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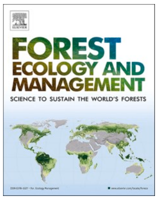

Modeling post-fire regeneration patterns under different restoration scenarios to improve forest recovery in degraded ecosystems

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ABSTRACT

Background: Changes in disturbance regimes triggered by land use and climate change can significantly alter forest ecosystems by modifying the distribution of some species and hindering post-disturbance tree regeneration dynamics. Applied nucleation (AN) could be a valuable active restoration approach for promoting natural recovery in forest ecosystems affected by stand-replacing disturbances as it improves seed availability and microsite conditions.

Objectives: The study aimed to investigate the potential of AN under different scenarios in a mountain forest ecosystem of the Northwestern Italian Alps dominated by Scots pine (*Pinus sylvestris* L.). The area was affected by a large stand-replacing fire in 2005 and post-fire salvage logging that amplified ecosystem degradation and dampened natural tree regeneration.

Methods: We assessed the main drivers guiding natural post-fire natural recovery and identified suitable sites for tree regeneration through a machine learning correlative model (Bayesian Additive Regression Tree, BART). Specifically, we used several environmental predictors (e.g., topography, wind direction, and distance from seed trees) to model the occurrence of natural tree regeneration. We predicted the probability of tree regeneration presence at landscape scale under the current situation (fire followed by salvage logging) and a set of AN scenarios characterized by an increase in *nuclei* density, since distance from seed trees emerged as the most important driver for natural tree regeneration. Starting from the situation 16 years after the fire, we reclassified the prediction raster into a binary map of intervention priority (priority and non-priority patches), using the probability value that maximized the model accuracy (true skill statistic; TSS) as threshold. Patches with scarce pine regeneration were considered as high intervention priority sites for AN. These predictions made it possible to assess the most efficient active management scenario in terms of promoting forest recovery.

Conclusions: The simulations showed the positive effects of AN on natural tree regeneration and the importance of site selection for plantations, proving that AN could be a promising post-fire management technique that can minimize human interventions and their associated economic and ecological costs. To our knowledge, this work is the first AN simulation in a temperate mountain ecosystem. The selection of favorable sites can be further improved by considering fine-scale characteristics through field experiments and cross-scale integration.

1. Introduction

Forest restoration, including post-fire management, is a key topic in the current forest management agenda (Moreira et al. 2012; Long et al. 2014; United Nations 2018; Alayan et al. 2022). Changes in fire regimes (Turner 2010; Pausas and Keeley 2021) and land use (Mantero et al. 2020) require new insights into the ecological consequences of active post-fire interventions due to their potential implications on ecosystem recovery (Alayan et al. 2022). Many nature-based solutions, which consist of actions to protect, sustainably manage, and restore natural and semi-natural ecosystems (Cohen-Shacham et al. 2016; Seddon et al. 2019), have been progressively proposed to restore forest ecosystems that are facing degradation processes as a consequence of global change (Cohen-Shacham et al. 2016; Seddon et al. 2019; Di Sacco et al. 2021).

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However, post-fire management in many European forest ecosystems is still mainly focused on salvage logging (Müller et al., 2019), sometimes followed by artificial plantation, even though the potentially negative interactions of this practice with natural recovery dynamics have been assessed worldwide in the past twenty years (Donato et al. 2006; Leverkus et al. 2018a; Leverkus et al. 2018b). More than ever, managers and policymakers need nature-based alternatives for degraded forests facing the new conditions generated by global change (Alayan et al. 2022).

The consequences of fire regime alteration are particularly noticeable in dry conifer forests (e.g., Scots pine stands – *Pinus sylvestris* L. – of the European Alps or ponderosa pine stands – *P. ponderosa* Douglas ex C. Lawson – of the US Rocky Mountains), where a reduction in tree regeneration density, shift in species distributions, and delay in post-fire recovery has been observed (Tapias et al. 2004; Stevens-Rumann et al., 2017). Moreover, mountain conifer stands are already experiencing a contraction in their range because of direct climate change effects, such as the increased frequency of drought periods and the rise in mean temperature. These alterations are hindering natural tree regeneration dynamics at the lower edge of their distributions and increasing diebacks (Vacchiano et al. 2012; Rigling et al. 2013; Harvey et al. 2016; Timofeeva et al. 2017; Morales-Molino et al. 2021). A major consequence of these altered dynamics is usually a shift in forest composition (e.g., an increase in xeric broadleaves such as downy oak (*Quercus pubescens* Willd.) in the Alps), or a transition towards shrubland or grassland. These shifts can be accelerated by the effects of altered fire regime on post-fire recovery (Silva et al. 2011; Karavani et al. 2018; Baltzer et al. 2021). Indeed, pioneer sprouting species, such as European aspen (*Populus tremula* L.), quaking aspen (*P. tremuloides* Michx.), and goat willow (*Salix caprea* L.), can regenerate immediately after a fire and benefit from the availability of light and the absence of competition typical of post-fire environments (Reinhardt et al. 2001; Nuñez et al. 2003; Úbeda et al. 2006). Hence, these species often colonize areas affected by stand-replacing events before obligate seeders, potentially altering the provision of ecosystem services and landscape patterns (Vayreda et al. 2016). Post-fire interventions (e.g., salvage logging) may further dampen post-fire recovery, for instance reducing tree regeneration density, shifting the species distribution, and delaying post-fire recovery. These alterations may trigger degradation phenomena, such as soil erosion (Beghin et al. 2010; Marzano et al. 2013), with a consequent need for active interventions to restore the functions of degraded landscapes (Stanturf et al. 2014).

