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SHORT- AND MEDIUM-TERM DRIVERS OF POST-FIRE REGENERATION DYNAMICS IN THE CONTEXT OF GLOBAL CHANGE AND ALTERED DISTURBANCE REGIMES

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Abstract

Many threats to the functioning of ecosystem have been arising from global change. Among them, climate and land use changes are considered the main drivers affecting forest ecosystems globally.

Awareness toward the importance of understanding complex ecological interactions between global change components is growing among ecosystem managers and stakeholders.

This PhD thesis aimed at understanding the consequences of global changes on disturbance regimes, focusing on their potential impacts on forest ecosystems and, particularly, on post-fire dynamics of mountain conifer stands. The first objective was to investigate the consequences of land abandonment on forest disturbance regimes at a global scale and hence to fulfill a gap of knowledge concerning the role of land use change in disturbance regime alterations, especially in mountain ecosystems. This objective was pursued through a systematic review based on worldwide studies that explored the ecological consequences and management implications of land abandonment on forest disturbance regimes. We observed a significant imbalance in terms of research locations and types of analyzed disturbance, with most studies exploring changes in wildfire regime characteristics in the Mediterranean area.

The increase of wildfire severity and frequency, resulting from woody encroachment, combined with the harsher environmental conditions damped by ongoing climate change can hinder regeneration recruitment, particularly for obligate seeders in mountain ecosystems. Therefore, rethinking current post-fire management strategies in mountain ecosystem is crucial to mitigate the consequences of wildfire regime alterations on forest ecosystems. Indeed, in the last decades, traditional post-disturbance practices (e.g., salvage logging) have

been gradually replaced by nature-based solutions, that are more effective and less expensive. These practices can be extremely useful to restore degraded ecosystems by facilitating post-fire recovery and avoiding degradation processes, but they require a proper knowledge of all the factors affecting regeneration dynamics. Assessing the drivers of post-fire regeneration in conifer stands in North-Western Italian Alps and modeling the outcomes of a novel post-fire management strategy were respectively the second and third steps of the investigations described in this thesis. The results of these studies highlighted the importance of a proper planning and targeted measures, when implementing post-fire restoration strategies. Moreover, active intervention should be considered only when natural dynamics are delayed, and there are risks of triggering degradation phenomena (e.g., erosion). The results obtained with this thesis have shed some light on the post-fire dynamics in conifer stands in the context of global change and altered disturbance regimes. These findings could be helpful to enhance potential mitigation strategies and ecologically appropriate restoration approaches.

Chapter 1

Introduction

1.1 Global change and disturbance regimes

Human-related activities have been transforming the biosphere since the late Pleistocene, altering climate and landscape characteristics, and irreversibly affecting ecosystems with an escalating magnitude of change through millennia (Ellis et al. 2010; McDowell et al. 2020; Sage 2020; Ellis et al. 2021; Mottl et al. 2021). Alterations in the structure and functioning of the Earth System, induced by biophysical and socioeconomic changes have been referred as global change (Steffen et al. 2007). In the last centuries industrial processes, new technologies, and agricultural intensification allowed a significant increase in the population growth rate, inducing even more profound changes in the Earth System (Ellis et al. 2013). Changes in land cover and land use caused by human activities such as deforestation and, more recently, land abandonment, together with increased emissions of greenhouse gases have strongly impacted climate, due to the biogeochemical and biogeophysical feedbacks with the atmosphere (Allen et al. 2010; Ellis et al. 2013). The increase in global mean temperature and in the frequency and duration of climate extremes, such as droughts, are among the most evident consequences of climate change (McDowell et al. 2020; IPCC 2022). These alterations have unneglectable consequences on health, environment, and economy worldwide. From an ecological point of view anthropogenic climate and land use changes are causing rapid alterations, affecting every aspect of ecosystems, including natural disturbances (Seidl et al. 2011; Bebi et al. 2017; Kulakowski et al. 2017; Seidl et al. 2017).

A disturbance was defined by White and Pickett (1985) as “any relatively discrete event that disrupts the structure of an ecosystem, community, or population, and changes resource availability or the physical environment". Disturbances are usually described through their regimes, referring to their spatial and temporal dynamics over time (White and Pickett 1985; Turner 2010). The characteristics of a disturbance regime includes disturbance frequency, return interval, rotation period, disturbance size, intensity, severity, and residuals (White and Pickett 1985; Turner et al. 1998; Turner 2010) (Fig. 1.1).

Term	Definition
Frequency	Mean or median number of events occurring at an average point per time period, or decimal fraction of events per year; often used for probability of disturbance when expressed as the decimal fraction of events per year.
Return interval	Mean or median time between disturbances; the inverse of frequency; variance may also be important, as this influences predictability.
Rotation period	Mean time needed to disturb an area equivalent to some study area, which must be explicitly defined.
Size	Area disturbed, which can be expressed as mean area per event, area per time period, or percentage of some study area per time period.
Intensity	Physical energy of the event per area per time (e.g., heat released per area per time period for fire, or wind speed for storms); characteristic of the disturbance rather than the ecological effect.
Severity	Effect of the disturbance event on the organism, community, or ecosystem; closely related to intensity, because more intense disturbances generally are more severe.
Residuals	Organisms or propagules that survive a disturbance event; also referred to as biotic legacies. Residuals are measure of severity, and thus (at least within one disturbance) an index of intensity.

Fig. 1.1: *Definitions of components of a disturbance regime (from Turner et al. 2010).*

Disturbances and landscapes have strong interactions. Indeed, disturbances shape ecosystems structures and dynamics by altering their state and trajectories, but are also affected by landscape structure, land cover and use, as well as climate

(Turner 2010; Bebi et al. 2017; Kulakowski et al. 2017). Despite the common perception of disturbances is associated to the idea of damaged or destroyed ecosystems, they are key ecological drivers of spatial and temporal heterogeneity and of biodiversity (Turner 2010). Since disturbances are closely related to ecosystem processes, an alteration in their regime could affect post-disturbance recovery and trigger degradation processes, with potentially far-reaching impacts (Turner 2010; Thom and Seidl 2016; Pausas and Keeley 2021). Indeed, an increase in fire frequency and severity could severely constrain natural regeneration, of both resprouter and seeders (Doblas-Miranda et al. 2017). A decrease in the resprouting ability of plant has been observed due to higher fire frequency and severity (Doblas-Miranda et al. 2017). Similarly, a failure of obligate seeders regeneration could occur when intervals between fires are shorter than the time required to reach sexual maturity (Màrcia et al. 2006; Espelta et al. 2008; Doblas-Miranda et al. 2017; Taboada et al. 2018). Moreover, alteration in fire frequency could lead to lower density, height, and reproductive ability (Espelta et al. 2008). Changes in climate and land use are responsible for the alteration of the historical disturbance regimes in forest ecosystems by introducing novel disturbances or modifying the characteristics of the existing ones (e.g., Turner 2010; Meddens et al. 2012; Thom and Seidl 2016). The effects of climate change on disturbance regimes have been thoroughly analyzed over the recent decades. Intense drought episodes, together with heat stress, are shifting tree species distributional range, altering forest composition and structure, inducing physiological stress, increasing forest mortality, and dieback (Allen et al. 2010; Barros et al. 2017). A big focus was also pulled on wildfires (Seidl et al. 2017), due to their profound impact and potential damage on human population and vegetation community. Despite the existing research bias towards some disturbances (i.e., wildfire, drought, insects, and pathogens) and locations (i.e., North America and Europe), climate-change induced alterations on disturbance regimes are spiking in the majority of forest biomes, threatening ecosystems balance and services provision (Thom and Seidl 2016; Millar and Stephenson 2015; Seidl et al. 2017). Similarly, the profound changes in land use and land cover that are taking place, especially in some areas of the World, are already altering disturbance regimes. However, the effects of such changes are more difficult to identify and classify, given the variety of the phenomena and their relatively recent emergence. Land abandonment, for instance, affected over 9 Mha in Europe between 1990 and 2000 (Pointereau et al. 2008), and almost 150 Mha worldwide in the last three centuries (Ramankutty and Foley 1999). Despite the importance and the global nature of this phenomenon, it has not been extensively studied, with an evident knowledge gap in the area of natural disturbances, that needed to be filled, especially in mountainous regions (Haddaway et al. 2014).

1.2 Post-disturbance dynamics

Changes in disturbance regimes triggered by land use and climate change have the potential to alter significantly the ecological communities, shifting the ecological niche of some species and delaying or blocking post-disturbance regeneration dynamics (Turner 2010). Species adapted to a certain disturbance regime might become unable to regenerate when the characteristics of that regime change abruptly (e.g., changes in frequency or severity), leaving room for species that are better adapted to the new conditions (Turner 2010). The stress induced by changes in disturbance regimes could be also enhanced by changes in climate conditions and land cover, that were already causing a decline in species located at the fringes of their distributional range (Hanewinkel et al. 2013). Mountain areas of the Mediterranean region have been subjected to thousands of years of human alterations, that created spatially-structured landscape mosaics (Scarascia-

Mugnozza et al. 2000). Those landscapes are extremely complex, characterized by great biodiversity and endemic species. However, the resulting ecosystems are fragile and are particularly sensitive to changes, due to the harsh and unpredictable climate, the difficult socio-economic conditions, and their history of over-exploitation (Scarascia-Mugnozza et al. 2000). As a result of these conditions, forests of the Mediterranean mountains are often hotspots of changes in disturbance regimes, climate, and land use, that lead to rapid ecosystems changes (Doblas-Miranda et al. 2017).

Considering wildfire, one of the most common disturbances in the Mediterranean area, changes in the severity, frequency, or extension of its regime could irreversibly affect ecosystems, leading to shift from forest types to shrublands or grasslands, especially for species without fire-adaptive traits (Enright et al. 2015; Stevens-Rumann et al. 2017; Haffey et al. 2018; Turner et al. 2019). Increase in temperature and prolonged drought periods are promoting wildfire activity, acting together with land use change, that is creating more homogeneous and connected landscapes, through the process of tree and shrub encroachment. This process is causing a shortening of the wildfire interval, as well as an increase in the severity of wildfires. Seedling recruitment after wildfire, which mostly occurs in the first year after the event (Keeley et al. 2006), has already a greater possibility to fail, due to an increase in the frequency of years with unfavorable conditions for seedling establishment and survival (e.g., harsher and drier climate conditions; Enright et al. 1996, 2014, Stevens-Rumann et al. 2017). The shortening of the wildfire interval can reduce the probability of seedling recruitment even further, by reducing the time available to plants for seed accumulation and possibly leading to a shift in species composition toward more flammable species (D'Antonio and Vitousek 1992; Brown and Johnstone 2012), with the consequent disappearance of slow growing and slowly maturing species

(Westerling et al. 2011). Conifer species without fire-related traits are particularly sensitive to changes in wildfire regime, since they can only rely on the arrival of propagules from the unburnt edge for post-fire regeneration (Moser et al. 2010). Wildfire regime characteristics are the main aspects affecting the dynamics of stands dominated by those species, that can be replaced by shrubland or resprouting broadleaves (e.g., oak species; Moser et al. 2010). Scots pine (*Pinus sylvestris* L.) is the most widespread coniferous species in Europe (Mirov 1967), and it is particularly sensitive to the effects of climate and land use changes, especially in the European Alps, that are at the Southern edge of its distribution (Gimmi et al. 2010). Wildfire regime in Scots pine stands is characterized by wildfire with moderate severity and low frequency (Agee 1998; Fernandes et al. 2008; Hille 2006). Scots pine is an early successional and light requiring species, able to establish and grow under the favorable conditions created post-fire (Robakowski et al. 2014). Propagule availability for this species after a disturbance is primarily guaranteed by the seed rain from live trees and the dispersal capacity of the seeds (Greene et al. 2005; Krüssmann 1983; Zasada et al. 1992). However, its regeneration dynamics in the actual context of wildfire regime alteration in the Mediterranean area, will likely be delayed or altered, as already observed in other studies (e.g., Rodrigo et al. 2004; Moser et al. 2010; Enríquez-de-Salamanca 2022). The widespread distribution of Scots pine in the European Alps, together with its lack of fire-related traits and the susceptibility to changes in wildfire regime, make post-fire management of this species particularly important in the next future. (Enríquez-de-Salamanca 2022). In order to develop adequate strategies, it is fundamental to have an in-depth understanding of all the factors affecting regeneration dynamics, including the characteristics of the wildfire event, the environmental conditions of the affected area, the pre-fire forest attributes, and the most important drivers affecting regeneration settlement and success (Martín-Alcón and Coll 2016).

1.3 Post-disturbance management and ecological restoration

Given the widespread changes in wildfire regimes worldwide and the resulting difficulties in post-fire recovery, particularly for species lacking fire-related traits, managers and policymakers are facing new challenges when it comes to plan post-fire management strategies. However, the alterations resulting from the above-mentioned processes can also be seen as a chance to restore ecosystems, by targeting post-fire management plans towards specific ecological objectives (Leverkus et al. 2019). As an example, wildfire can help restoring natural ecosystems, promoting a transition towards native and less flammable species (Leverkus et al. 2019). Post-fire management has been a controversial topic in the past decades, with many different theories and studies (e.g., the Donato controversy related to the management of the Biscuit Fire area; Donato et al. 2006; Newton et al. 2006; Leverkus et al. 2018a, Thorn et al. 2018; Thorn et al. 2020). The most common post-fire practice adopted worldwide is still salvage logging, consisting in the harvesting of dead or damaged trees from sites after disturbance events (Lindenmayer and Noss 2006; Lindenmayer et al. 2008). The negative consequences of salvage logging began emerging at the beginning of the 21th century (Donato et al. 2006), and have been studied thoroughly in the past decades (e.g., Lindenmayer and Noss 2006; Lindenmayer et al. 2008; Leverkus et al. 2018a, b). Even though salvage logging has been proven to have negative impacts on natural regeneration, soil erosion, and biodiversity (e.g., Marzano et al. 2013; Leverkus et al. 2018a, b; Marcolin et al. 2019), its application is still frequent. There are several reasons for this practice to be still so widely used despite all the negative evidences (Leverkus et al. 2018a; Müller et al. 2019)

