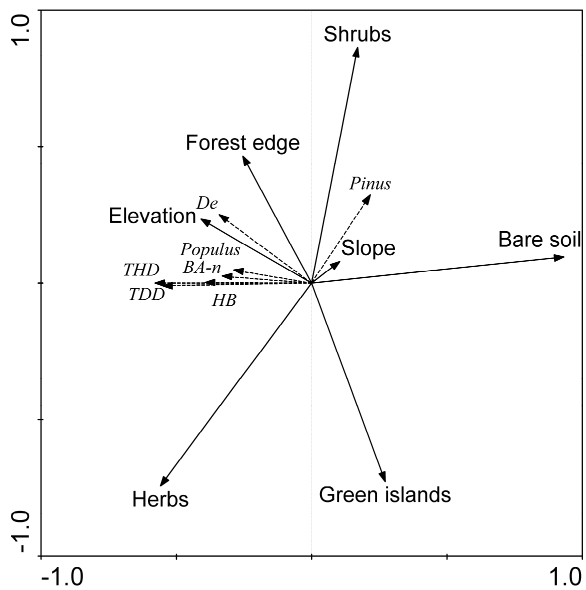

Figure 3 - Redundancy analysis (RDA of 90 plots) of natural regeneration structure in relation to environmental variables. Dashed arrows are the natural regeneration structure variables (BA-n = natural regeneration basal area, De = tree density, THD = tree height diversity, TDD = tree diameter diversity, Div-Bril = Brillouin diversity index, Populus = relative dominance of *Populus tremula,* Pinus = relative dominance of *Pinus sylvetris*). Full line arrows represent the "biplot scores of environmental variables" (Elevation = elevation, Forest edge= forest proximity, Slope = slope steepness, Green islands = green islands proximity, Herbs = herbs cover, Shrubs = shrubs cover, Bare soil = bare soil cover).