Mediterranean mountains are among the ecosystems most affected by the direct and indirect effects of global change. Indeed, the increase in mean annual temperature (e.g., +1.8 °C in the European Alps in the last 50 years; Klein et al. 2016), associated with extreme droughts (Cook et al. 2018) resulted in phenological and elevational shifts (Lenoir et al. 2008; Vitasse et al. 2021), dieback (Allen 2009; Morales-Molino et al. 2021), and in an increase in frequency and severity of fires (Pausas and Keeley 2021). Moreover, the widespread land abandonment that occurred in the marginal mountain areas of the Mediterranean region resulted in large forest cover gain on traditionally managed land (i.e., meadows, pastures, and croplands), with a consequent fuel build-up associated to an increase in fire risk (Mantero et al. 2020).

A proper diagnosis of the initial conditions and clear restoration objectives are fundamental to set up tailored post-fire management strategies, balancing economic and ecological aspects (Stanturf et al. 2014; Holl et al. 2020). Restoration activities in Mediterranean mountain ecosystems have often been based on standard plantation techniques following a regular planting scheme over large areas, without considering the small-scale spatial variability of favorable microsites, particularly relevant with increasing elevation or under harsher site conditions. Neglecting these fine processes and patterns may result in increased costs, altered forest structure and lower seedling survival rate. Conversely, taking advantage of natural tree regeneration is usually ecologically sound and economically feasible, but its likelihood of success can be hindered by post-disturbance environment and practices and possible cascading effects (Holl et al. 2020; Di Sacco et al. 2021). Natural tree regeneration approaches include a spectrum of different levels of human intervention that partially or totally rely on natural dynamics to restore natural ecosystems (Di Sacco et al. 2021). Specifically, Applied Nucleation (AN) and the Framework Species Approach can accelerate post-disturbance dynamics in those scenarios where natural tree regeneration is delayed for different reasons (Rey Benayas et al. 2008; Corbin and Holl 2012; Holl et al. 2020; Di Sacco et al. 2021). AN consists of planting small groups of trees, called *nuclei*, which have the potential to restore forest cover in a highly disturbed site both through facilitation in the colonization of other species and the dispersal of seeds from the *nuclei* itself (Corbin and Holl 2012; Di Sacco et al. 2021). This technique mimics natural successional processes by improving stressful abiotic conditions, facilitating seedling establishment, and increasing seed availability, with the aim of leading to forest expansion over time (Rey Benayas et al. 2008; Corbin and Holl 2012; Aradottir and Halldorsson 2018; Holl et al. 2020). AN can enhance seedling recruitment by improving microclimate conditions (i.e., temperature and moisture), reducing wind disturbance, and improving soil quality (Rey Benayas et al. 2008; Corbin and Holl 2012). This technique seems to be promising in cost-benefits terms, but it requires higher accuracy during the planning and planting stages (Rey Benayas et al. 2008; Corbin and Holl 2012).

Accurate planning is crucial for a successful AN application and should consider the characteristics of the surrounding landscape and the influence of some technical parameters, such as optimization of the number of *nuclei*, their size, and their distance (Corbin and Holl 2012; Castro et al. 2021). For instance, *nuclei* dimension has been proven to influence seedling surviving rates, seed rain, and seedling recruitment in tropical forests (Corbin and Holl 2012; Zahawi and Augspurger, 2006; Holl et al. 2020). Some authors observed that small *nuclei* (i.e., < 64 m^2) might not improve microsite conditions in terms of shade, temperature, and humidity, are more difficult to manage, and are not so attractive to animals that scatter seeds (Zahawi and Augspurger 2006; Holl et al. 2020). As observed by Holl et al. (2020), the spacing between *nuclei* is another crucial aspect to consider when planning AN projects, though it has not been thoroughly studied. The optimal spacing between *nuclei* depends on several different factors, such as the dispersal ability of species, the size of disturbed patches, and socio-economic factors (e.g., available funds for tree planting, risk of degradation phenomena). Moreover, practitioners should consider the average sexual maturity of the species for them to disseminate (e.g., 10 to 15 years for Scots pine; Skilling 1990). AN is a relatively recent and promising technique that has mainly been applied in tropical ecosystems (Corbin and Holl 2012; Shaw et al. 2020). However, it has the potential for application in other ecosystems, especially those where natural tree regeneration tends to exhibit succession by nucleation, like mountain ones (Shaw et al. 2020). To maximize results avoiding excessive costs, it is fundamental to define a management strategy that considers site characteristics and, even more, natural tree regeneration presence. This is particularly important for those situations where natural tree regeneration is extremely abundant in some parts of the affected site (i.e., medium fire severity areas) and completely absent in others (i.e., high fire severity areas, steep slopes) due to the characteristics of the species (e.g., lack of fire-adaptive traits; Mantero et al. 2023).

The aim of this study was to investigate the main drivers influencing post-fire tree regeneration patterns and abundance, define spatially explicit restoration needs, and intervention priority areas for AN within a dry Scots pine stand affected by a stand-replacing fire followed by salvage logging. Specifically, we wanted to (i) evaluate post-fire tree regeneration 16 years after the fire; (ii) assess drivers of post-fire tree regeneration; (iii) map sites where active restoration should be prioritized based on the probability of natural post-fire tree regeneration presence; (iv) define the most effective AN scenario through modeling. Analyzing natural tree regeneration dynamics in Scots pine stands affected by stand replacing fires is particularly important in the current scenarios of climate and land use changes. The alterations in fire regimes induced by such changes are leading to more frequent and more severe fires, hindering the post-fire recovery of Scots pine stands, able to survive to low intensity surface fires, but highly sensitive to crown fires. Understanding post-fire tree regeneration dynamics and promoting forest recovery is a fundamental topic nowadays, especially for mountain forests exerting protective functions (Lingua et al. 2023). We focused primarily on Scots pine and European aspen regeneration dynamics because we considered them to be the two most important species in the site. In fact, the burned stand was a pure Scots pine stand, but European aspen was by far the most abundant species among tree regeneration.