Economically, timber is still valuable if the wood is retrieved immediately after a disturbance event (Lindenmayer et al. 2008; Müller et al. 2019). Socially, a disturbed forests is often perceived as a destroyed ecosystem that need to be restored by human action (Beghin et al. 2010; Leverkus et al. 2018a). Moreover, these interventions are sometimes justified by arguable ecological motifs, like synergism with other disturbances (e.g., wildfires or insect outbreaks; Seidl et al. 2016; Müller et al. 2019; Burton et al. 2020). Eventually, a new awareness is spreading, even among land managers and policymakers, leading to a higher demand for more ecologically and economically feasible post-fire management techniques to restore burnt forests. An effective strategy to minimize human interventions and their associated economic and ecological costs, consist in taking advantage of natural regeneration, whether with a passive or an active approach (Di Sacco et al. 2021). Passive restoration, relying on the spontaneous recovery of native tree species that establish within areas affected by natural disturbances (Crouzielles et al. 2017), should be preferred whenever there are no risks of triggering ecosystems degradation and damages to human communities and infrastructures in the absence of active intervention (Beghin et al. 2010; Moreira et al. 2012; Chazdon et al. 2021). However, passive restoration is not always feasible, especially in those areas largely anthropized, where there is no possibility of waiting for natural timing, further degradation processes are expected, or natural regeneration is hindered for different reasons. In those cases where human action is advisable to avoid detrimental consequences on both ecosystems and society, there is a spectrum of different levels of active intervention, from Assisted Natural Regeneration (ANR) to Applied Nucleation (AN; Di Sacco et al. 2021). The lowest level of active intervention, ANR, aims to accelerate natural successional processes by removing or reducing obstacles to natural forest regeneration, such as competitors (e.g., grass or shrubs) and recurring disturbances (e.g., wildfire, grazing, and wood harvesting; Shono et al. 2007). ANR can be used to restore degraded areas, or to accelerate natural dynamics, and since it does not require planting or post-planting care, could be a cost-effective technique (Shono et al. 2007). However, ANR is most suitable for restoring areas where some level of natural succession is in progress, with a minimum number of seedlings, that varies depending on species, site conditions, and the time required for the restoration to be completed, that, as a general indication, should be around 200-800 seedlings ha^{-1} (Shono et al. 2007). In those area where natural regeneration dynamics are hindered for different reasons (e.g., distance from seed sources, availability of propagules), the use of AN approaches could be useful to accelerate natural regeneration dynamics, usually being a more cost-effective technique than plantation. AN consists in planting small groups of trees, called *nuclei*, that will expand by both facilitating colonization by other species, and by dispersing seeds themselves, being able to restore forest cover within a highly disturbed site (Corbin and Holl 2012; Di Sacco et al. 2021). This technique mimics natural successional processes, by improving stressful abiotic conditions (i.e., high temperature, low humidity), facilitating seedling establishment, and increasing seed availability, thus leading to forest expansion over time (Rey Benayas et al. 2008; Corbin and Holl 2012; Aradottir and Halldorsson 2018; Holl et al. 2020). AN is a relatively recent and promising technique, that found its main application in tropical ecosystems, aiming to restore abandoned and overexploited fields (Corbin and Holl 2012; Shaw et al. 2020). However, it has the potential for an application in other ecosystems, especially those where natural regeneration tends to exhibit succession by nucleation, as in mountain areas (Shaw et al. 2020). Moreover, its use requires lower costs and has a reduced ecological footprint than plantation, needing few preliminary operations (Holl et al. 2020). AN could thus be an effective strategy to restore degraded landscapes, avoiding excessive costs, while mimicking the ecological dynamics of ecosystems. The application of AN techniques requires an accurate planning, that must consider, in addition to site characteristics, also the presence of natural regeneration and the dynamics already in place.

1.4 Thesis objectives and outline

This thesis aims to understand post-fire dynamics of mountain conifer stands, in the context of climate and land use changes. The structure of the thesis is based on the following objectives:

(i) investigating the most relevant effects of land abandonment and land use legacy on the regime of different types of forest disturbances;

(ii) identifying the most important environmental drivers of post-fire regeneration in areas affected by a mixed severity wildfire and disentangling their impact on the spatio-temporal dynamics of post-fire recovery in mountain forests;

(iii) modeling the probability of post-fire regeneration presence across the landscape under the current situation and a set of applied nucleation (AN) scenarios in an area affected by a large stand-replacing wildfire and subsequent post-fire salvage logging operations.

The thesis consists of five chapters: introduction (Chapter 1), research chapters (Chapters 2 to 4) and conclusions (Chapter 5). Research chapters are organized as standalone research papers. Chapter 2 and Chapter 3 have been published and Chapter 4 has been submitted for publication. Chapter 2 "The influence of land abandonment on forest disturbance regimes: a global review" aims at highlighting the most relevant effects of land abandonment and land use legacy on the regime of different types of forest disturbances, providing insight into land use change/disturbances interactions. Chapter 3 “Short-term drivers of post-fire forest regeneration in the Western Alps” investigates short-term forest recovery after a large mixed severity wildfire, characterized by a high spatial heterogeneity resulting from varying levels of fire severity on the predominantly forested landscape. Chapter 4 “Modelling post-fire regeneration patterns under different restoration scenarios to improve forest recovery in degraded ecosystems” focuses on the identification of the most important drivers of post-fire recovery and hence defines intervention priorities for active restoration based on the probability of post-fire natural regeneration presence within an area affected by a stand-replacing wildfire and consequent salvage logging.

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Chapter 2

The influence of land abandonment on forest disturbance regimes: a global review

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Abstract

Background

Since the nineteenth century, rural areas have experienced progressive abandonment mostly due to socioeconomic changes, with direct and indirect effects on forest disturbance regimes occurring in these human-dominated landscapes. The role of land abandonment in modifying disturbance regimes has been highlighted for some types of disturbances, albeit being still somewhat overlooked compared to climate change.

Objectives

This literature review is aimed at highlighting the most relevant effects of land abandonment and land use legacy on the regime of different types of forest disturbances, providing insight into land use change/disturbances interactions.

Methods

We searched in the Scopus and Web of Science databases for relevant studies at the global scale dealing with eight major natural disturbances: avalanche, flooding, herbivory, insect outbreak, landslide, rockfall, wildfire and windthrow. We classified papers into five relevance classes, with the highest score (4) assigned to studies quantitatively measuring the interactions between abandonment dynamics and disturbance regimes.

Results

Most papers focused on wildfires in Mediterranean Europe in the twentieth century, where landscape homogenization, and fuel build-up contributed to worsening their frequency, size, and severity. Dense forests developed following land abandonment instead exert inhibiting effects toward mass movements such as avalanches, rockfalls, and landslides. Regarding the other investigated disturbances, we found only a few studies presenting site-specific and partly contrasting effects.

Conclusions

Land abandonment triggers ecological processes at the landscape scale, altering land cover patterns and vegetation communities, which in turn affect disturbance regimes. Implications for land and resource management mostly depend on the stage at which post-abandonment secondary succession has developed.

Keywords: Land use change, Disturbance ecology, Wildfire, Landslide, Avalanche, Windthrow, Rockfall, Insect outbreak, Flooding, Herbivory

2.1 Introduction

Land abandonment has recently been identified as the most important local-scale cause of landscape change in Europe (Ameztegui et al. 2016; Levers et al. 2016; Plieninger et al. 2016). Mountainous and marginalized areas of Europe have been being depopulated since the end of nineteenth century and mostly from the second half of twentieth century (Varga et al. 2018), leading to massive changes in land cover and land use (MacDonald et al. 2000; Tasser et al. 2007; Sitzia et al. 2010; San Roman Sanz et al. 2013). Only between 1990 and 2000, agricultural land abandonment involved over 9 Mha in 20 European countries (Pointereau et al. 2008). In Russia, after the fall of the Soviet Regime, more than 40 Mha of arable land had been abandoned within 20 years (Prishchepov et al. 2012).

The phenomenon of land abandonment is however strongly affecting several other regions around the world (Cramer et al. 2008; Munroe et al. 2013), with an exponential increase in rate and extent since the 1950s (Cramer et al. 2008). Ramankutty and Foley (1999) estimated 1.47 million km^2 of abandoned croplands worldwide between 1700 and 1992: according to this study, eastern North America experienced the earliest and largest cropland abandonment (starting from mid to late nineteenth century); the phenomenon then began to become widespread also in Eurasia, mostly from the 1960s. Aide et al. (2012) estimated more than 360,000 km^2 of recovered woody vegetation resulting from abandoned agricultural land in South America.

Despite the widespread and growing trend of global agricultural abandonment, its importance is often neglected compared to other two processes also significantly determining global environmental change, i.e., increasing competition for land (Smith et al. 2010; Sikor et al. 2013) and expansion of land use activities (Foley et al. 2005).

Land abandonment is defined as a process ‘whereby human control over land (e.g., agriculture, forestry) is given up, and the land is left to nature’ (FAO 2006). Several drivers are responsible for land abandonment and are typically classified into three main categories: (1) unadapted agricultural systems and land mismanagement (leading for example to overexploitation or soil degradation); (2) ecological or environmental drivers (including such factors as elevation, slope, aspect, soil erosion, climate); (3) socioeconomic drivers (including for instance migration and rural depopulation, market incentives, technology, industrialization) (e.g. Rey Benayas et al. 2007; Haddaway et al. 2014; Lasanta et al. 2017). This latter category (and among its factors, rural–urban migration) has been suggested to be the most prominent globally (Rey Benayas et al. 2007). Marginal and mountain areas are often hotspots of change, where many of the drivers included in these three categories act simultaneously and can result in complex interactions.

Land abandonment reflects global trends and regional features, but it is mostly local socioecological conditions that guide its direction, pace, and outcomes. The main result of land abandonment is commonly an uncontrolled colonization by woody vegetation in the abandoned areas that leads to the establishment of shrublands, woodlands or forests, with various landscape, environmental and socioeconomic impacts (Lasanta et al. 2017).

In terms of societal trade-offs, positive, as well as negative consequences, whose relevance can differ in different parts of the world, may result from land abandonment. These consequences can also occur over varying temporal and spatial scales (Hall et al. 2012). Among the possible problems arising from the abandonment of agricultural land, Rey Benayas et al. (2007) identified five main ones: the reduction of landscape heterogeneity, soil erosion and desertification, reduction of water stocks, local biodiversity decrease and loss of cultural and aesthetic values. This is particularly true for those landscapes that were shaped by millennia of human intervention, where land cultivation resulted in complex and heterogeneous systems with a mosaic of diversified patches ensuring high levels of species and structural diversity. The Mediterranean basin and other dry regions of the world are more likely to experience the detrimental consequences of land abandonment, with increasing degradation processes. Conversely, in the absence of dispersal as well as abiotic and biotic limitations, revegetation can result in positive impacts on carbon sequestration, soil recovery, nutrient cycling, biodiversity (e.g., higher number of species typical of woodland or forest habitats), hydrological regulation, erosion reduction (Rey Benayas et al. 2007; Haddaway et al. 2014; Plieninger et al. 2014). Opportunities for ecosystem restoration can thus arise from abandonment, through both passive processes and active rewilding initiatives (Torres et al. 2018; Perino et al. 2019).

An increase in forest cover around the world has been associated with the cessation of agricultural activities and consequent land abandonment (Lambin and Geist 2006). Post-abandonment forest expansion has been commonly observed on steep slopes of mountainous regions all over the world (e.g., MacDonald et al. 2000; Fukamachi et al. 2001; Southworth and Tucker 2001; Gehrig-Fasel et al. 2007; Gellrich et al. 2007; Kuemmerle et al. 2008; Meyfroidt and Lambin 2008; Hartter et al. 2010; Cao et al. 2011; Aide et al. 2012; Brown et al. 2012; Garbarino et al. 2020). This ‘forest transition’ (a reversal from net deforestation to reforestation in a region; Munroe et al. 2013) may be favored by national or international policies integrating environmental concerns and promoting ecosystem restoration (see for instance the Common Agricultural Policy (CAP) in the European Union; Pointereau et al. 2008).

Abandonment outcomes, either positive or negative, result in changes of landscape properties that could affect disturbance regimes, introducing novel disturbances within the system or modifying the characteristics of the existing ones. Land abandonment can thus be considered one of the most important drivers of regime shifts for several disturbances acting at different spatial scales. Abandonment of large areas can result in a more homogeneous landscape, change vegetation structure and composition (sometimes favoring the presence of invasive species), increase fuel load and/or vertical continuity or in general density and distribution of biomass. All of these modifications have potential impacts on the occurrence and characteristics of disturbances (e.g., landscape homogenization can promote the spread of certain disturbances and increase their size and severity). However, possible effects on disturbance regimes are controversial and may vary locally, based on trajectories of land abandonment (e.g., time since abandonment, cultivation legacies, local climate, and soil conditions).

The role of land abandonment on disturbance regimes in human-dominated landscapes has been recognized for some types of disturbances, particularly for those defined as natural hazards, due to the presence of people and human assets threatened by their occurrence, with potential negative impacts on society. Nevertheless, compared to land use change, climate change is still more often described as the main driving force affecting disturbance regimes globally (Dale et al. 2000; Seidl et al. 2017). Gravity- driven disturbances (e.g., rockfalls, avalanches, landslides), whose occurrence is more frequent in mountain areas, where steeper slopes have a higher probability of being abandoned, could then be most affected by land abandonment. Indeed, in their systematic map on the environmental impacts of farmland abandonment in high altitude/mountainous regions, Haddaway et al. (2014) identified a knowledge gap in the area of natural disturbances.

This literature review is based on worldwide studies and explores the effects of land abandonment on natural forest disturbance regimes. Evidence existing on interactions between this form of land use change (LUC) and the occurrence of different types of disturbances leading to short- or long-term shifts in their regimes could provide useful insights into resource management implications in marginal and abandoned areas.

2.2 Materials and methods

To explore the effects of land abandonment on disturbance regimes, we exploited the Scopus and Web of Science databases, conducting a literature search including only papers published in English. Using these online databases, we performed a preliminary scoping to identify the most relevant terms to include in the search string.

A disturbance is defined here according to the widespread definition by White and Pickett (1985) as ‘‘any relatively discrete event in time that disrupts ecosystem, community, or population structure, and changes resources, substrate availability or physical environment’’. After the preliminary scoping, we decided to also include the term natural hazard, defined as ‘‘a natural process or phenomenon that may have negative impacts on society’’ (UNISDR 2009), which is often applied to identify those disturbances affecting people or human assets. We only considered disturbances caused by an agent of natural origin, and not other kind of disturbances, such as those related to the cessation of agriculture and industrial activities.

The disturbance types considered for this research were (1) avalanche, (2) flooding, (3) herbivory, (4) insect outbreak, (5) landslide, (6) rockfall, (7) wildfire and (8) windthrow. We searched for interactions of land abandonment with disturbance regimes, possibly altering one or more of the main components of a regime (i.e., frequency, size, severity) and also with disturbance risk (danger x vulnerability). The terms were searched in titles, abstracts, and keywords.

The final search string, reported here as applied in Scopus, includes the following key terms: ‘‘TITLE-ABS- KEY (‘‘land-use’’ OR ‘‘land-cover’’ OR ‘‘land-use change’’ OR ‘‘land use change’’ AND abandonment OR ‘‘secondary succession’’ OR ‘‘forest development’’ OR ‘‘fallow land’’ OR ‘‘marginal land’’ OR ‘‘old-field succession’’ OR ‘‘forest expansion’’ OR ‘‘new forest’’ AND fire OR wildfire OR ‘‘forest fire’’ OR wind* OR storm OR ‘‘ice storm’’ OR flooding OR landslide OR rockfall OR ‘‘rock fall’’ OR avalanche OR ‘‘snow gliding’’ OR herbivory OR ungulates OR browsing OR insect OR ‘‘bark beetle’’ OR hazard* OR disturbance* AND forest* OR woodland* OR shrubland*)’’.