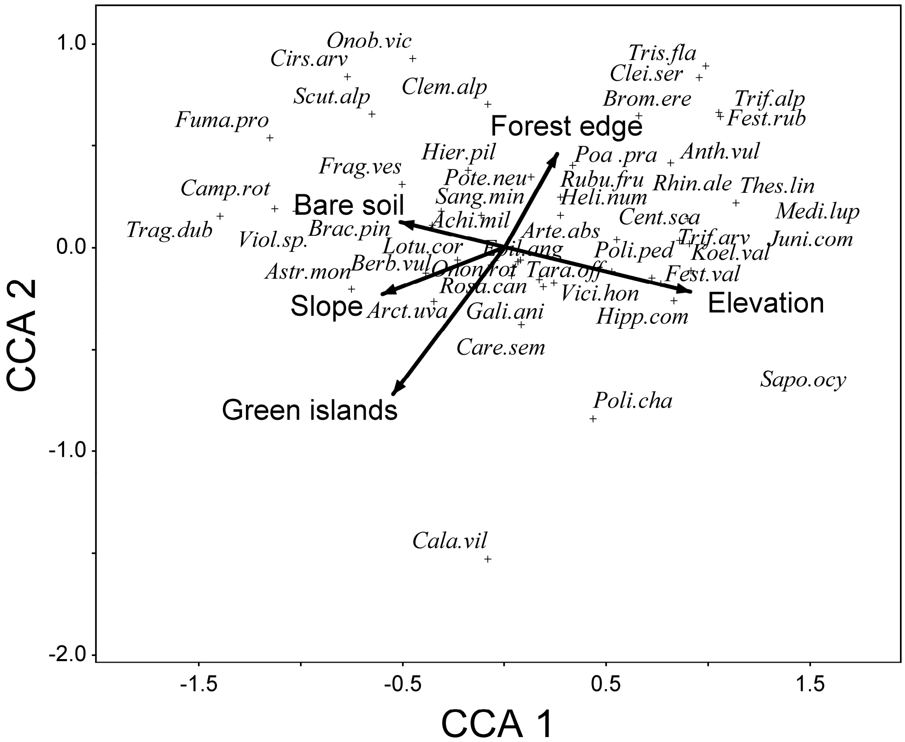

Figure 4 - Canonical correspondence analysis (CCA) of the cover of herb and shrub layers in relation to the environmental variables (Elevation = elevation, Forest-edge = forest proximity, Slope = slope aspect, BareSoil = bare soil cover, Green islands = green islands proximity) expressed by vectors. Herbs and shrubs species are indicated by dots symbols (*Achi.mil=Achillea millefolium; Anth.vul=Anthyllis vulneraria; Arct.uva=Arctostaphylos uva-ursi; Arte.abs=Artemisia absinthium; Astr.mon=Astragalus monspessulanus; Berb.vul=Berberis vulgaris; Brac.pin=Brachypodium pinnato; Brom.ere=Bromus erectus; Cala.vil=Calamagrostis villosa, Camp.rot=Campanula rotundifolia; Care.sem=Carex sempervirens; Cent.sca=Centaurea scabiosa; Cirs.arv=Cirsium arvense; Clei.ser=Cleistogenes serotina; Clem.alp=Clematis alpina; Epil.ang=Epilobium angustifolium; Fest.rub=Festuca rubra; Fest.val=Festuca valesiaca; Frag.ves=Fragaria vesca; Fuma.pro=Fumana procumbens; Gali.ani=Galium anisophyllon; Heli.num=Helianthemum nummularium; Hier.pil=Hieracium pilosella; Hipp.com=Hippocrepis comosa; Juni.com=Juniperus communis; Koel.val=Koeleria vallesiana; Lotu.cor=Lotus corniculatus; Medi.lup=Medicago lupulina; Onion.rot=Ononis rotundifolia; Onob.vic=Onobrychis viciifolia; Poa.pra=Poa pratensis; Poli.cha=Poligala chamaebuxus; Poli.ped=Poligala pedemontana; Pote.neu=Potentilla neumanniana; Rhin.ale=Rhinantus alectorolophus; Rosa.can=Rosa canina; Rubu.fru=Rubus fruticosus; Sang.min=Sanguisorba minor; Sapo.ocy=Saponaria ocymoides; Scut.alp=Scutellaria alpine; Tara.off=Taraxacum officinale; Thes.lin=Thesium linophyllon; Trag.dub=Tragopogon dubius; Trif.alp=Trifolium alpestris; Trif.arv=Trifolium arvense; Tris.fla=Trisetum flavescens;Vici.hon=Vicia honobrichioides; Viol.sp=Viola* sp.).