2. Materials and methods

2.1. Study site

The study site was located in the European Alps within the municipality of Verrayes (Aosta Valley Region, NW Italy), in an area named Bourra (45°46′21′′ N, 7°29′55′′ E). The area was located on a south facing slope and its elevation ranged between 1650 and 1800 m. a.s.l. Ophiolite and schist characterized the geology of the area and the soils were classified as Entisols (Soil Taxonomy, USDA). Mean annual precipitation was approximately 800 mm, with long and dry periods in summer (less than 200 mm from June to August) and February (period 1989–2013 according to Chelsa V1.2; Karger et al. 2017; Karger et al. 2018). Mean annual temperature was 7.7 °C (period 1989–2013 according to Chelsa V1.2; Karger et al. 2017; Karger et al. 2018). Vegetation was dominated by Scots pine, with a sporadic presence of European larch (*Larix decidua* Mill.) Norway spruce (*Picea abies* (L.) H. Karst.), downy oak, European aspen, and birch (*Betula pendula* Roth.). In March 2005 a high severity fire affected the area, burning about 257 ha (Fig. 1). In a large patch (160 ha; 62 %) in the central part of the area the fire showed a stand-replacing behavior, leading to the complete mortality of the previous Scots pine stand, with the only exception of a few small green islands. Following the event, salvage logging operations started in 2007 (Marzano et al. 2013), including most of the area affected by stand-replacing fire. In those areas dead trees were removed from the sites, while branches were left piled up. Some management units were however left unsalvaged, with complete deadwood retention, allowing for comparison between the two treatments (salvaged vs unsalvaged).

2.2. Sampling design and data collection

We selected an area of 67 ha inside the fire perimeter to compare the impact of salvage logging (SL) and deadwood retention (DR) on natural tree regeneration. We collected tree regeneration data in autumn 2021 by surveying 223 plots (density~3 plots ha^{-1}) with a 6 m radius, which were located through a random sampling design and with a minimum distance of 40 m from each other. 75 plots were in DR areas, while 148 were located in SL areas (Fig. 1). We recorded the coordinates of each plot by using a Trimble R2 GNSS receiver with submetric accuracy. In each plot, we recorded species composition and height of tree regeneration (including obligate seeders and facultative sprouters for which the number of stems was recorded), and ground cover data of Poaceae, forbs, bare soil, litter, shrubs, coarse woody debris (CWD), and rocks by visually estimating the percentage cover to the nearest 5 %. CWD was divided into piles of branches resulting from salvage logging operations (CWD_piles) and sparse logs (CWD_log).

2.3. Regeneration patterns

We analyzed tree regeneration dynamics for all the species in the study site 16 years after the fire based on tree regeneration species composition, density, and ground cover. We assessed differences in terms of tree regeneration density between SL and DR areas and applied the Kruskal-Wallis test by rank to test for significant differences between

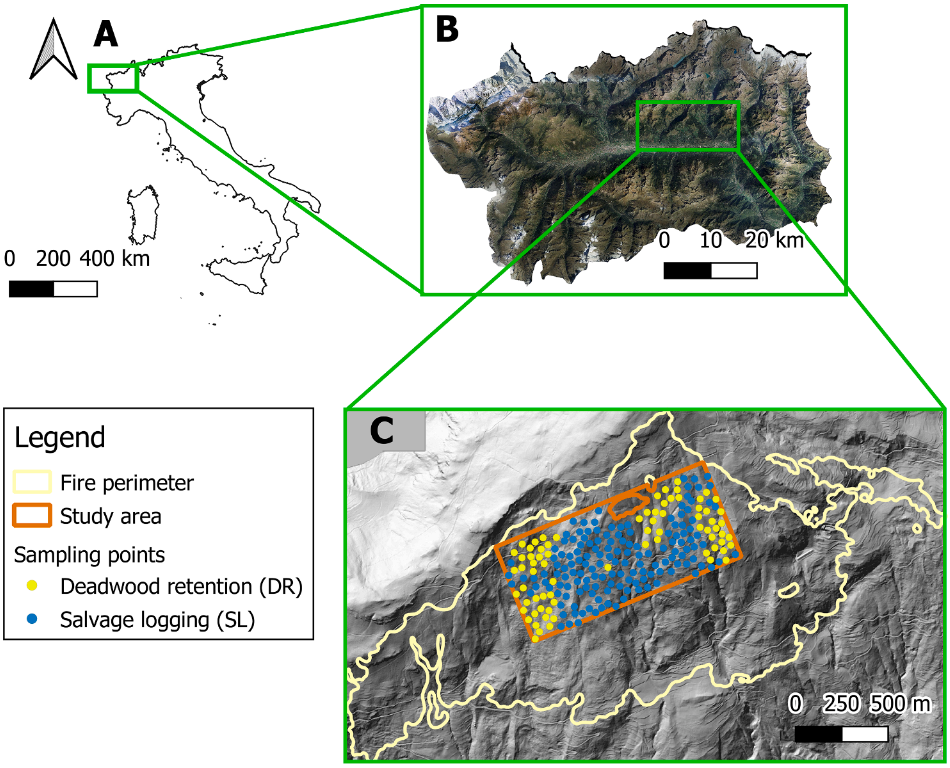

Fig. 1. Location of the study area within **A** Italy, **B** Aosta Valley region, and **C** perimeter of the 2005 fire with location of the 223 plots used to assess tree regeneration pattern. Plots within salvage logging areas (SL) are marked in blue and plots within deadwood retention areas (DR) in yellow.

total density in the two treatments. We then focused on Scots pine regeneration dynamics and analyzed Scots pine regeneration density based on the distance to the nearest seed tree to assess its influence on Scots pine regeneration abundance. We considered 50 m to seed trees to be a critical distance for seed dispersal according to evidence in the literature (Debain et al. 2007; Vilà-Cabrera et al. 2011; Mantero et al. 2023). We applied the Kruskal-Wallis test by rank to test for significant differences between Scots pine regeneration density in plots closer than 50 m to the nearest seed tree and further away. We assessed differences in ground cover between the two different post-fire treatments (SL and DR).