We ranked each paper based on its suitability for the aims of the review by giving a score from 0 to 4, corresponding to no or high relevance, respectively. We considered highly relevant (R4) those papers that quantitatively measured the interactions between abandonment dynamics and disturbance regimes. We classified papers as moderately-highly relevant (R3) when the abandonment phenomenon and disturbance regime characteristics were linked through a qualitative approach. We considered the relevance as moderate-low (R2) when the interactions between land abandonment and disturbance regime shifts were only mentioned. We gave a score of 1 (R1) to articles with low relevance, only citing land abandonment and/or disturbance regime shifts, or to the papers that only analyzed other effects of land abandonment (e.g., soil erosion, increase or decrease in biodiversity, changes in C stock). Finally, we gave a score of 0 (R0) to those papers with no relevance (containing the queried words without focusing on the topic), which were therefore discarded.

The search was conducted by one of the authors (GM) on 18 May 2020, to include all studies published until 31 December 2019. Duplicate articles found on both databases were removed. The relevance of the resulting papers was then assessed following a stepwise classification procedure. All titles and abstracts (n = 900) were read in the first step by GM to attribute relevance 0 and 1. Introduction and discussion sections of the remaining papers (n = 194) were read in a second step by GM to attribute relevance 2 to 4. To assess the homogeneity of the evaluation and the absence of biased judgment, 100 randomly chosen articles were also checked by DM, and the resulting classification was compared with that obtained by GM.

The papers with high ranking (≥ 3; n = 98) were then screened by MG, DM and RMa, and read in full by GM and RMa.

We assessed the abundance of papers on a yearly basis, standardizing the number of articles found in our research by the total number of papers published for each year, containing both the keywords ‘‘land use’’ and ‘‘forest’’.

For papers with a relevance higher than 2 we examined the geographical distribution of the studies by disturbance type, based on available or derived coordinates, assigning the relative biome according to Olson et al. (2001). We also summarized the main effects of land abandonment on disturbance regime characteristics (i.e., size, frequency, severity) and risk, as reported in those papers.

For the papers with the highest relevance (4) we retrieved data on land use prior to abandonment, time since abandonment and effects on the main disturbance regime, in terms of increase or decrease in frequency or severity, and higher or lower risk.

On a subset of studies with relevance 4, quantitatively assessing land use change and regime alterations following land abandonment, we further reported the percentage of change for each land use class. We considered the following land use classes: forest, cropland (including grassland), shrubland, and urban.

2.3 Results and discussion

2.3.1 Literature review

The results of the article selection and classification workflow are reported in Fig. 2.1.

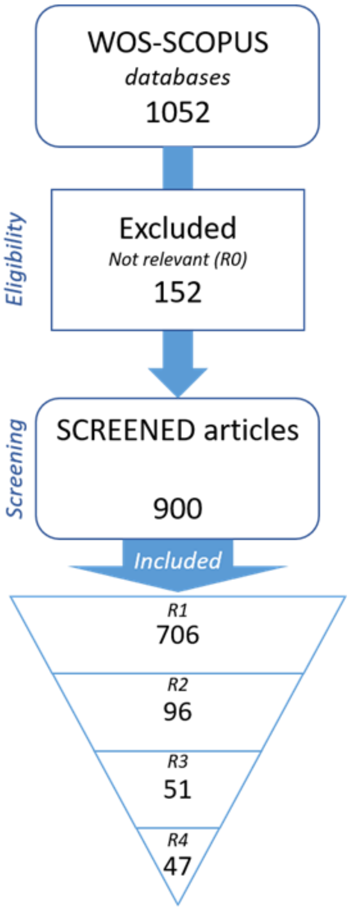

Fig. 2.1: *Article selection and classification workflow of 1052 papers resulting from the WOS-SCOPUS query: "land-use" OR "land-cover" OR "land-use change" OR "land use change" AND abandonment OR "secondary succession" OR "forest development" OR "fallow land" OR "marginal land" OR "old-field succession" OR "forest expansion" OR "new forest" AND fire OR wildfire OR "forest fire" OR wind* OR storm OR "ice storm" OR flooding OR landslide OR rockfall OR "rock fall" OR avalanche OR "snow gliding" OR herbivory OR ungulates OR*

browsing OR insect OR "bark beetle" OR hazard OR disturbance* AND forest* OR woodland* OR shrubland*. The article relevance (R) for the aims of the review ranges from 0 (not relevant) to 4 (highly relevant).*

The relative frequency of published papers per year (Fig. 2.2) showed a slight increase in the number of published works from 1985 to 2019, but without a clear trend. Prior to 2000, there were very few papers with relevance higher than 2. If we assessed the abundance of papers on a yearly basis with two WOS-SCOPUS queries including, respectively, the key terms ‘‘land-use change’’ AND disturbance*, and ‘‘climate change’’ AND disturbance*, we found that, from 1985 to 2019, their number greatly increased (e.g. WOS TOPIC ‘‘land-use change’’ AND disturbance*: n = 0 in 1985, 25 in 2005 and 161 in 2019; WOS TOPIC ‘‘climate change’’ AND disturbance*: n = 0 in 1985, 95 in 2005 and 1094 in 2019). Papers dealing with climate change always exceeded in number those dealing with land use change, being around 6 times more frequent in 2019. This result highlighted the strong focus on climatic drivers compared to land use change ones.

Among papers analyzing a specific disturbance in relation to land abandonment (n = 287), wildfire was by far the most studied (65.8%) and had the largest number of studies in the higher relevance classes (R3 = 62.7%; R4 = 53.2%; Fig. 2.3), followed by flooding (10.5%) and landslide (8.4%).

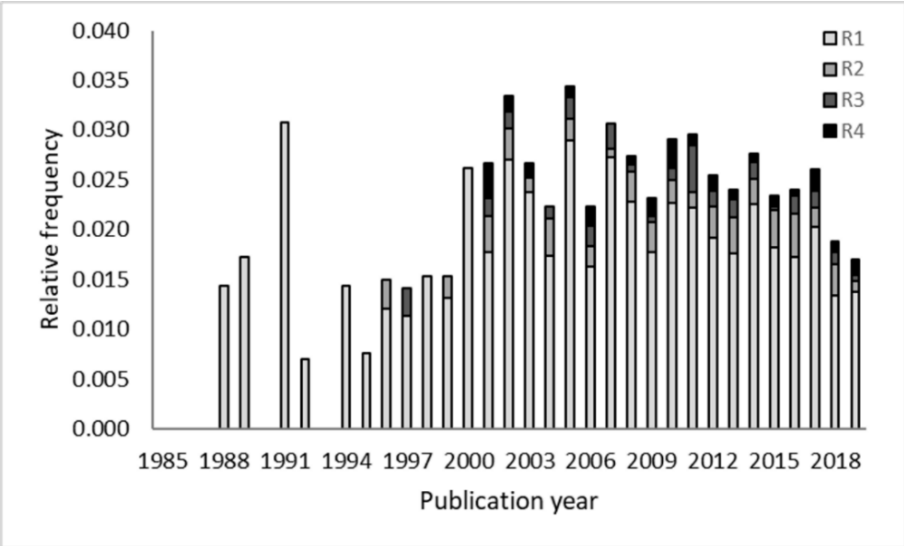

Fig. 2.2: *Number of published papers per year standardized by the total number of papers published in the same year containing both the keywords "land use" and "forest", grouped by relevance score (1 - 4), for the period 1985 – 2019. Only papers with a relevance ≥ 1 (n=900) are included.*

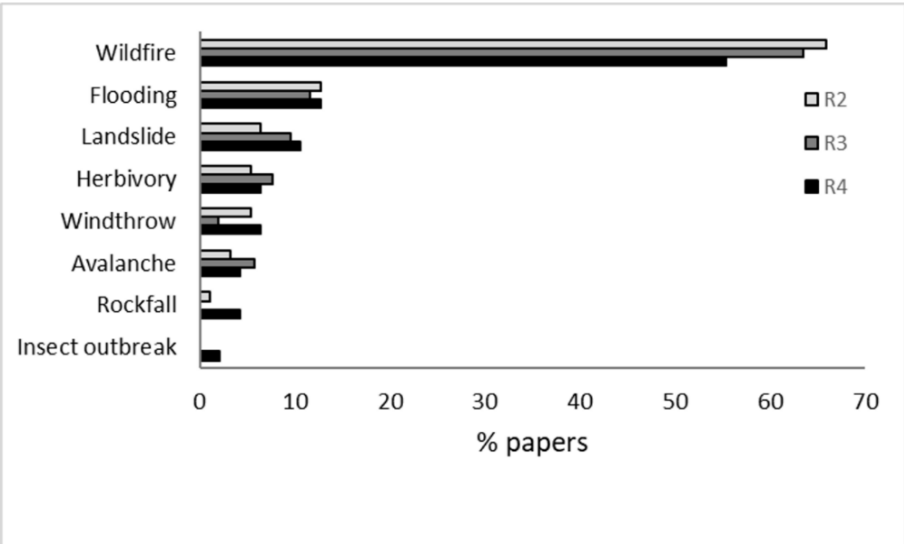

Fig. 2.3: *Relevance (R) proportion by disturbance type among papers with relevance ≥ 2.*

From a map of the most relevant (R ≥ 2) papers of our literature search we observed that the majority (84%) of studies were located in Europe and among these, 60% were in the Mediterranean region (Fig. 2.4). This result appeared to be mostly driven by the socioeconomic changes that occurred in this area during the twentieth century as a result of rural–urban migration (Rey Benayas et al. 2007) and the related scientific attention to this phenomenon.

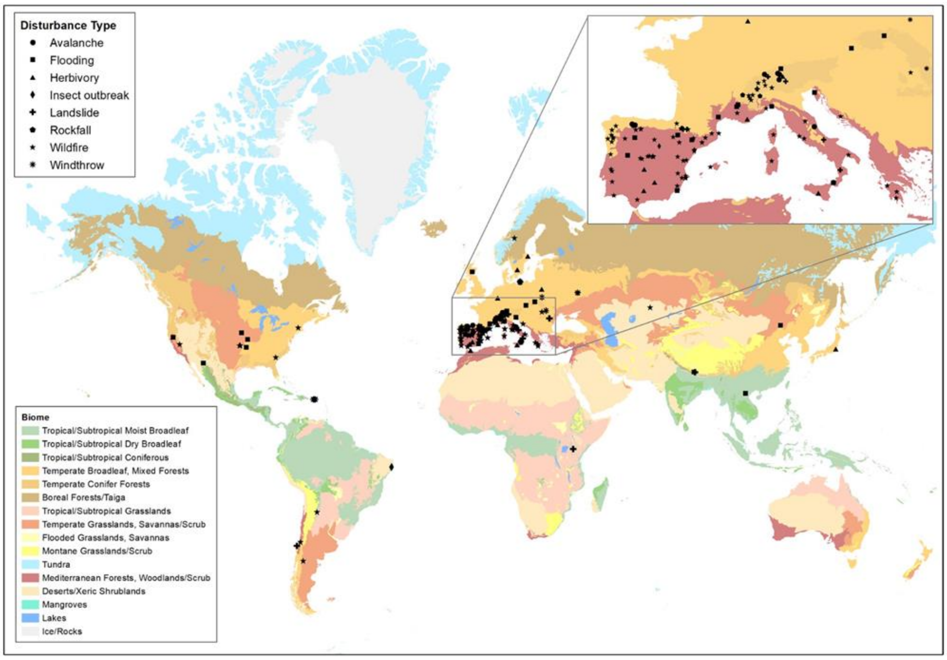

Fig. 2.4: *Geographic distribution of papers with relevance ≥ 2 (n=194) by disturbance type (avalanche, flooding, herbivory, insect outbreak, landslide, rockfall, wildfire and windthrow). Biome classification follows Olson et al. (2001).*

Several of the papers with relevance 4 (40%) used spatial data derived from remote sensing sources. For example, Moreira et al. (2001) used aerial photographs of Northern Portugal from 1958 to 1995, whereas Lloret et al. (2002) employed land cover maps of 1956, 1978, and 1993 and wildfire occurrence maps of the 1975–1990 period in Catalonia. Models such as GLMM (e.g., Viedma et al. 2015) or GAM (e.g., Zumbrunnen et al. 2011) were also widely applied (38.3% of the studies), while only a few used historical archives (e.g., García-Hernández et al. 2017b), dendrochronology (e.g., Sarris et al. 2014), and chronosequences (e.g., García-Ruiz et al. 2015).

Our literature search highlighted that the main land abandonment effects were an increase in the severity of wildfires, herbivory and windthrow. However, a decrease in frequency was observed for flooding, avalanches and rockfalls (Table 2.1). Considering only the highly relevant papers (R4), we observed that the majority were located in the Mediterranean region and South America, that the most common former land use was cropland followed by pasture and the abandonment stage ranges between 20 and 100 years (Table 2.2). Only a small sample of 14 papers among the highly relevant ones tried to quantitatively assess land cover change due to abandonment and its effect on disturbance regimes. All of them showed an increase of woody vegetation (trees and/or shrubs encroachment) with a consequent increase of disturbance risk, except for rockfall (Table 2.3).