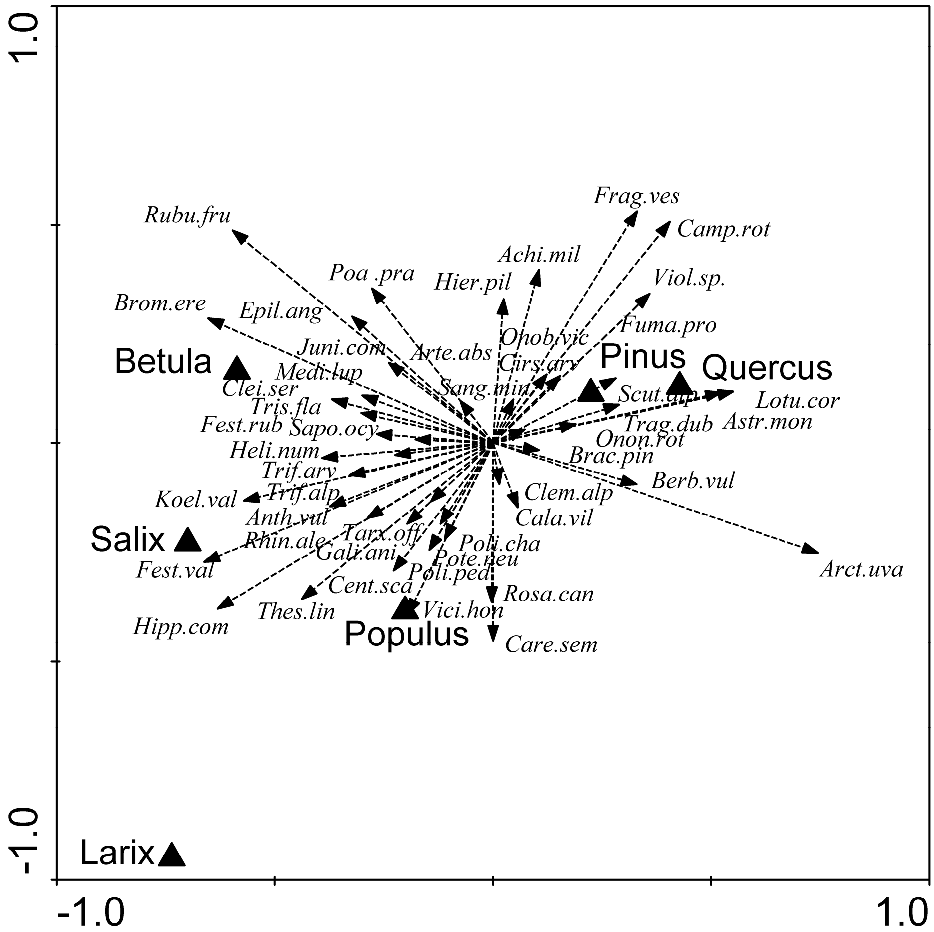

Figure 5 - Redundancy analysis (RDA) of the cover of herb and shrub layers in relation to the regeneration composition. Dashed arrows are the herb and shrub species (*Achi.mil=Achillea millefolium; Anth.vul=Anthyllis vulneraria; Arct.uva=Arctostaphylos uva-ursi; Arte.abs=Artemisia absinthium; Astr.mon=Astragalus monspessulanus; Berb.vul=Berberis vulgaris; Brac.pin=Brachypodium pinnato; Brom.ere=Bromus erectus; Cala.vil=Calamagrostis villosa; Camp.rot=Campanula rotundifolia; Care.sem=Carex sempervirens; Cent.sca=Centaurea scabiosa; Cirs.arv=Cirsium arvense; Clei.ser=Cleistogenes serotina; Clem.alp=Clematis alpina; Epil.ang=Epilobium angustifolium; Fest.rub=Festuca rubra; Fest.val=Festuca valesiaca; Frag.ves=Fragaria vesca; Fuma.pro=Fumana procumbens; Gali.ani=Galium anisophyllon; Heli.num=Helianthemum nummularium; Hier.pil=Hieracium pilosella; Hipp.com=Hippocrepis comosa; Juni.com=Juniperus communis; Koel.val=Koeleria vallesiana; Lotu.cor=Lotus corniculatus; Medi.lup=Medicago lupulina; Onion.rot=Ononis rotundifolia; Onob.vic=Onobrychis viciifolia; Poa.pra=Poa pratensis; Poli.cha=Poligala chamaebuxus; Poli.ped=Poligala pedemontana; Pote.neu=Potentilla neumanniana; Rhin.ale=Rhinantus alectorolophus; Rosa.can=Rosa canina; Rubu.fru=Rubus fruticosus; Sang.min=Sanguisorba minor; Sapo.ocy=Saponaria ocymoides; Scut.alp=Scutellaria alpina; Tarx.off=Taraxacum officinale; Thes.lin=Thesium linophyllon; Trag.dub=Tragopogon dubius; Trif.alp=Trifolium alpestris; Trif.arv=Trifolium arvense; Tris.fla=Trisetum flavescens; Vici.hon=Vicia honobrichioides; Viol.sp=Viola* sp.). Triangular dots are regeneration species (Populus = *Populus tremula*, Pinus = *Pinus sylvestris*, Larix = *Larix decidua*, Quercus = *Quercus pubescens*, Salix = *Salix caprea*, Betula = *Betula pendula*) categorical variables.