2.4. Drivers of forest regeneration

We investigated the drivers of regeneration presence only for the two main species in the area, Scots pine and European aspen. We used the presence/absence of Scots pine and European aspen regeneration across the 223 plots as response variable and a set of environmental drivers as covariates (Table 1). We used the existing literature to select the most important environmental variables guiding post-fire forest recovery (e.g., Marzano et al. 2013; Perrault-Hébert et al. 2017; Haffey et al. 2018; Andrus et al. 2022; Kiel and Turner 2022).

We derived topographic variables from a 2 m resolution digital terrain model (DTM; Regione Valle d'Aosta 2008), which included elevation, slope, roughness, aspect, terrain ruggedness index (TRI), terrain position index (TPI), and Euclidean distance to gullies. Since the aspect is a circular variable, we converted it into eastness by computing its sinum. We mapped seed trees using a canopy height model generated from airborne laser scanner data acquired in 2011 with an average cloud density of 10 points per m^2. We considered all the trees with a height above 5 m as potential seed trees. We considered wind effects by computing the 'Wind Effect' and the 'Wind Exposition Index' indices with SagaGIS v7.8.2. Both indices are dimensionless, with values below one corresponding to wind-shadowed areas, and values above one indicating areas exposed to wind. We obtained wind speed and direction data at 10 and 50 m height for the study site from the New European Wind Atlas (https://map.neweuropeanwindatlas.eu/).

We built correlative regeneration models for both Scots pine and European aspen using Bayesian Additive Regression Trees (BART). BART is a modeling procedure based on an ensemble of trees, similarly to boosted regression trees and random forest. It employs a sum-of-trees model and a Bayesian framework. Trees are first constrained as weak learners by priors regarding structure and nodes, then updated through an iterative Bayesian backfitting Markov Chain Monte Carlo (MCMC) algorithm, which ultimately generates a posterior distribution of predicted classification probabilities instead of a single estimate (e.g., prevalence; Chipman et al. 2010; Carlson 2020). We chose this approach as overfitting results are lower than other similar methods (Carlson 2020; Baquero et al. 2021). Moreover, many studies showed the good predictive power of this model compared to other additive regression trees and ensemble models with multiple algorithms, especially for small datasets (Konowalik and Nosol 2021; Plant et al. 2021).

We trained BART models for Scots pine and European aspen by using the embarcadero R package, a wrapper for the `dbarts` package (Carlson 2020). The `embarcadero` implementation has several features that make it a powerful tool for mapping, such as automated variable selection, measure of uncertainty, posterior distributions on partial dependence plots, and two-dimensional and spatially projected partial dependence plots (Carlson et al. 2022). We used covariates at different spatial resolutions (2, 10, 20, 30, and 40 m) to assess variations in the predictive performance of the models as evaluated with the AUC (area under the receiving operator curve; Hosmer and Lemeshow 1989). To have a complementary measure of model performance we calculated the standardized true skill statistic (sTSS; Allouche et al. 2006). Accordingly, we selected the best spatial resolution and calculated the slope of the Miller calibration line for the best resolution as a proxy for the reliability and transferability of a model. We used a block spatial cross-validation through the package `blockCV` to retrieve the most unbiased estimate of model performance (Valavi et al. 2018).

We measured the variable importance to select the most important drivers of Scots pine and European aspen regeneration by counting the number of times a given variable was used by a tree split across the full poster draw of trees (Carlson 2020). We created partial dependence plots through the function `partial` of the embarcadero package to see how the principal environmental variables influenced the presence/absence of Scots pine and European aspen regeneration.

Table 1
Environmental and regeneration variables included in the BART model for assessing the main drivers of Scots pine and European aspen regeneration presence.

Variable	Category	Original spatial resolution (m)	Unit	Data source
Elevation	Topography	2	m	DTM
Slope		2	°	DTM
Roughness		2	m	DTM
Eastness		2	–	DTM
Terrain rudgeness index		2	–	DTM
Topographic position index		2	–	DTM
Distance to gullies		2	m	DTM
Wind effect at 50 m height	Climate	2	–	DTM
Wind effect at 10 m height		2	–	DTM
Wind exposition		2	–	DTM
Distance to seed trees	Vegetation	1	m	CHM

2.5. Management scenarios

We predicted the probability of Scots pine regeneration presence across the entire fire perimeter under the current situation and a set of applied nucleation (AN) scenarios. Starting from the current situation, we reclassified the prediction raster into a binary categorical map, according to the probability threshold that maximized the TSS. We obtained this threshold using the function `getThreshold` in the `modEVA` package. Pixels with values lower than the threshold were defined as of high intervention priority, whilst pixels with values above the threshold corresponded to low intervention priority. We positioned AN *nuclei* (10 m radius; Schönenberger, 2001) in high intervention priority areas larger than 0.5 ha (patchy approach). The *nuclei* density ranged from 5 over the entire area (0.02 *nuclei* ha^{-1}) to 1 every 1000 m^2 (2.07 *nuclei* ha^{-1}). We calculated the new Euclidean distance from forest edges/green islands and the clusters for each scenario and then projected the probability of Scots pine presence. We assessed the changes in Scots pine regeneration probability of presence and the extent of high intervention priority areas according to nucleation density. We then positioned the *nuclei* in the entire area, regardless of the Scots pine regeneration presence probability, to see the possible outcomes of a random AN (extensive approach), with the same range of density as the patchy approach. All the analyses were conducted using `R version 4.2.2` (R Core Team 2022).