Disturbance type	Abandonment related effects	N
Wildfire	Increase in size	11
	Increase in frequency	25
	Increase in severity	10
	Increase in risk	50
	Decrease in frequency	1
Flooding	Increase in severity	1
	Increase in risk	1
	Decrease in frequency	3
	Decrease in severity	4
Landslide	Increase in frequency	2
	Increase in risk	6
	Decrease in frequency	1
	Decrease in risk	2
Herbivory	Increase in severity	6
	Decrease in severity	1
Windthrow	Increase in size	2
	Increase in severity	4
	Increase in risk	1
Avalanche	Decrease in frequency	2
	Decrease in severity	4
	Decrease in risk	1
Rockfall	Decrease in frequency	2
	Decrease in risk	1
Insect outbreak	Decrease in severity	1

Table 2.1: *Summary of the main effects of land abandonment on disturbance regime characteristics according to the articles with relevance ≥ 2.*

ID	Reference	Location	Biome	Land use		Disturbance			
				Former Land Use	Y	Type	F	S	R
6	Viedma et al. 2015	Spain (Central-Western)	Mediterranean Forests, Woodlands & Scrub	Cropland (trees and herbs), Agroforestry Pasture	40	Wildfire			H
24	Loepfe et al. 2010	Spain (Tivissa, Igualada, Ports)	Mediterranean Forests, Woodlands & Scrub	Cropland	40	Wildfire		+	H
27	Mouillot et al. 2003	France (Venaco)	Mediterranean Forests, Woodlands & Scrub	Cropland, Pasture	100	Wildfire			H
43	Moreira et al. 2001	Portugal (Minho)	Temperate Broadleaf & Mixed Forests	Cropland (herbs), Pasture	40	Wildfire	+		H
59	Tonini et al. 2018	Portugal	Mediterranean Forests, Woodlands & Scrub	Cropland (trees and herbs), Agroforestry Pasture	20	Wildfire	+		H
79	Lloret et al. 2002	Spain (Tivissa)	Mediterranean Forests, Woodlands & Scrub	Cropland	30	Wildfire	+		H
93	Cervera et al. 2019	Spain (Bages, Berguedà)	Mediterranean Forests, Woodlands & Scrub	Cropland (trees and herbs), Agroforestry	40	Wildfire			H
112	Martínez et al. 2009	Spain	Mediterranean Forests, Woodlands & Scrub		40	Wildfire			H
119	Zumbrunnen et al. 2011	Switzerland (Valais, Ticino)	Temperate Conifer Forests	Cropland, Forest	40	Wildfire	+		H
125	Martínez-Fernández et al. 2013	Spain	Mediterranean Forests, Woodlands & Scrub		50	Wildfire	+		H
128	Vega-García and Chuvieco 2006	Spain (Alto Mijares)	Mediterranean Forests, Woodlands & Scrub		40	Wildfire			H
129	Aragó et al. 2016	Spain (Castellón)	Mediterranean Forests, Woodlands & Scrub			Wildfire			H
130	Fernandes et al. 2014	Portugal (Northern and Central)	Mediterranean Forests, Woodlands & Scrub		70	Wildfire			H
134	Chas-Amil et al. 2015	Spain (Galicia)	Temperate Broadleaf & Mixed Forests			Wildfire	+		H
137	Carmona et al. 2012	Chile (Maule Region)	Mediterranean Forests, Woodlands & Scrub	Cropland, Agroforesty		Wildfire			H

ID	Reference	Location	Biome	Land use		Disturbance			
				Former Land Use	Y	Type	F	S	R
257	Lopez Iglesias et al. 2013	Spain (Galicia)	Temperate Broadleaf & Mixed Forests		50	Wildfire			
393	Moreira et al. 2010	Portugal	Mediterranean Forests, Woodlands & Scrub		40	Wildfire	+		H
403	Aráoz and Grau 2010	Argentina (North-Western)	Tropical & Subtropical Grasslands, Savannas & Shrublands	Pasture	40	Wildfire			
415	Azevedo et al. 2010	Portugal (Franca parish)	Mediterranean Forests, Woodlands & Scrub	Cropland	50	Wildfire	+	+	H
437	Zumbrunnen et al. 2012	Switzerland (Canton Valais)	Temperate Conifer Forests	Cropland, Forest	50	Wildfire	+		H
447	Koutsias et al. 2012	Greece (Peloponnisos)	Mediterranean Forests, Woodlands & Scrub		50	Wildfire			H
538	Vilar et al. 2016	Mediterranean Basin	Mediterranean Forests, Woodlands & Scrub		56	Wildfire	+		
621	Quintero et al. 2019	Spain (Central-Western)	Mediterranean Forests, Woodlands & Scrub			Wildfire	+		
633	Bajocco et al. 2019	Italy (Sardinia)	Mediterranean Forests, Woodlands & Scrub	Cropland, Pasture		Wildfire	-		
647	Jajtic et al. 2019	Croazia (Dalmatia)	Mediterranean Forests, Woodlands & Scrub		50	Wildfire	+		H
334	Keesstra et al. 2005	Slovenia (Dragonja)	Mediterranean Forests, Woodlands & Scrub	Cropland	50	Flooding	-	-	
369	García-Ruiz et al. 2008	San Salvador (Arnas)	Mediterranean Forests, Woodlands & Scrub	Cropland (herbs)	50	Flooding	-	-	
577	Faccini et al. 2017	Italy (Sturla basin)	Mediterranean Forests, Woodlands & Scrub	Cropland, Pasture	50	Flooding			H
579	Martínez-Fernández et al. 2017	Spain (Upper Esla)	Mediterranean Forests, Woodlands & Scrub	Cropland, Pasture	50	Flooding		-	
598	Szwagrzyk et al. 2018	Poland (Ropa basin)	Temperate Conifer Forests			Flooding		-	

ID	Reference	Location	Biome	Land use		Disturbance			
				Former Land Use	Y	Type	F	S	R
671	Ortega et al. 2014	Spain (Rivillas, Azohía rivers)	Mediterranean Forests, Woodlands & Scrub			Flooding		+	
248	Gariano et al. 2017	Italy (Calabria)	Mediterranean Forests, Woodlands & Scrub	Cropland (trees and herbs)	40	Landslide	+		
276	Beguería 2006	Spain (Ijuez Valley)	Temperate Broadleaf & Mixed Forests	Cropland, Pasture	40	Landslide	-		
525	Malek et al. 2015	Romania (Buzau Subcarpathians)	Temperate Grasslands, Savannas & Shrublands	Cropland, Pasture	20	Landslide			L
570	Pisano et al. 2017	Italy (Rivo basin)	Mediterranean Forests, Woodlands & Scrub	Cropland, Pasture	40	Landslide			H
618	Malek et al. 2018	Romania (Carpathians)	Temperate Grasslands, Savannas & Shrublands		30	Landslide			L
372	Delibes-Mateos et al. 2009	Spain (Andalusia)	Mediterranean Forests, Woodlands & Scrub		30	Herbivory		+	
378	Silva et al. 2009	Brasil (Coimbra forest)	Tropical & Subtropical Moist Broadleaf Forests	Cropland	47	Herbivory		-	
642	Petersson et al. 2019	Sweden (Southern)	Temperate Broadleaf & Mixed Forests	Cropland, Pasture, Forest	100	Herbivory		+	
104	Schelhaas et al. 2010	Europe	na		50	Windthrow		+	H
160	Flynn et al. 2010	Puerto Rico (Luquillo, Carite, Ciales)	Tropical & Subtropical Moist Broadleaf Forests	Cropland, Pasture	80	Windthrow		+	
242	Lomascolo and Aide 2001	Puerto Rico (Luquillo, Carite, Ciales, Utuado)	Tropical & Subtropical Moist Broadleaf Forests	Cropland, Pasture	60	Windthrow		+	
199	García-Hernández et al. 2017b	Spain (Asturian Massif)	Temperate Broadleaf & Mixed Forests	Pasture	60	Avalanche		-	
277	García-Hernández et al. 2017a	Spain (Asturian Massif)	Temperate Broadleaf & Mixed Forests	Pasture	60	Avalanche		-	
256	Farvacque et al. 2019	France (Crolles)	Temperate Broadleaf & Mixed Forests	Cropland (trees and herbs)	160	Rockfall	-		H
1051	Lopez-Saez et al. 2016	France (Crolles)	Temperate Broadleaf & Mixed Forests	Cropland (trees and herbs)	160	Rockfall	-		H

ID	Reference	Location	Biome	Land use		Disturbance			
				Former Land Use	Y	Type	F	S	R
165	Rodríguez-García et al. 2017	Spain (Guadalajara, Segovia, Soria)	Mediterranean Forests, Woodlands & Scrub	Cropland, Pasture		Insect outbreak		-	

Table 2.2: *Effects of land abandonment on disturbance regime, in terms of increase (+) or decrease (-) in frequency and severity, and risk (H= higher; L=lower) according to the papers with the highest relevance (4). Biome classification follows Olson et al. (2001). Article IDs refer to the complete list of papers provided in the supplemental material (provided in the online version of the paper: https://doi.org/10.1007/s10980-020-01147-w). Y refers to the number of years since land abandonment occurred. F, S, and R refer to the frequency, severity, and risk of the regime.*

ID	Reference	Location	Land use change				Disturbance			
			Forest	Shrubland	Cropland	Urban	Type	F	S	R
6	Viedma et al. 2015	Spain (Central-Western)	5%	2%	-13%	na	Wildfire			H
24	Loepfe et al. 2010	Spain (Tivissa)	-17%	21%	-8%	2%	Wildfire		+	H
24	Loepfe et al. 2010	Spain (Igualada)	-22%	19%	2%	2%	Wildfire		+	H
24	Loepfe et al. 2010	Spain (Ports)	-1%	7%	-6%	1%	Wildfire		+	H
43	Moreira et al. 2001	Portugal (Minho)	20%	9%	-13%	-1%	Wildfire	+		H
59	Tonini et al. 2018	Portugal	-23%	24%	-20%	na	Wildfire	+		H
79	Lloret et al. 2002	Spain (Tivissa)	-25%	30%	-7%	0%	Wildfire	+		H
93	Cervera et al. 2019	Spain (Bages, Berguedà)	10%	0%	-7%	na	Wildfire			H
128	Vega-García and Chuvieco 2006	Spain (Alto Mijares)	11%	1%	-8%	-14%	Wildfire			H
415	Azevedo et al.2011	Portugal (Franca parish)	7%	7%	6%	0,5%	Wildfire	+	+	H
577	Faccini et al. 2017	Italy (Sturla basin)	37%	-7%	-31%	1%	Flooding			H
248	Gariano et al.2017	Italy (Calabria)	11%	na	-22%	2%	Landslide	+		
276	Beguería 2006	Spain (Ijuez Valley)	-17%	18%	-14%	-1%	Landslide	-		
570	Pisano et al. 2017	Italy (Rivo basin)	17%	-3%	2%	na	Landslide			H
256	Farvacque et al. 2019	France (Crolles)	22%	na	-51%	na	Rockfall	-		L
1051	Lopez-Saez et al. 2016	France (Crolles)	25%	na	-55%	22%	Rockfall	-		L

Table 2.3: *Changes in land use and effects on disturbance regime, in terms of increase (+) or decrease (-) in frequency and severity, and risk (H= higher; L=lower), resulting from land abandonment according to the papers with the highest relevance (4; n=11) quantitatively assessing land use changes. Article IDs refer to the complete list of papers provided in the supplemental material (provided in the online version of the paper: https://doi.org/10.1007/s10980-020-01147-w). F, S, and R refer to the frequency, severity, and risk of the regime.*

2.3.2 Land abandonment and natural disturbances

Wildfire

Most of the retrieved papers (n = 189, Fig. 2.3) investigated the interactions between wildfires and land abandonment. Considering only papers with relevance ≥ 2, the Mediterranean Region was the most studied area, with 75% of the studies. In the Mediterranean Region, most study sites were located on the Iberian Peninsula (70% of the Mediterranean studies).

There is a general agreement in the literature that land abandonment led to fuel build-up and higher landscape homogeneity, and both raised wildfire risk or altered the fire regime by increasing frequency, size, and severity. In the Valencia province (eastern Spain), an increase in fire frequency and size has been observed since the 1970s due to the rural exodus and abandonment of traditional land use (Pausas and Fernández-Muñoz 2012). At the early stages of the secondary succession triggered by land abandonment, fire-prone vegetation is widespread and dominant (Bonet and Pausas 2007; Baeza et al. 2011) thus increasing fuel connectivity, e.g., allowing fires to spread further (Pausas and Fernández-Muñoz 2012).

Similar results regarding LUC and trends of wildfire regimes were reported in several highly relevant studies that compared different periods. Viedma et al. (2015) observed a twofold increase, from 26 to 42%, in the proportion of hazardous land cover types, due to agricultural land abandonment, when studying changes in fire risk from 1950 to 2000 in Spain. Notably, the main contribution to LUC came from the abandonment of agricultural land until 1986, while in subsequent years it was mainly driven both by fire occurrence and encroachment dynamics of natural vegetation (e.g., densification of open stands to conifer stands). Moreira et al. (2001) found that a considerable fuel build-up (20–40%) contributed to a threefold increase in the number of wildfires in the 1980–1996 period in Northern Portugal. This fuel accumulation was caused by a significant decrease in agricultural and low shrubland cover in favor of tall shrublands and forests. Similarly, Lloret et al. (2002) and Vega-García and Chuvieco (2006) assessed the strong effect of landscape homogeneity on wildfire propagation in Eastern Spain, which was caused by the expansion of shrublands to the detriment of forested areas and agricultural lands. Loepfe et al. (2010) also found that the loss of the traditional rural mosaic, resulting from a selective abandonment of marginal agricultural land, led to more homogeneous landscapes where an increase in the number of wildfires was observed. Moreover, these authors found two feedbacks in the fire-landscape relationship: a decrease in fire occurrence was created by fire through the transformation of dense forests into shrublands with a lower fuel load, while an increase in fire propagation was the result of further landscape homogenization produced by fire. Recurrent wildfires, low resilience, and poor dispersal abilities of forest species can instead sometimes favor the persistence of highly flammable shrublands (Mouillot et al. 2003). Frequent fires also reduce or temporarily remove the vegetation cover, exposing soil to erosion agents, and can alter the soil infiltration capacity, increasing soil hydrophobicity and thus inducing changes in the water cycle (Llovet et al. 2009; Calsamiglia et al. 2017). In Portugal, Gonçalves et al. (2011) found that the abandonment of traditional grazing activities led to fuel build-up. The frequent use of uncontrolled fires for pasture renovation emerged as the primary cause for wildfire occurrence outside the typical fire season (summer). Tonini et al. (2018) studied the effects of rural abandonment on the relationship between the extent of the rural–urban interface (RUI) and that of wildfires in Portugal. RUI, defined as the area where structures and other human developments meet or intermingle with semi-natural forests and agricultural areas (Tonini et al. 2018), is an alternative to the concept of wildland-urban interface (WUI) and has been identified as the most fire-prone area in the Mediterranean region. From 1990 to 2012, the RUI in Portugal increased by about 70% and the area affected by fire within it doubled, despite a 35% decrease in the total burned area. To summarize, almost all the studies retrieved from the literature search assessed an increase in all the components of wildfire regimes (mostly frequency) and risk in the last decades.

Flooding

Studies regarding flooding and land abandonment were located mainly in Europe and the USA. Changes in land use and land cover determined modifications in many of the factors affecting both flooding risk and severity. However, while many studies observed the effects of urbanization in flood-prone areas, leading to an increase in flood peak discharge and, therefore, to flood damage (e.g., Huong and Pathirana 2013), fewer focused on the consequences of land abandonment on this disturbance (Szwagrzyk et al. 2018). The expansion of vegetation cover following land abandonment often alters hydraulic flow and water balance (Szwagrzyk et al. 2018), increasing water interception and reducing erosion, runoff, and sediment supply to the stream (García-Ruiz et al. 2011; Martínez-Fernández et al. 2017; Szwagrzyk et al. 2018). Increased forest cover may also induce channel narrowing and further vegetation encroachment (Martínez-Fernández et al. 2017). Szwagrzyk et al. (2018) modelled the effects of forest expansion in the Polish Carpathians, finding out that the increase in forest cover would likely reduce the adverse effects due to urbanization, leading to a decrease in flood peak discharge. Similarly, Martínez- Fernández et al. (2017) registered a decrease in the average mean annual discharge and median annual maximum flow after the colonization of woody vegetation.

Conversely, the development of woody cover on old abandoned terraces might increase hydrogeological instability and worsen the soil drainage (Faccini et al.

2017). Other negative effects were caused by an increase in solid transport in the streams, caused by soil erosion in the collapsed terraces and increased frequency of shallow landslides (Faccini et al. 2017).

There is still an open debate on the effectiveness of forest cover changes in mitigating floods (Bradshaw et al. 2007; Laurance et al. 2007); consequently, impacts on this disturbance regime have not yet been distinctly identified. The effects of land abandonment on flooding are not linear, and differences between studies may be due to the stage of secondary succession, for instance because of the lower interception of rain by shrubs and small trees compared to large trees, as well as to the characteristics of the site (García-Ruiz et al. 2008). However, in their global-scale study on developing countries, Bradshaw et al. (2007) demonstrated the correlation between forests and flood regimes and suggested that reforestation could determine a reduction in flood occurrence and severity. It is worth mentioning that to mitigate the impact of floods, several nations, particularly the more flood-prone ones, are investing in reforestation projects or trying to reduce the loss of native forests (Mather et al. 1999; Bradshaw et al. 2007).

Landslide

Most studies regarding the interactions between landslide and land abandonment have been conducted in the Mediterranean region. Land abandonment can affect soil characteristics in several ways, leading to an improvement in soil quality or a worsening of land degradation processes. Colonization by shrubs and trees generally increases interception, infiltration, and water uptake by vegetation, improving soil protection against rain splash, particles detachment and runoff (Symeonakis et al. 2007; García-Ruiz and Lana- Renault 2011; García-Ruiz et al. 2013). Positive effects on soil characteristics comprise an increase in soil organic matter (SOM) content, aggregates stability, hydraulic connectivity and water holding capacity, causing a decrease in soil erosion, streamflow, and sediment discharge (García-Ruiz and Lana-Renault 2011; García-Ruiz et al. 2013; Lana-Renault et al. 2018). Instead, the abandonment of agricultural terraces or forest degradation caused by wildfires emerged as the most relevant factors enhancing runoff and soil erosion (Symeonakis et al. 2004). Contrasting effects of land abandonment on landslides were highlighted, depending on site properties and vegetation characteristics. A slightly negative effect on the occurrence rate was observed in the Pyrenees (Spain) in the second half of the twentieth century, where the revegetation of former agricultural lands was able to erase scars of previous landslides but had limited capacity in preventing landslide occurrence on hillslopes covered by dense shrubs or young forest cover (Beguería 2006). Similarly, in Southern Italy (Calabria region), the number of rainfall-induced landslides increased in heterogeneous agricultural areas and forests during recent (1966–2010), compared to previous years (1921–1965) (Gariano et al. 2017). This is likely due to the presence of early stages of vegetation and young forests in these land cover classes, as LUC was characterized by a decrease of arable land (- 3261 km^2) and an increase of heterogeneous agricultural areas (+ 2464 km^2) and forests (+ 1658 km^2). Abandoned croplands transformed into shrublands or pastures appear to be very susceptible to landslides, according to Pisano et al. (2017), probably because of the lack of management triggering soil erosion and the consequent instability. The abandonment of bench-terraced fields, formerly used to ease cropping and avoid soil degradation, often caused their collapse due to the occurrence of small landslides (Lasanta et al. 2001; García-Ruiz and Lana-Renault 2011; García-Ruiz et al. 2013). This created concentrated runoff and sediment flows along preferential pathways (Lana-Renault et al. 2018) that could evolve into gullies (Lasanta et al. 2001). Conversely, forest expansion due to land abandonment can decrease the extent of areas subjected to landslide susceptibility because of the increased slope stability generated by roots aggregation effects and the regulation of soil moisture, thanks to evapotranspiration processes (Beguería 2006; Malek et al. 2015, 2018; Pisano et al. 2017). Woody vegetation does not always exert positive effects on soil stability since dense shrubs and tree cover on abandoned terraces can increase flood and landslide risk, as observed using the Curve Number (CN) registered on these land use categories in Sturla Valley (Genoa, Italy) (Faccini et al. 2017). The CN is the parameter used to forecast direct runoff or infiltration from rainfall excess (United States Department of Agriculture 1986) and its increase corresponds to a faster runoff for the lower time of concentration, proving that the development of woody vegetation worsens the previous condition of hydrogeological stability and soil drainage (Faccini et al. 2017). In general, the effects of land abandonment on landslides are strictly connected to soil properties and site characteristics affecting vegetation structure and its ability to stabilize the slopes and prevent shallow landslides.

Herbivory

Studies assessing relationships among land abandonment and herbivory that were retrieved from the literature search did not show any specific geographical cluster but were heterogeneously spread across continents. Both mammal and insect species were investigated as disturbance agents. Although the magnitude of herbivore impact on plant colonization is not completely clear (Edenius et al. 2011; Bobiec et al. 2011), land abandonment generally leads to an increase in the number of herbivorous mammals, which mostly affects tree regeneration. Edenius et al. (2011) provided some insight into how land abandonment influenced aspen density in Sweden: land use changes were identified as an important driver of change in aspen abundance, while moose browsing had a limited role in the investigated aspen dynamics. Oak regeneration in the Białowieża National Park was found to occur successfully in abandoned agricultural fields without being associated with other less preferred woody species as protection against herbivory, despite the presence of wild (mostly browsing) ungulate species (Bobiec et al. 2011). The abundance of big-game species (e.g., Iberian wild goat, red deer, roe deer and wild boar) in Andalusia (Spain) has been affected by recent land use changes, and a considerable increase in both density and geographical range has been observed due to the expansion of Mediterranean scrubland and woodland cover (Delibes- Mateos et al. 2009). In the same area, landscape homogenization has been proved to lead to segregation between big-game (in mountain areas) and small-game species (in agricultural areas) (Delibes-Mateos et al. 2009). In tropical ecosystems, the expansion of cultivated lands, deforestation and landscape fragmentation has increased the abundance of leaf-cutting ants (e.g., Fowler et al. 1986; Jaffe 1986; Vasconcelos and Cherrett 1995; Terborgh et al. 2001), while land abandonment can cause their decrease (Silva et al. 2009). In the Coimbra forest (Brazil) a decrease in the number of nests of *Atta cephalotes* (a leaf-cutting ant) after land abandonment was registered, due to a pronounced decline in the provision of palatable plants in natural secondary succession and maybe because of the increased abundance of predator or parasite communities (Silva et al. 2009). The effects of land abandonment on herbivores depend on the species considered and on their optimal habitats. For those herbivores which thrive on croplands, abandonment means a decrease in palatable species and, as a consequence, a decrease in the population. In contrast, for those species typical of shrublands and woodland, land abandonment means an increase in size and connection of patches of suitable habitat.

Windthrow

Trends of increasing wind damage to European forests have been reported for the last decades (Schelhaas et al. 2003; Seidl et al. 2014; Bebi et al. 2017); they partially reflect an improvement in the reporting of windthrow data over time, but are mostly related to the increased forest cover and associated changes in stand structure (Schelhaas et al. 2003, 2010; Kulakowski et al. 2017), with taller and older stands being generally more prone to windthrow. Conversely, changes in the landscape pattern leading to a reduced fragmentation can make it less susceptible to windthrow (Laurance and Curran 2008; Zeng et al. 2009).

Despite some evidence reporting an increase in frequency and intensity of wind storms due to climate change, the higher windthrow severity (measured in terms of damaged timber) registered in European forests has been mostly attributed to a higher susceptibility related to the increase in growing stock and average stand age (Schelhaas 2008; Kulakowski et al. 2011; Schuck and Schelhaas 2013; Lindner and Rummukainen 2013; Mason and Valinger 2013).

Structural and compositional characteristics of post-abandonment secondary forests, shaped by time since abandonment and legacies of previous land use, thus strongly influence stand vulnerability.

Similar patterns to European forests were also found in tropical regions, with stand age affecting the response to hurricane force wind disturbance (Lomascolo and Aide 2001; Flynn et al. 2010). In these studies, early stages of succession were less affected compared to old secondary forests, due to trees being smaller in diameter and height.

If current trends of increasing forest area, growing stocks, and share of old forests continue, as projections for the future suggest, vulnerability to storm damage will thus probably further increase (Schelhaas et al. 2010). Forest management goals aiming at mixed stands (increasing the share of deciduous tree species) and higher harvest removals could contribute to slowing down this tendency (Gardiner et al. 2010; Schelhaas et al. 2010).

Avalanche

According to the relevant studies found in the literature, mainly located in the Alps, the effects of land abandonment on avalanche regime are contrasting and mostly depend on the development stage of the secondary succession. Several authors (e.g., Bebi et al. 2009; Kulakowski et al. 2011; García-Hernández et al. 2017a, b) observed a decrease in damage (severity) and frequency due to forest expansion following land abandonment. García-Hernández et al. (2017b) underlined the close relationship existing between damage caused by avalanches and socioeconomic changes, analyzing over 126 events that occurred between 1800 and 2015 in NW Spain. While the highest damage rate co-occurred with the peak demand for wood, population growth and intensive grazing (mostly between 1850 and 1950), a clear reduction in the damage rate due to natural reforestation was observed after the rural exodus during the second half of the twentieth century. However, natural reforestation of slopes is spatially heterogeneous and strongly depends on avalanche frequency, which inhibits the development of tree cover (Tasser et al. 2007; Bebi et al. 2017; Beato Bergua et al. 2019). When the avalanche release zone is placed hundreds of meters above the tree line, even the development of a new forest would not be able to counteract this disturbance (Bebi et al. 2017; Beato Bergua et al. 2019). The primary function of the forest in counteracting avalanches is both to prevent their release and to slow down the small ones, but it has a limited effect on those with massive dimensions and that have already reached a high speed (Bebi et al. 2009). Newesely et al. (2000) assessed that the colonization of abandoned land by shrubs has a limited protective function against avalanches and erosion, but it could instead trigger gliding avalanches. What emerged from the reviewed studies is that the development stage of the secondary succession strongly influenced the avalanche phenomenon, acting either as a limiting or exacerbating factor. The probability of avalanche release was reduced in areas characterized by the development of a dense forest, whereas it can be heightened in the initial/intermediate development stages of the secondary succession when a compact layer of low and flexible dwarf shrubs is present (Newesely et al. 2000; Bebi et al. 2009). Early successional vegetation can also be dominated by long grasses that can favor glide-snow avalanches release (Feistl et al. 2014).

Since vegetation structure, coupled with snow characteristics and topography, has a significant impact on the frequency and magnitude of avalanches, proper and active silvicultural management can influence avalanche regime and increase the protective function of the forest (Bebi et al. 2009).

Rockfall

Very few papers (n = 4) were found dealing with this disturbance and land abandonment, whereas several studies dealt with the impact of climate change on rock instability and rockfall hazard (Lopez-Saez et al. 2016; Berger et al. 2017; Lingua et al. 2020). An increase in rockfall occurrences has already been observed in years with weather anomalies (Berger et al. 2017); triggering factors (e.g., long and high intensity precipitations, freeze–thaw processes, high temperature variations over a short period) are related to weather conditions (Lingua et al. 2020). If climate change will most likely lead to an increase in rockfall occurrence (Berger et al. 2017), possible interactions with land use and land cover changes should be also taken into account (Lopez-Saez et al. 2016), in order to better understand changes in rockfall regimes. The rockfall process requires the presence of steep slopes (usually exceeding 30°) where rock blocks can be released, so this phenomenon is often confined to mountain areas. In these areas, the widespread increase in forest cover since the abandonment of marginal crops and pastures should provide increased protection against rockfall propagations (Berger et al. 2017). If trees in the release zone can sometimes influence the start of a rockfall event (by speeding up weathering and cracking processes with their roots), in the path of the rocks rolling down the slope their mitigation effect can be significant and particularly effective if the rock size is smaller than 5 m^3 (Lingua et al. 2020).

Rockfall is a site-specific phenomenon, but interactive effects of climate and land use change bring about a general reduction at least in its severity, mostly due to the increased protective effects of forests, resulting from longer forested slopes, larger basal area and higher density of stands, and higher broadleaves proportion (Lingua et al. 2020).

The agropastoral decline in mountain valleys is often accompanied by a higher demand for protection against gravity-driven hazards due to intense peri-urban expansion and increased human transit for recreational purposes. There is thus a need for a spatially precise characterization of risk and adequate forest management to guarantee the protection function over time.

In the French Alps, Lopez-Saez et al. (2016) and Farvacque et al. (2019) documented that land abandonment was followed by a rapid natural afforestation and intense peri urbanization from the second half of the nineteenth century. Lopez-Saez et al. (2016) demonstrated that these changes in landscape pattern affected the rockfall regime in the area by gradually reducing frequency and severity (resulting from a gradual decrease of the mean kinetic energy of rocks) as the forest cover of the slopes increased since 1850. The authors attributed these results mostly to the increase in forest density, particularly for those stands located on the upper part of the slopes. Effects on rockfall regimes thus depend on the speed of natural afforestation processes since abandonment. Moreover, since all forests are subject to stand dynamics that can modify their protection effectiveness, active forest management is often required to maintain a stand in this efficiency window. In the absence of adequate silvicultural interventions, older stands may offer reduced protection, and when tall trees collapse or are uprooted by windthrow and snowbreak, they can release the rocks they were anchoring. On the other hand, it has been demonstrated that an important residual protective function is still provided by deadwood on the ground for a long period (several decades) through an increase in surface roughness (Wohlgemuth et al. 2017).

Farvacque et al. (2019) obtained similar results to Lopez-Saez et al. (2016), where a strong decrease in rockfall risk (particularly for low-volume/high-frequency classes) resulted from the tree-rock interactions, allowing a reduction in both the reach probability and energy of rockfalls.

Although the limited number of papers found on this topic does not allow general statements to be made, the increase of forest cover following land abandonment can reduce rockfall risk and severity due to the capacity of trees to intercept rocks along slopes. The magnitude of these effects is amplified by the increase in size and/or density of trees with lengthening time since abandonment, as long as site conditions are favorable for tree growth and until senescence dynamics reduce tree resistance.

Insect outbreak

Only one study, although highly relevant, was found relating insect outbreak and land abandonment. Rodríguez-García et al. (2017) discussed the positive effects of changes in forest structure and composition caused by land abandonment in Spain. In particular, the abandonment of traditional land use led to a transition from pure *Juniperus thurifera* forests to mixed forest, which experienced lower levels of cone damage, due to the increased difficulty for arthropods to find host plants. The authors also observed that the damage level depended on the arthropod group and cone abundance.

One possible reason for the current lack of studies dealing with insect outbreaks is related to the amount of time since abandonment: most forest stands developed after land abandonment in the twentieth century may often not yet be susceptible to insect outbreaks. When certain structural characteristics (e.g., large diameters for bark beetles) are reached, those stands could become vulnerable due to the presence of suitable host trees.

2.4 Conclusions

Several interactions were highlighted between land abandonment and disturbance regimes. The analysis of the existing literature revealed a noticeable imbalance regarding the number of studies per type of disturbance and evidenced specific hotspots where most studies were performed, with the great majority of study sites being located in Europe. Specific reasons for these differences should be further investigated. Despite preliminary scoping and a large number of key terms included, our search may have failed to identify all of the available literature on this topic. Moreover, we only considered the effect of land abandonment on natural disturbances, while it could be interesting considering also the consequences of the cessation of anthropogenic disturbances related to agriculture, such as the intensive use of pesticides, machinery, or irrigation.