3. Results

3.1. Regeneration patterns

The mean tree regeneration density was 1527 stems ha^{-1}. European aspen was by far the most widespread species (1103 ± 167 stems ha^{-1}, 72 %), followed by goat willow (149 ± 25 stems ha^{-1}, 10 %), Scots pine (94 ± 19 seedlings ha^{-1}, 6 %), and European larch (32 ± 9 seedlings ha^{-1}, 2 %). Other species, like whitebeam (*Sorbus aria* Crantz), downy oak, and birch were sporadic and accounted for around 10 % of the total tree regeneration (See Supplementary Material, Fig. S1, Table S1).

We found statistically significant differences in terms of total tree regeneration density between SL and DR areas (Kruskal Wallis test, $P < 0.05$). Indeed, the mean tree regeneration density in SL areas was 976 ± 150 stems ha^{-1}, while in DR areas it was 2615 ± 394 stems ha^{-1}; Fig. 2).

Tree regeneration showed heterogeneous spatial patterns within the study area. In particular, we found significant differences for the density of Scots pine regeneration according to the distance from seed trees. Scots pine regeneration density in plots located within the first 50 m close to seed trees was significantly higher (269 ± 81 seedlings ha^{-1}) than that in plots located farther away from seed trees (48 ± 7 seedlings ha^{-1}; Kruskal Wallis test, $P < 0.05$). Only 91 plots out of 223 presented Scots pine regeneration.

The most important ground cover was shrubs in both treatments (44 % in SL and 43 % in DR), followed by Poaceae (35 % in SL and 34 % in DR). SL plots were characterized by a lower amount of CWD, mainly consisting in piles of branches resulting from salvage logging operation (6 % of CWD_piles and 2 % of CWD_log). In DR areas we found a greater amount of CWD, dominated by bigger logs (2 % of CWD_piles and 11 % of CWD_log; See Supplementary Material, Fig. S2). The other ground cover classes were similar between SL and DR areas.

3.2. Drivers of forest regeneration

The BART model with the highest accuracy for Scots pine regeneration was the one with a spatial resolution of 10 m. The accuracy values of the model according to a 5-fold spatial block cross-validation are reported in the Supplementary Material (Fig. S3). The mean AUC was 0.65, the mean sTSS was 0.28 and the slope of the Miller calibration line was 1.14. The low accuracy values of Scots pine were associated to type-I errors (Sensitivity = 0.61), meaning that expected presence for Scots pine regeneration (i.e., modeled) was higher than observed. The variable importance plot (VIMP) ranked all predictors of the BART model according to their influence on Scots pine regeneration presence, showing that distance from seed trees was the most important factor, followed by eastness, and distance to gullies (See Supplementary Material, Fig. S4). The partial dependence plots of the three most important variables showed the shape of the relationship between predictors and predicted variables within the BART model (Fig. 3). The maximum probability of finding Scots pine regeneration was close to seed trees, with a trend that sharply decreases from a distance around 50 m. The maximum probability was also found on both sides of gullies and in their proximity.

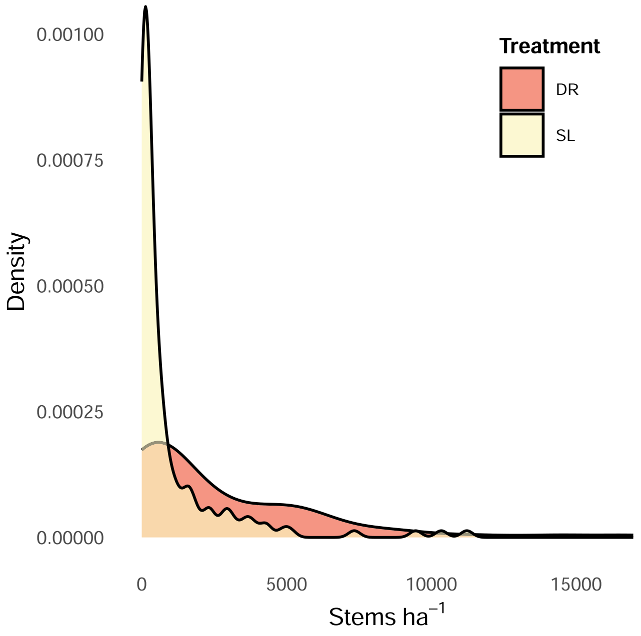

Fig. 2. Kernel density estimate of tree regeneration density distribution (stems ha^{-1}) in deadwood retention (DR) and salvage logging (SL) plots. The height of the curve is scaled such that the area under the curve equals one. The density estimate was performed with a Gaussian kernel.

As for Scots pine, also models for European aspen achieved the highest accuracy with a spatial resolution of 10 m. The accuracy values of the model according to a 5-fold spatial block cross-validation are reported in the Supplementary Material (Fig. S5). The mean AUC was 0.51, the mean sTSS was −0.02, and the slope of the Miller calibration line was 0.0044. Accordingly, we did not consider the model to be informative and we did not further interpret its results. In this case, the low accuracy was mostly related to type-II errors (Specificity = 0.64), meaning that aspen was also present where the model predicted its absence.

3.3. Management scenarios

Presence probability of Scots pine regeneration ranged from 0.06 to 0.90 within the fire perimeter, with a mean value of 0.51 ± 0.18 and the highest values in the outer part of the area (Fig. 4a). Uncertainty ranged from 0.20 to 0.86, with a mean value of 0.53 ± 0.10 and a positive correlation to the presence probability (Fig. 4b). We reclassified the probability raster of Scots pine regeneration presence into a binary map of intervention priority for the AN simulation (threshold = 0.37). The total extent of high intervention priority areas was 57.4 ha, with the biggest patches mainly located in the central part of the landscape, far away from seed trees, while the total extent of low intervention priority areas was 184.4 ha (Fig. 4c).