While the effects of land abandonment on wildfires have often been studied, particularly in the Mediterranean Region, a much lower number of articles focused on interactions with other disturbances. This is not unexpected considering that land abandonment and rural depopulation occurred at a high rate in countries of Southern Europe, where wildfires are one of the most frequent disturbances and typically have a high impact on both the human population and vegetation communities.

For disturbances other than wildfire, opposite effects of land abandonment on their regime were observed, and regarding the same disturbance type, these effects were sometimes contrasting. Differences among studies could be attributed to differences in site characteristics or legacies of prior land use.

Another limitation of the available literature, particularly regarding under-represented disturbances, is the scarcity of quantitative assessments, truly measuring the process of abandonment and the resulting changes on disturbances. When addressing abandonment-related impacts on disturbances, a key issue is represented by time since abandonment and the relative vegetation successional dynamics. There is still a lack of knowledge on the longer-term effects of land abandonment based on forest succession over time. Current changes in disturbance regimes attributed to changes in land use may thus be fluctuating according to long-term successional trajectories of forests, which are by their nature dynamic systems (Sebald et al. 2019). This calls for monitoring of land abandonment evolution over time, particularly when land and resource management are involved.

Moreover, land abandonment alone is only one possible factor of the whole equation. Interactions with climate change or feedbacks resulting from interactions among disturbances should also be taken into account (e.g., Schelhaas et al. 2010; Doblas- Miranda et al. 2017; Kulakowski et al. 2017; Potterf and Bone 2017; Beato Bergua et al. 2019). At a global scale, the phenomenon of land abandonment can result in opportunities for restoring natural communities and enhancing the provision of important ecosystem services. There are situations where land abandonment could produce, at least in the short- or medium-term, an increase in disturbance size, frequency, or severity, sometimes mostly because of the resulting increase in forested areas, and this should raise concern about potential consequences for human society. However, natural disturbances are an integral component of forest dynamics, and this process can be viewed as part of a path towards conditions more similar to those characterizing some ecosystems prior to intense human exploitation.

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Chapter 3

Short-term drivers of post-fire forest regeneration in the Western Alps

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Abstract

Background

The Mediterranean basin is currently facing major changes in fire regimes as a result of climate and land use changes. These alterations could affect the ability of forests to recover after a fire, hence triggering degradation processes and modifying the provision of fundamental ecosystem services. Examining patterns and drivers of post-fire forest recovery, particularly for obligate seeders without specific fire-adaptive traits, thus becomes a priority for researchers and land managers.

Objectives

We studied the post-fire dynamics of Scots pine (*Pinus sylvestris* L.) stands affected by a mixed severity fire in North-Western Italy, aiming to understand the impact of fire on soil properties and assess drivers, spatial distribution, and characteristics of short-term post-fire recovery.

Results

We observed that fire did not significantly affect soil organic carbon (OC) content, while we detected significantly lower nitrogen (N) content in severely burnt sites. Regeneration density was particularly abundant in medium severity areas, while it drastically decreased in high severity patches. The most abundant tree species in the regeneration layer was Scots pine, followed by goat willow (*Salix caprea* L.), European aspen (*Populus tremula* L.), and, to a lesser extent, European larch (*Larix decidua* Mill.). Slope, fire severity, and distance from seed trees emerged as the most important drivers of post-fire forest regeneration patterns.

Conclusions

Our results highlight the importance of preserving seed trees from salvage logging, even if they are damaged and have a low survival probability. Active post-fire management, such as tree planting, should be limited to large and severely burnt patches, where natural forest regeneration struggles to settle, increasing the risk of ecosystem degradation. These findings could be useful for informing land managers, helping them to enhance potential mitigation strategies in similar ecosystems and plan appropriate restoration approaches.

Keywords: Biological legacies, Fire regime, Global change, *Pinus sylvestris*, Post-fire regeneration, Scots pine stands, Seed trees, Western Alps

3.1 Introduction

Climate and land use changes are currently modifying the disturbance regimes under which forest landscape have been shaped for millennia (Pausas et al. 2008; Turner 2010; Leverkus et al. 2019; Mantero et al. 2020; Pausas and Keeley 2021). These alterations could affect the ability of forests to recover after a disturbance, which could in turn trigger degradation processes (Dury et al. 2011; Johnstone et al. 2016; Fernandez-Vega et al. 2017), thus modifying the provision of fundamental ecosystem services (Turner et al. 2013; Seidl et al. 2016; Thom and Seidl 2016; Kulakowski et al. 2017).

The potential ecosystem transformations resulting from global change and altered disturbance regimes are becoming a pressing issue (Littlefield et al. 2020). The increasing number of large stand-replacing fires, the shortening of the return intervals, as well as the post-fire climatic conditions, often characterized by severe droughts, all raise concern about regeneration recruitment, particularly for obligate seeders (Enright et al. 2015; Turner et al. 2019). Examining patterns and drivers of post-fire forest recovery thus becomes a priority for researchers and land managers.

Mediterranean mountain forests are particularly sensitive to global change due to the historical anthropogenic pressure and their low resilience (San Roman Sanz et al. 2013; Doblas-Miranda et al. 2017). In these areas, the widespread land abandonment acts synergistically with climate change (Bebi et al. 2017; Kulakowski et al. 2017) and with harsher environmental characteristics, possibly hindering regeneration dynamics (Castro et al. 2004a, b; Marzano et al. 2013). Under these new conditions, large and severe wildfires often occur in stands characterized by species lacking specific fire-related traits (e.g., Scots pine, *Pinus sylvestris* L.). After these events, a deficiency or a delay in the establishment of natural regeneration has been observed, often due to the cascading effects of post-fire management interventions, most likely resulting in degradation processes (Beghin et al. 2010; Marzano et al. 2013).

Salvage logging is still one of the most common post-disturbance practices. It consists of the harvesting of dead or damaged trees from sites after disturbance events, sometimes followed by plantation (Lindenmayer and Noss 2006; Lindenmayer et al. 2008). However, several negative consequences on natural regeneration processes and on the provision of ecosystem services have been demonstrated to occur after this practice (Donato et al. 2006; Lerverkus et al. 2018a, b), acting as a second disturbance with combined effects that could be more than simply additive (Leverkus et al. 2018b). Consequently, lower-impact post-fire management activities are increasingly considered (Moreira et al. 2012; Vallejo et al. 2012; Marques et al. 2016; Wohlgemuth et al. 2017; Leverkus et al. 2021). Passive restoration is often the most ecologically appropriate solution (Beghin et al. 2010; Moreira et al. 2012; Honey-Rosés et al. 2018; Chazdon et al. 2021), but active intervention is required whenever degradation processes may affect natural dynamics (Stewart et al. 2003).

Whatever the chosen post-disturbance management strategy, taking advantage of natural regeneration can reduce costs and be more effective. Natural regeneration indeed ensures the presence of a plant community adapted to site conditions, enhances species diversity, limits soil erosion, and increases soil fertility (FAO 2019; Shono et al. 2020). Natural regeneration can be passive, or it may be assisted or managed (Di Sacco et al. 2021), with an approach to forest restoration spanning a gradient of active anthropic interventions, from assisted natural regeneration (ANR) to applied nucleation (AN) (Zahawi et al. 2013; FAO 2019; Shono et al. 2020; Di Sacco et al. 2021). These practices could facilitate post-disturbance ecosystem recovery, avoiding degradation processes, but this requires accurate planning and an in-depth understanding of all the factors affecting regeneration dynamics, including the characteristics of the fire event, the environmental conditions of the affected area, and the pre-fire forest attributes (Martín-Alcón and Coll 2016). Among them, disturbance severity has been shown to strongly influence seedling recruitment (Turner et al. 1999; Turner et al. 2003; Jayen et al. 2006; Maia et al. 2012; Hollingsworth et al. 2013). In particular, fire can produce different impacts on the below- and above-ground components of forest ecosystems. Depending on the magnitude of the event, soil organic matter and mineral phases can be heavily affected (Knicker 2011; Jordanova et al. 2019), even if a fire-induced increase in temperatures is generally limited to the top five cm (Neary et al. 1999) due to low soil thermal conductivity (DeBano et al. 1998). Also, fire severity affects the type, amount, and quality of biological legacies like soil and crown seed banks or deadwood. Biological legacies can have positive effects on ecosystem recovery, promoting regeneration settlement and establishment (Franklin 1990; Peterson and Leach 2008; Castro et al. 2012). Deadwood, for instance, provides safe microsites for recruitment, particularly in harsh environmental conditions (Coop and Schoettle 2009; Grenfell et al. 2011; Marzano et al. 2013; Marcolin et al. 2019; Marangon et al. 2022). Another key aspect affecting post-fire regeneration, especially for obligate seeders, is the distance from seed sources, including both forest edges and isolated seed trees or green islands inside burnt areas. The survival of a crown seed bank, together with seed dispersal ability, has been recognized as the most important factor in propagule provisioning for conifers, as the soil seed bank is often destroyed by fire (Krüssmann 1983; Zasada et al. 1992; Greene et al. 2005; Donato et al. 2009).

Short-term (< 5 years) post-fire recovery shapes future stand trajectories, directing forest dynamics in the long-term (van Mantgem et al. 2006; Swanson et al. 2011; Meng et al. 2015). The increase in the size and frequency of high severity fires (Seidl et al. 2017; Mantero et al. 2020) and the trends of increasing temperature and water deficit are threatening tree seedling establishment and survival, potentially leading to shifts from forest types to shrublands or grasslands (Stevens-Rumann et al. 2017; Haffey et al. 2018). The uncertainty about post-fire recovery of conifer-dominated stands (Harvey et al. 2016; Stevens-Rumann et al. 2017; Serra-Diaz et al. 2018), especially in sensitive forests characterized by species lacking direct post-fire regeneration mechanisms, is mounting concern about ecosystem resilience (Harvey et al. 2016; Stevens-Rumann et al. 2017).

The unprecedented wildfires that struck North-Western Italy in early fall 2017 offered an opportunity to study post-fire forest regeneration patterns, focusing specifically on tree regeneration from seeds, under the new environment generated by global change. The present study aimed to investigate short-term forest recovery after the largest of these fires, characterized by a high spatial heterogeneity resulting from varying levels of fire severity on the predominantly forested landscape. We thus assessed the post-fire regeneration dynamics in Scots pine stands affected by a mixed severity fire in the Western Alps (Italy) to answer the following research questions: (i) What is the impact of fire on soil properties across a fire severity gradient? (ii) What are the short-term regeneration patterns? (iii) What are the most important drivers influencing post-fire regeneration by seeds?

3.2 Methods

3.2.1 Study area

The study area was located in the municipalities of Bussoleno and Mompantero (45.15°, 7.067°) (Susa Valley, Piedmont, Northwestern Italy). The altitude of the study area ranged between 500 m and 2500 m a.s.l. and the soils are Cambisols according to the Working Group World Reference Base for Soil Resources (WRB) (IUSS Working Group WRB 2014). The mean annual precipitation was approximately 800 mm and the mean annual temperature was 12 °C. Vegetation was dominated by downy oak (*Quercus pubescens* Willd.) and shrubs at lower elevations and Scots pine, European beech (*Fagus sylvatica* L.), and European larch (*Larix decidua* Mill.) at higher elevations. Silver fir (*Abies alba* Mill.) stands, sweet chestnut (*Castanea sativa* Mill.) stands, and mixed broadleaves (*Acer pseudoplatanus* L., *Tilia platyphyllos* Scop., and *Fraxinus excelsior* L.) stands were sporadically present.

Autumn 2017 was characterized by an uncommon fire season in Piedmont (Northwestern Italy) that was triggered by exceptional weather conditions, which were dominated by high temperatures and scarce rainfall (Bo et al. 2020; Rita et al. 2020). The average temperature of October 2017 was 2.9 °C higher than the 1970-2000 period and the average precipitation was 98% lower (ARPA Piemonte 2017). The extreme climatic conditions were further exacerbated by the intense local phenomena of foehn, a dry and warm down-slope wind. As a result of these extraordinary meteorological conditions, between late October and early November 2017, 10 large fires struck the region, burning about 9700 ha (7200 ha covered by forests), a much larger area than the annual average (2800 ha) of the previous 20 years (ARPA Piemonte 2017). The Susa fire was the largest event, with an extent of around 4000 ha (2500 ha of forests). The fire resulted in a complex mosaic of high severity patches (13%) within a matrix of low and medium severity patches (44% and 43%, respectively) (Morresi et al. 2022).

3.2.2 Sampling design and data collection

We adopted a stratified random sampling design based on the fire severity map produced in a previous study (Morresi et al. 2022), obtained by integrating both field and satellite (Sentinel-2) data, with fire severity expressed as Relative differenced Normalized Burn Ratio (RdNBR) (Miller and Thode 2007) and classified in three categories: unburnt to low, medium, and high. The adopted fire severity map did not discriminate between unburnt and low severity classes due to uncertainties related to the remote sensing approach. We conducted field surveys only in pure Scots pine stands. We organized the data collection according to the study aims, using three sets of data, with sampling plots partially overlapping (Fig. 3.1).

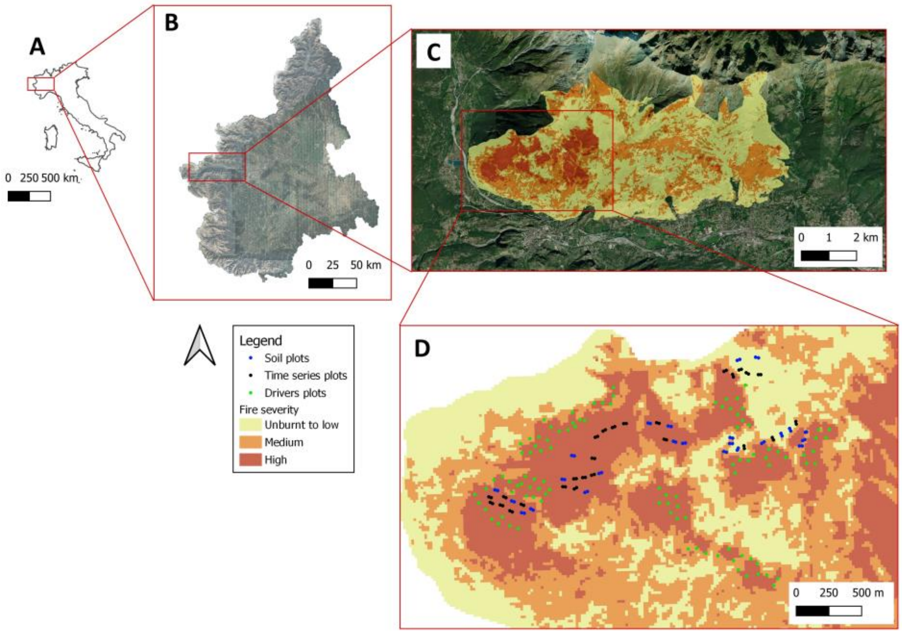

Fig. 3.1: *Location of the study area within* ***A*** *Italy,* ***B*** *Piedmont region, and* ***C*** *perimeter of the Bourra wildfire with* ***D*** *location of the plots used for the analyses. Soil plots are indicated in blue, time series plots in black and drivers plots in green. Time series plots include the soil plots and driver plots include time series plots and soil plots.*

3.2.3 Fire severity and soil properties

In July 2020 we randomly selected soil sampling points (defined as "soil plots", n = 48; Fig 3.1d) among the plots also used for analyzing short-term seedling regeneration patterns (see the following paragraph for details). Soil plots were distributed as follows: 26 in high severity patches, 13 in medium severity patches, and 9 in unburnt to low severity patches. After litter removal, visual inspection revealed the presence of a superficial blackish horizon (at most sites), a typical feature that can be found in fire affected soils (Certini et al. 2011). We collected the superficial (blackish) and underlying sub-superficial organo-mineral A horizons to a depth < 5 cm, so as to sample the portion of the pedon most heavily affected by the fire. We air-dried, sieved (2 mm mesh), ground (0.5 mm mesh), and stored soil samples at room temperature until laboratory analysis.

We measured soil pH in a 1:2.5 soil:deionized water suspension after 2 hours shaking (van Reeuwijk 2002). We determined total carbon (C) and nitrogen (N) by dry combustion with a Unicube CHNS Analyzer (Elementar, Langenselbold, Hesse, Germany). We evaluated carbonate content volumetrically after soil treatment with HCl (Nelson 1982) and we subtracted inorganic C content from total C to obtain organic carbon (OC) content.

3.2.4 Short-term seedling regeneration patterns

We measured a total of 100 plots (defined as "time series plots"; Fig. 3.1d) at the end of the first post-fire growing season (autumn 2018) and we remeasured them in the two following years (autumn 2019 and 2020). We spatially distributed the time series plots as follows: 66 plots in high severity patches, 15 in medium severity patches, 19 in unburnt to low severity patches. Each plot consisted of two concentric subplots of 2 and 5 m radius. We assessed pre- and post-fire tree structure and composition in the 5 m plot, by collecting species and status (dead or alive) of each tree individual (DBH > 7.5 cm). We recorded abundance and species of all tree seedlings and ground cover in the 2 m plot. We attributed ground cover classes on the field by visually estimating the percent cover of Gramineae, forbs, bare soil, shrubs, coarse woody debris (CWD), and rocks.

3.2.5 Drivers of forest recovery

We collected environmental drivers, obtained from both field surveys and GIS-derived data (Table 3.1), in 213 circular plots sampled in autumn 2020 (defined as “drivers plots”, including the 100 “time series plots”; Fig 1d). Plots were distributed as follows: 156 plots in high severity areas, 37 in medium severity areas, and 20 in low severity areas. We applied the same sampling design adopted for the time series dataset.

We derived topographic variables from a 5 m resolution digital terrain model (DTM; Regione Piemonte 2011) obtaining raster datasets of slope, elevation, Heat Load Index (HLI) (McCune and Keon 2002), and roughness. We obtained the HLI through the R package `spatialEco` (Evans 2021). We calculated roughness using the R package `terra` (Hijmans 2022). The roughness value for each pixel is calculated as the difference between the maximum and the minimum elevation value among a 3x3 moving window around the pixel (Wilson et al. 2007).

To map seed trees, i.e., those individuals with some green foliage during the first growing season after the fire, surrounding each plot, we established a relation between the percentage of seed trees in the plots surveyed in 2018 and a vegetation index derived from satellite imagery. Specifically, we computed the Normalized Difference Red-Edge (NDRE) index using a RapidEye multispectral image (5 m spatial resolution), acquired on 30 June 2018. This image was obtained from the ESA RapidEye Full archive (https://earth.esa.int/eogateway/catalog/rapideye-full-archive-and-tasking) processed according to Level 3A (radiometric, sensor and geometric corrections). NDRE is similar to the Normalized Difference Vegetation Index (NDVI) but it uses the red-edge wavelength instead of the red wavelength. NDRE is well suited for fire severity mapping as it is particularly sensitive to variations in chlorophyll content (Chuvieco et al. 2006; Korets et al. 2010; Fernández-Manso et al. 2016). To map living trees, we classified NDRE values using a threshold discriminating between RapidEye pixels containing only dead trees and those with some survived individuals. We first selected plots with no survived trees, as assessed during field surveys, and computed the average NDRE value at the plot level, using pixels whose centroid fell within that plot. We then computed the 95th percentile of their NDRE values, equal to 0.25, and considered pixels with values higher than this threshold as likely containing living trees. Afterwards, we calculated the Euclidean distance from each plot to the nearest pixel containing seed trees in a GIS environment. We aggregated the cells of all the variables in raster format to 20 m to match the resolution of the fire severity map.

Variable Code	Description	Spatial resolution	Unit	Data source
Elevation	Elevation	20 m	m a.s.l.	DTM
HLI	Heat Load Index (McCune and Keon, 2002)	20 m	-	DTM
Slope	Slope	20 m	°	DTM
Roughness	Degree of irregularity of the surface	20 m	m	DTM
Fire severity (RdNBR)	Fire severity based on Morresi et al. (2022)	20 m	-	Morresi et al. 2022
Gramineae	Gramineae cover	-	%	Field
Forbs	Forbs cover	-	%	Field
Bare soil	Bare soil cover	-	%	Field
Shrubs	Shrubs cover	-	%	Field
CWD	Coarse woody debris cover	-	%	Field
Rock	Rock Cover	-	%	Field
Distance to Seed trees	Distance from the nearest seed tree	20 m	m	RapidEye
Seedlings density	Density of seed-origin individuals	-	Seedlings number ha^{-1}	Field

Table 3.1: *Variables used to assess the main drivers of forest seedling regeneration in the Susa fire (Susa Valley, Italy). Dash (-) indicates the absence of the spatial resolution (i.e., field measurement) or unit (i.e., dimensionless indices).*

3.2.6 Data analysis

We performed all the statistical analyses using the `R language` (R Core Team 2022). We assessed differences in soil characteristics according to fire severity classes by analyzing the following parameters: organic carbon content (OC), nitrogen content (N), carbon-to-nitrogen ratio (C/N), and pH. We employed the Kruskal-Wallis test (Kruskal and Wallis 1952) to detect significant differences in soil parameters according to the fire severity classes since normality assumptions were not satisfied (Shapiro-Wilk test; Shapiro and Wilk 1965). In case of a significant difference among groups, we used Dunn's test to perform pairwise comparisons (Dunn 1964).

We assessed short-term seedling regeneration dynamics using the time series dataset (2018-2020 period). We assessed patterns in ground cover, seedling density, and species composition throughout the study period. We calculated the Brillouin index as a measure of species diversity (Brillouin 1956) with the R package `vegan` (Oksanen et al. 2020). Since the assumptions of normality were not satisfied, we used PERMANOVA (Anderson 2017) to assess the differences in ground cover among the three fire severity classes, while we used the Kruskal-Wallis test by rank to test for significant differences in seedling density and species diversity among the different fire severity classes. We performed pairwise comparison by using the Dunn's test.

We predicted the total seedling regeneration density based on several environmental drivers (Table 3.1) through a Random Forest (RF) regressive model. We employed `randomForestSRC` R package to build the RF model (Ishwaran and Kogalur 2022). We calculated variable importance (vimp) through the Breiman-Cutler permutation (Breiman 2001), and we obtained partial dependence plots through the `ggRandomForests` R package (Ehrlinger 2016). We created partial dependence plots for the three most important variables by integrating the effects of variables according to the covariate of interest, and we constructed graphs by selecting evenly-spaced points alongside the distribution of the covariate. We evaluated the model performance by using the out-of-bag (OOB) R^2. We performed the same model to assess Scots pine and broadleaf seedling density based on the environmental drivers in Table 3.1, evaluating differences in species dispersal capacity and colonization ability (See Supplementary Material, Figs. S3.2, S3.3, S3.4, and S3.5).

3.3 Results

3.3.1 Fire severity and soil properties

Topsoils in unburnt to low severity plots were characterized by an average OC content of 42.47 g kg^{-1} (± 21.02 g kg^{-1}) (Fig. 3.2a) and an average N content of 3.17 g kg^{-1} (± 1.28 g kg^{-1}) (Fig. 3.2b). High severity plots showed lower N contents (P = 0.046; Fig. 3.2b) compared to unburnt to low severity plots. C/N values (Fig. 3.2c), in the range of 8.60 to 17.40 (± 2.01), did not vary significantly along the fire severity gradient (P > 0.1), as well as soil pH (P > 0.1) (Fig. 3.2d; mean value 5.63 ±0.78), and OC content (P > 0.1; Fig. 3.2a).

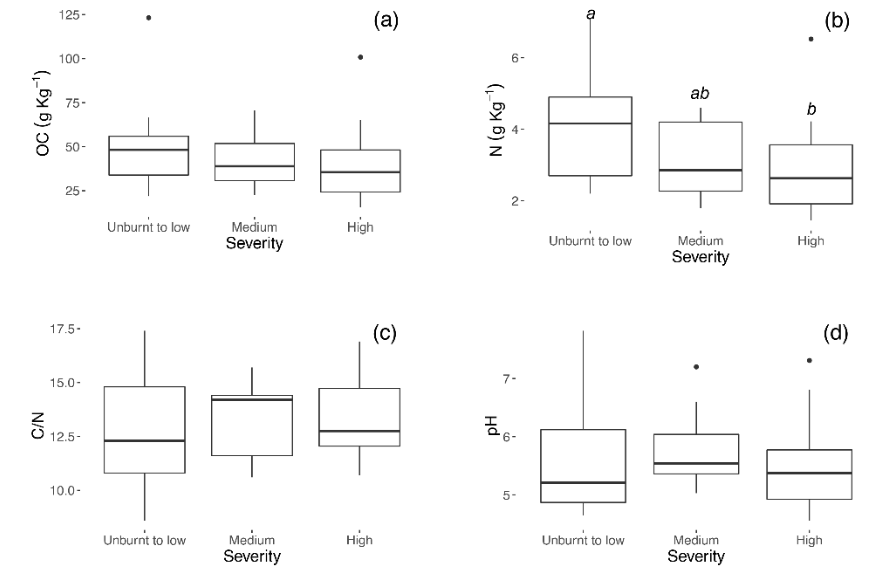

Fig. 3.2: *(a) Soil organic carbon content (OC) (g kg^{-1}), (b) nitrogen content (N) (g kg^{-1}), (c) carbon-to-nitrogen ratio (C/N), and (d) pH in the four fire severity classes in 2020 in the Susa fire (Susa Valley, Italy). Different letters indicate significant differences among fire severity classes according to the Dunn's post-*hoc *tests for pairwise comparisons.*

3.3.2 Short-term seedling regeneration patterns

Bare soil was the dominant ground cover class in the entire study area, but fire severity classes showed different responses (Fig. 3.3). Bare soil, from the first to the third year since the fire, decreased from 81% to 64% in medium severity areas and from 78% to 48% in high severity areas. We observed a gradual increase of shrubs, Gramineae, and forbs throughout the years, mainly in high severity areas (Fig. 3.3). We found differences in ground cover (between medium and high severity in 2019 (P = 0.054*)* and between unburnt to low and high severity in 2020 (P = 0.09).

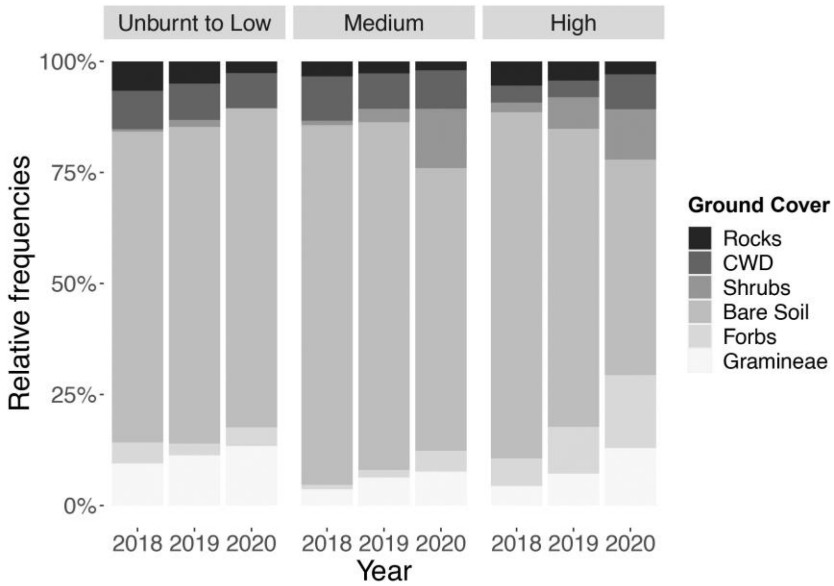

Fig. 3.3: *Ground cover percentage according to fire severity classes in 2018, 2019, and 2020 in the Susa fire (Susa Valley, Italy).*

We found the highest values of seedling regeneration density in the medium severity areas for all three years of observation (mean = 42 138 seedlings number ha^{-1}), while high severity areas had the lowest density (mean = 6509 seedlings number ha^{-1}; Fig. 3.4). There were differences in terms of density among all fire severity classes (P < 0.05). The pairwise comparisons among group levels showed that seedling regeneration density in medium severity areas was higher than in the other fire severity classes for all the years of observation (P < 0.05) (Fig. 3.4). We observed an increase in Scots pine density between 2018 and 2019, followed by a sharp decrease in 2020. This trend was common among all fire severity classes, but the only slightly significant difference was found in unburnt to low severity between 2018 and 2019 density (P = 0.059) (Table 3.2).