We observed that the probability of presence of Scots pine regeneration and the decrease in the extent of high intervention priority areas were positively correlated to the increase of *nuclei* density throughout the scenarios (minimum density = 0.02 *nuclei* ha^{-1}, maximum density = 2.7 *nuclei* ha^{-1}) (Fig. 5). However, their relationship was not linear, either for the patchy approach or for the extensive approach (Fig. 5). Comparison between the two approaches showed differences in terms of the effectiveness of the two strategies. At low density of *nuclei*, the patchy approach maximizes Scots pine regeneration presence probability, while the extensive approach is more effective for higher *nuclei* densities (Fig. 5a). Similarly, a certain extent of the high intervention priority areas in the patchy approach required a lower density of *nuclei* than in the extensive approach (Fig. 5b). For *nuclei* densities between 0.02 and 0.7 *nuclei* ha^{-1} the differences in terms of extent of high intervention priority areas between the two approaches reached around a third of the current extent of high intervention priority areas (Fig. 5b).

The mean Scots pine regeneration presence probabilities corresponding to a *nuclei* density of 1.0 *nucleus* ha^{-1} were 0.58 ± 0.001 and 0.59 ± 0.001 for the patchy and extensive approach respectively (Fig. 5a). Similarly, the extents of high intervention priority areas for a *nuclei* density of 1.0 *nucleus* ha^{-1} were 17.7 ha and 15.12 ha for the patchy and extensive approach respectively (Fig. 5b). The effectiveness of the two approaches was comparable for *nuclei* density values between 0.4 and 0.65 *nuclei* ha^{-1} (Fig. 5; See Supplementary Material, Fig. S6).

4. Discussion

Improving our knowledge on spatial patterns and drivers of tree regeneration in areas affected by stand-replacing fires and subsequent salvage logging is essential to plan effective management strategies. We proposed a correlative modeling approach at the landscape scale to detect areas in which to prioritize active post-fire management due to the low abundance of post-fire natural tree regeneration.

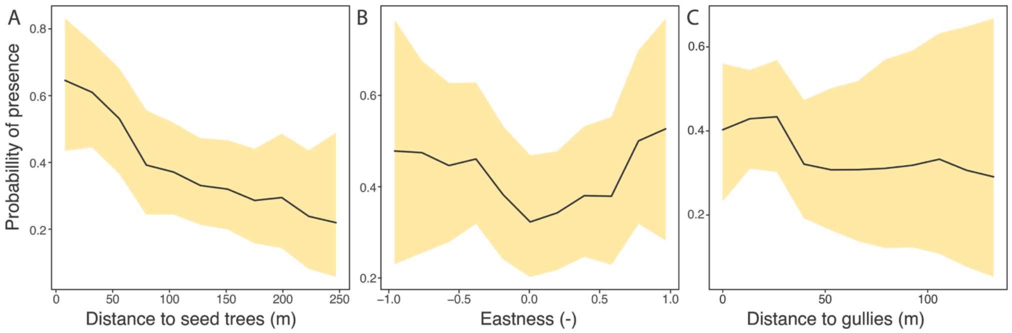

Fig. 3. Partial dependence plots of the three principal drivers of Scots pine regeneration presence generated by single-instance Bayesian additive regression trees implementation: **A** distance to seed trees, **B** eastness, **C** distance to gullies. Y axis represents the probability of Scots pine regeneration presence. Yellow area represents 95% confidence interval.

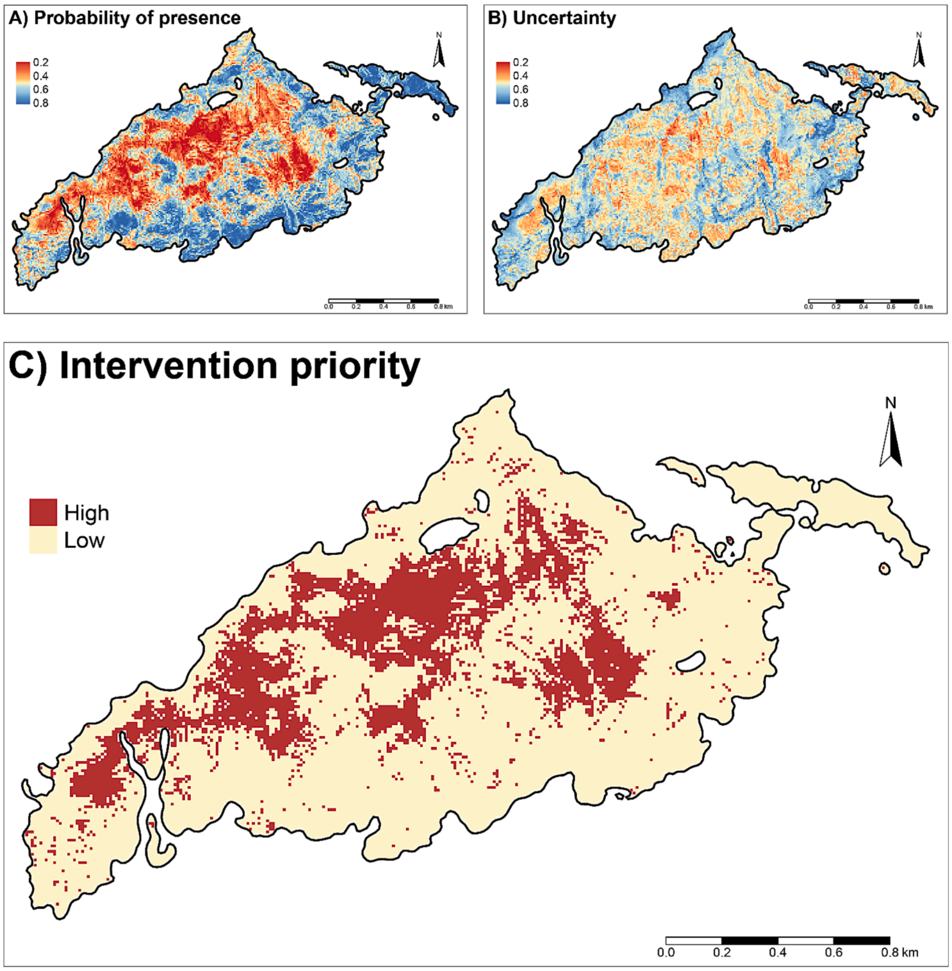

Fig. 4. **A** Probability of presence of Scots pine regeneration according to the BART model, **B** probability uncertainty based on the 5th and 95th percentile, **C** binary map of intervention priority according to the threshold that maximized the model TSS (=0.37).

4.1. *Regeneration patterns and drivers*

In the Bourra site, Scots pine regeneration density was still low over a decade after the fire and the low recovery rate was mainly related to the long distance from seed sources, in agreement with other observations in Mediterranean mountain forests (e.g., Debain et al. 2007; Vilà-Cabrera et al. 2011; Vitali et al. 2019; Mantero et al. 2023). Moreover, post-fire salvage logging operations contributed to the low tree regeneration establishment in the area (Marzano et al. 2013; Marcolin et al. 2019; Lingua et al. 2023). Indeed, deadwood removal associated to salvage logging modified microclimatic conditions, leading to an increase in soil temperature and a decrease in relative humidity and soil moisture, resulting in a reduction of favorable microsites for seedlings establishment and survival, as proven by previous studies conducted in the same area (Marzano et al. 2013; Marcolin et al. 2019; Lingua et al. 2023).

Tree regeneration was dominated by European aspen, while Scots pine seedlings were rather sporadic and mostly confined to short distances from seed trees, due to the limited seed dispersal ability of this species (Debain et al. 2007; Vilà-Cabrera et al. 2011; Vitali et al. 2019; Mantero et al. 2023). Given the high fire severity, it is likely that the seed

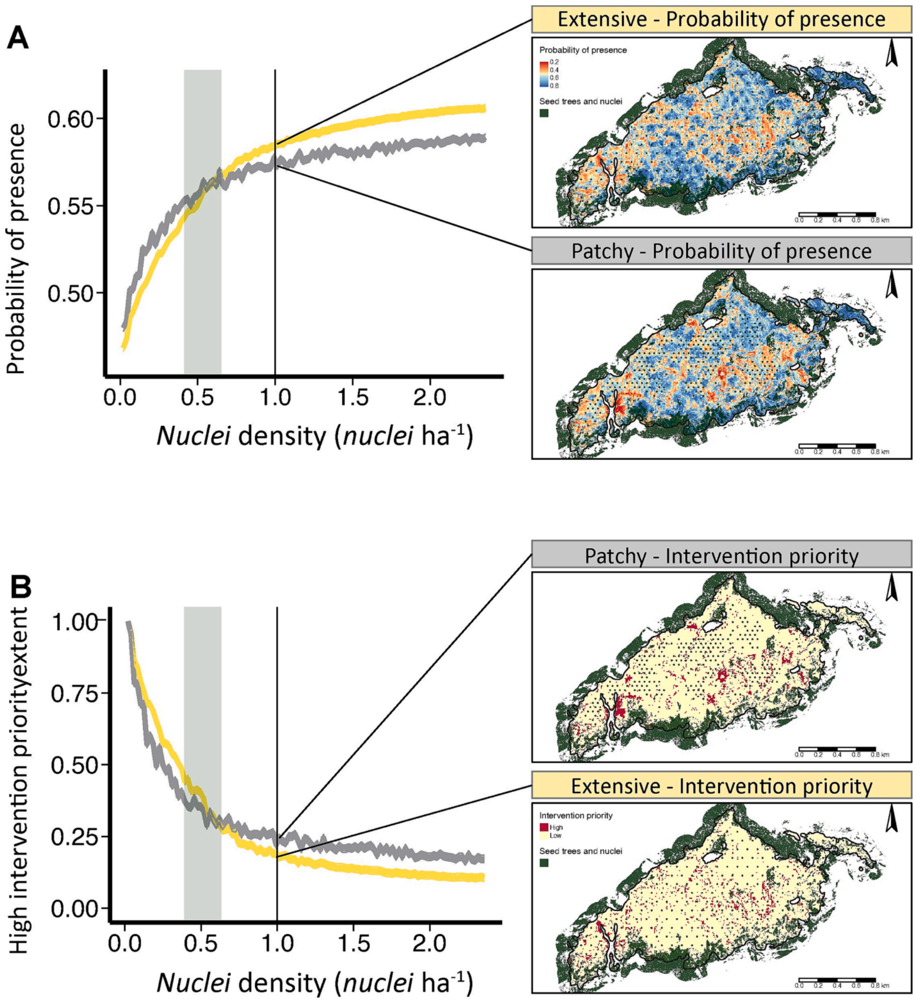

Fig. 5. Trends of **A** probability of presence of Scots pine regeneration according to the increasing *nuclei* density with standard error, **B** extent of high intervention priority areas with standard error. The yellow line represents the extensive approach, while the grey line represents the patchy approach. On the right we report probability of presence and intervention priority maps corresponding to an illustrative *nuclei* density of 1 *nucleus* ha^{-1}. The green band corresponds to *nuclei* density values where the slope of the response variable decreases abruptly (See Supplementary Material, Fig. S7).

soil bank was almost entirely destroyed. Therefore, all the gamic material possibly came from the crown seed bank of survived trees or forest edges after the fire. Scots pine regeneration also appeared to be mostly located on upper gully banks. Given the predominant southern exposure of the areas, better microclimatic conditions for Scots pine regeneration can be found on gully banks rather than on their bottom because of a lower exposition to direct solar radiation and warmer temperatures. Moreover, snow retention and water persistence can inhibit Scots pine survival in gully bottoms (Çolak 2003). Finally, Scots pine regeneration was not found in gully bottoms and flat areas because aspen formed dense stands in those topographic conditions.

4.2. Applied nucleation modeling

Analysis of the current situation highlighted low probability of presence of Scots pine regeneration in the core area of the site. Since the burnt area was characterized by a homogeneous high severity, very few seed trees survived. Therefore, most of the seeds came from the surrounding forest edges and were not able to penetrate the inner part because of the low seed dispersal ability of the species (Vilà-Cabrera et al. 2011; Vitali et al. 2019; Mantero et al. 2023). Considering that post-fire tree regeneration was still very low 16 years after the fire and we did not observe many young seedlings (i.e., 1–5 years), we believe that active post-fire management can be useful to accelerate natural dynamics. To identify sites more in need of active intervention, we adopted a correlative modeling, considering environmental (e.g., topographical features, wind exposition) and post-fire conditions (e.g., distance from seed trees, Scots pine seedling occurrence).

The great false positive and false negative rates of the Scots pine and aspen model, respectively, can be interpreted as evidence of altered ecosystem conditions after post-management practices, as demonstrated in other works conducted in the same area (Marzano et al. 2013; Marcolin et al. 2019; Lingua et al. 2023). The high rate of false positives in Scots pine regeneration models implied that the model predicted more suitable conditions than observed. It is possible that suitable sites for Scots pine due to topographical features and distance from seed trees were not colonized by seedlings because of the negative impact of salvage logging on microsites conditions and the competition with aspens (Marzano et al. 2013; Leverkus et al. 2018a; Marcolin et al. 2019). Also, the low Scots pine regeneration abundance could be related to scarce seed production and browsing (Palmer and Truscott 2003).

Our simulations showed the positive effects of AN and the importance of site selection for the spatial distribution of *nuclei*. For a density of *nuclei* higher than 1 *nucleus* ha^{-1}, the slope of the probability of presence of Scots pine regeneration and extent of high priority sites decreased, and the two curves reached a plateau. This can be explained by the fact that environmental characteristics other than distance to seed source (e.g., eastness, slope) affected the post-fire regeneration of Scots pine. The presence of other obstacles to natural tree regeneration could be the reason why, for a higher nuclei density, the extensive approach became more efficient than the patchy approach. In fact, some sites will likely remain unsuitable for natural tree regeneration despite the presence of a close seed source. Therefore, effective AN planning requires a proper sites selection also at the micro scale (Castro et al. 2021). Nevertheless, the selection of high priority areas at this coarser resolution (i.e., 10 m) can be still considered a valuable tool for land managers, given its greater efficiency for lower *nuclei* density, thus minimizing human interventions and their associated economic and ecological costs.

5. Conclusions

In post-fire environments where passive tree regeneration is not sufficient to restore forest cover in the short-term, an appropriate active management strategy aiming to accelerate post-disturbance dynamics by increasing seed availability and improving site conditions is crucial. Appropriate planning is key to avoid excessive costs (e.g., widespread planting) and maximize tree regeneration success (Rey Benayas et al. 2008; Corbin and Holl 2012; Holl et al. 2020; Di Sacco et al. 2021). AN has been proven to be particularly useful in those situations where natural tree regeneration dynamics are slow, for example, due to a long history of human disturbances, since *nuclei* act as a source of seeds (Rey Benayas et al. 2020). The average sexual maturity of Scots pine ranges from 10 to 15 years of age (Skilling 1990). Therefore, this can be considered the period after which trees within the *nuclei* will start disseminating. The low Scots pine natural regeneration in the area suggests that AN is necessary to restore a forest stand in a reasonable time. Conversely, when seed trees are located nearby, it could be more effective to assess natural tree regeneration presence and abundance and evaluate the possibility of facilitating its development, rather than just planting (Holl et al. 2020).

This approach allows priorities to be detected at a coarse scale. However, some limitations arose from this study. First, this procedure should be upscaled from a landscape to a regional scale. Indeed, using this approach in disturbed sites with differences in terms of fire severity, species composition, post-fire management, and environmental conditions, can improve its generalizability and applicability. Second, due to the absence of post-fire plantation, we could not empirically validate the efficacy of the simulations. This issue could be partially overcome at the abovementioned regional scale, considering planted sites for validation purposes. Finally, there is a need for further cross-scale integrations considering safe species-specific microsites (Marzano et al. 2013). For instance, favorable microsites for Scots pine regeneration might include favorable topographic features and shelters from snow cover, grazers, and water runoff. The importance of CWD in facilitating tree regeneration establishment and survival, particularly in the first years after the disturbance, should be always taken into consideration (Castro et al. 2011; Marzano et al. 2013). Appropriate species selection is also fundamental.

The majority of studies found in the literature about AN were located in tropical areas, with AN being a technique mainly used to restore tropical ecosystems after years of agricultural overexploitation (e.g., Holl et al. 2020; Rey Benayas et al. 2020; Di Sacco et al. 2021). However, its application could also be implemented on restoration projects in mountain forests ecosystems, given the current shifts in fire regime and the difficulties in post-fire recovery that those stands are facing.

To our knowledge this work is the first attempt to simulate the effects of an AN project in a mountain conifer forest affected by a stand-replacing fire, considering several environmental factors. The results obtained from this study can be used by policymakers and stakeholders as a tool for planning precise and effective active interventions to restore disturbed stands.

6. Data availability statement

Data from the current study are available in the Figshare repository, doi: https://doi.org/10.6084/m9.figshare.23619018. The R code is available upon request.

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CRediT authorship contribution statement

Giulia Mantero: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing – original draft. **Nicolò Anselmetto:** Conceptualization, Methodology, Data curation, Formal analysis, Writing – review & editing, Visualization. **Donato Morresi:** Writing – review & editing, Visualization. **Fabio Meloni:** Data curation. **Paola Bolzon:** Data curation. **Emanuele Lingua:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Matteo Garbarino:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition, Writing – review & editing. **Raffaella Marzano:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2023.121520.

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