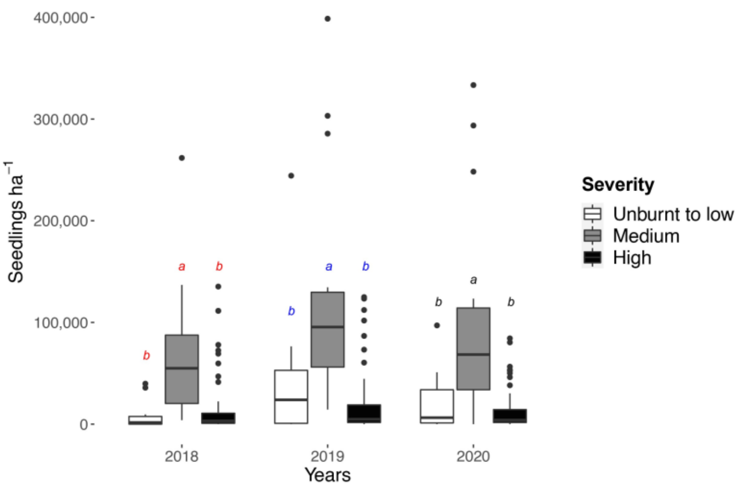

Fig. 3.4: *Box plots of seedling regeneration density in unburnt to low, medium, and high severity areas for 2018, 2019, and 2020 in the Susa fire (Susa Valley, Italy). Different letters indicate significant differences among fire severity classes according to the Dunn's post-hoc tests for all pairwise comparisons.*

		Seedling density													
Year	Fire severity	*Pinus sylvestris*		*Populus tremula*		*Salix caprea*		*Populus alba*		*Larix decidua*		*Abies alba*		*Other broadleaves*	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
2018	Unburnt to low	4398	7523	0	0	1508	4707	0	0	0	0	42	183	335	765
	Medium	45 784	47 582	424	1079	17 613	21 458	1538	4536	1220	2914	159	616	0	0
	High	9127	21 770	1784	2981	3629	9526	277	647	157	508	48	275	60	212
2019	Unburnt to low	28 983	43 625	209	447	4272	9008	0	0	1927	7634	586	641	209	584
	Medium	81 859	62 975	1910	2653	22 706	25 157	690	1851	17454	36 601	690	788	106	411
	High	7729	18 476	2833	3735	6101	11 186	494	891	301	749	277	783	48	191
2020	Unburnt to low	10 596	13 260	335	667	3937	8763	0	0	4063	10 429	544	653	209	520
	Medium	51 778	50 702	3395	4826	26 526	28 398	902	1616	19788	36 783	424	591	0	0
	High	4063	9707	1833	2489	5474	8815	555	1108	434	840	229	736	109	520

Table 3.2: *Annual mean seedling density (seedlings number ha^{-1}) and standard deviation (SD) for the main tree species in the different fire severity classes in 2018, 2019, and 2020 in the Susa fire (Susa Valley, Italy).*

In terms of species composition, Scots pine was the most abundant species in the fire severity classes and post-fire years, with the only exception of goat willow (*Salix caprea* L.) in high severity areas in 2020 (Table 3.2; See Supplementary Material, Fig. S3.1). The presence of other tree species was rather sporadic, apart from goat willow and European larch. In medium severity areas, Scots pine was by far the most widespread species, with seedling density after the first post-fire growing season being more than 10 times higher than in unburnt to low plots (P = 0.0003), almost 3 times in the second-year post-fire (P = 0.008), and more than 5 times in the third-year post-fire (P = 0.016). Goat willow and European larch were respectively the second and third most abundant species in the medium severity class. High severity areas were also dominated by Scots pine, but with much lower density compared to medium severity. Other relevant species, in the case of high severity, were goat willow and European aspen (*Populus tremula* L.) (Table 3.2).

The Brillouin diversity index showed the highest values in medium severity areas, with an increasing trend from 2018 (0.62) to 2020 (0.90) (See Supplementary Material, Table S3.1). The only significant difference was between unburnt to low and medium severities in 2018, immediately after the fire (P = 0.024) and between unburnt to low and high severity in 2019 (P = 0.062).

3.3.3 Drivers of forest recovery

The variable importance from the RF model identified slope as the most important factor influencing seedling density, followed by fire severity and distance from seed trees (Fig. 3.5). The out-of-bag (OOB) R^2 obtained from the RF was 0.42.

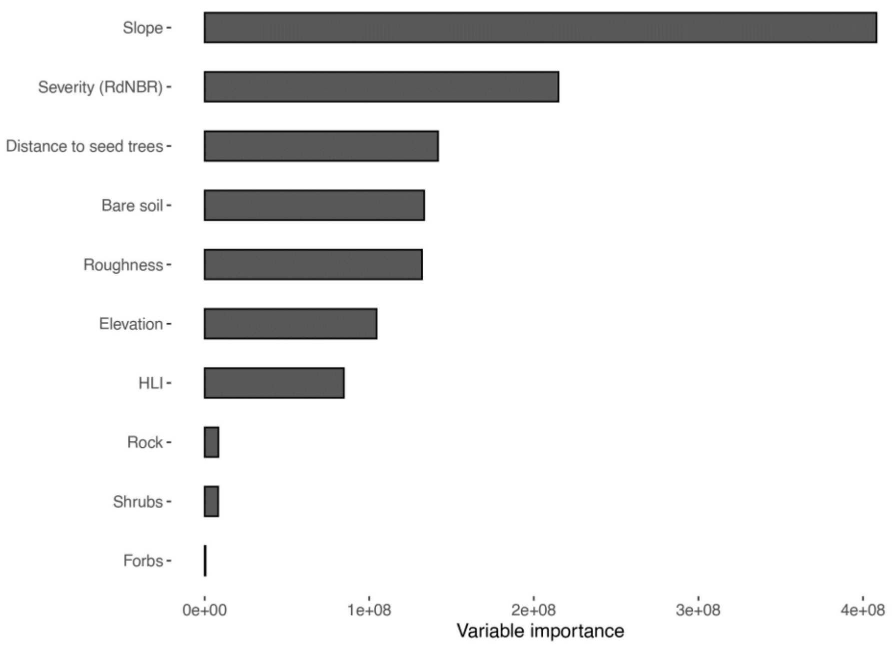

Fig. 3.5: *Variable importance (vimp) for seedling regeneration density (seedlings number ha^{-1}). The plot details vimp ranking for the regeneration density baseline variables, from the largest (slope) at the top, to the smallest (forbs) at the bottom. Vimp measures are shown using bars to compare the scale of the error increase under permutation. Only the first 10 variables are shown.*

According to the partial dependence plot, seedling regeneration density was scarce in steep slopes, showing an exponentially decreasing trend with increasing slope (Fig. 3.6a). The model predicted the maximum of seedling density in medium severity areas, while high severity areas were associated with lower forest seedling regeneration abundance (Fig. 3.6b). We found maximum seedling regeneration density close to seed trees, showing again an exponentially decreasing trend that reached a plateau around 50 meters from the seed trees, where seedlings were very few (Fig. 3.6c).

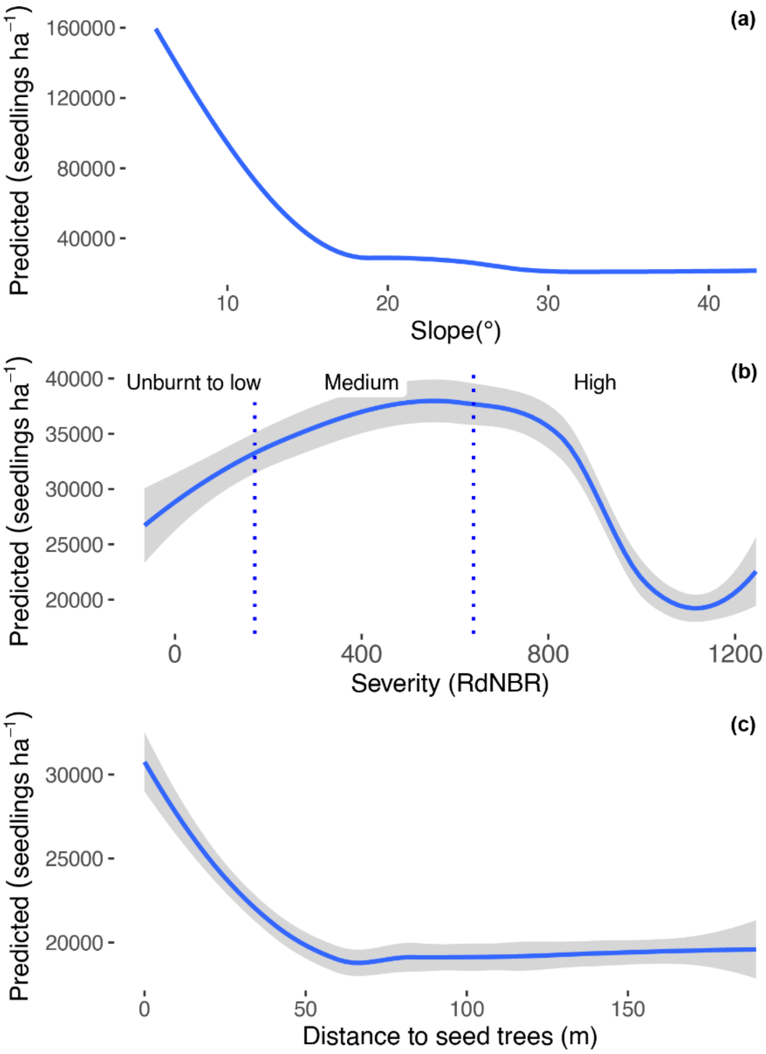

Fig. 3.6: *Partial dependence plots from RF of post-fire seedling regeneration density for the three main driver variables: (a) slope, (b) fire severity, (c) distance to seed trees. A partial dependence plot shows the effect of a particular predictor on the response variable after integrating the effect of the rest of predictors. The blue line indicates the average value over individual marginal effects of the variables, while the grey ribbon indicates the standard deviation of individual marginal effects. (b) Dotted vertical lines indicate thresholds for fire severity classes (Morresi et al. 2022).*

Scots pine and broadleaf RF models showed similar results to those obtained for the total seedling regeneration density (See Supplementary Material, Figs. S3.2, S3.3, S3.4, and S3.5). Scots pine seedling density was mainly influenced by bare soil, fire severity, and distance to seed trees (See Supplementary Material, Fig. S3.2). Predicted seedling density was positively correlated to bare soil, with an abrupt increase for percentage cover values higher than 70% (See Supplementary Material, Fig. S3.3a). Fire severity and distance to seed trees showed a trend similar to the one of total seedling regeneration density (See Supplementary Material, Figs. S3.3b and S3.3c). The main drivers of broadleaf seedling regeneration density were fire severity, elevation, and slope (See Supplementary Material, Fig. S3.4).

3.4 Discussion

Shedding light on short-term seedling regeneration patterns following a wildfire and their key drivers is essential to develop appropriate management strategies in the current context of global change. Early post-fire recovery and regeneration dynamics in Scots pine stands of the Alpine Region is a poorly explored issue that needs to be monitored.

3.4.1 Fire severity and soil properties

Fire severity did not significantly affect the monitored soil chemical parameters. We did not find any significant effect of fire severity on soil OC content, while existing studies reported a decrease in soil OC content in severely burnt areas (Certini 2005), contrasting (Neary et al. 2005), or mostly unchanged values (Fernández-García et al. 2019). We found instead a decreasing pattern in total N content from unburnt to low to high severity, as expected due to its volatilization caused by the fire (Raison 1979; Grogan et al. 2000; Smithwick et al. 2005). We found C/N values that are in line with existing data of fire-affected forest soils

(Knicker et al. 2006) and, as in our case, increasing fire severities do not always affect this parameter (Certini et al. 2011). An increase in soil pH frequently occurs after the passage of a wildfire (Badía and Martí 2003; Pereira et al. 2017). Yet, the alkalizing effect induced by ash incorporation within the soil matrix (Certini et al. 2011) was not always found to persist over long time periods (Zavala et al. 2014). However, we did not find any statistically significant effect of fire severity on soil pH.

In other forest environments, changes in soil OC and N were documented to be fundamental in ruling post-fire vegetation recovery (Caon et al. 2014). It is possible that other soil characteristics or nutrient availability would be more fitting to explain the effects of fire severity on soil and the potential implication for vegetation recovery, rather than OC content, N content, and pH alone. However, the objective of this work was to evaluate the role of typical chemical indicators on post-fire regeneration dynamics according to different levels of fire severity.

3.4.2 Short-term regeneration patterns

Since the first three years post-fire, seedling regeneration showed the highest density as well as the greatest diversity in species composition in medium fire severity areas. The most abundant regenerating species was Scots pine, probably due to the almost pure species composition of the previous stand. Nevertheless, three years after the fire (2020), goat willow showed a greater density than Scots pine in high severity areas, suggesting a potential shift from conifer to broadleaf species in stand-replacing patches. Medium severity areas presented a significant regeneration density of larch as well, probably due to the seed dispersal ability of this species. Larch was mostly located on the upper slopes of the study area, where fire severity was lower (personal observation). The most common broadleaves in the seedling layer were goat willow and European aspen, mainly in medium and high severity area. The density of these pioneer broadleaf species, whose seed origin has been assessed during the data collection campaign, is mainly due to their strong seed dispersal ability through anemochory (Myking et al. 2011; Tiebel et al. 2019). All the observed regenerating species were early successional and were therefore able to establish and grow under the favorable conditions (i.e., increased availability of light, exposed mineral soil and favorable seed beds) created post-fire (Reinhardt et al. 2001; Nuñez et al. 2003; Úbeda et al. 2006).

3.4.3 Drivers of forest recovery

The importance of fire severity in determining seedling density also emerged from the RF model, confirming that medium severity conditions maximize the probability of having high seedling densities for the species under investigation. In these areas, the wider presence of Scots pine seedlings, compared to the one observed in both unburnt to low and high severity areas, was probably related to more favorable conditions required for seedling recruitments.

Nevertheless, the most important parameter in influencing seedling abundance was slope, with a higher density in flat areas and almost no seedlings on slopes greater than 30°. This is confirmed in several studies analyzing post-fire regeneration recovery (e.g., Tsitsoni 1997; Han et al. 2015; Sass and Sarcletti 2017). Steeper slopes are more prone to soil surface erosion phenomena and, consequently, to seed runoff, while in flatter areas seeds tend to accumulate and there are more favorable moisture conditions (Tsitsoni 1997; Pausas et al. 2004; García-Jiménez et al. 2017; Ziegler et al. 2017).

We observed an exponential decrease in the abundance of seedlings at increasing distances from seed trees, reaching a plateau at a value of 50 meters (< 5000 seedlings ha^{-1}). Similarly, Vilà-Cabrera et al. (2011) found that 90% of Scots pine seedlings were in the first 25 meters from the seed source (50% within the first

10 meters). Debain et al. (2007) also observed that Scots pine regeneration density decreased 50 meters away from seed trees. In comparison with other pine species (*Pinus heldreichii* Christ, *P. peuce* Griseb., *P. uncinata* Mill.), Scots pine resulted as the one with the lowest dispersal distance, comparable only to *P. uncinata* (4.2 and 3.7 meters, respectively; Vitali et al. 2019). Thus, seed trees need to be preserved, even in the case of damaged individuals with a low probability of survival.

Alteration in fire regimes will likely cause an increase in the extent of high severity patches (Miller et al. 2012), making recovery harder because of the greater distance from seed sources (Harvey et al. 2016). Therefore, the role of seed trees inside high severity patches will become increasingly important. The key role of seed sources in this study is likely linked to fire severity and to the loss of the soil seed bank in medium and high severity areas, due to the high soil temperature reached during the fire. In several studies (e.g., Escudero et al. 1997; Reyes and Casal 1995; Nuñez and Calvo 2000), a decrease in germination was observed for temperature higher than 90° C and an exposure time greater than 5 minutes.

According to the RF model, ground cover classes did not show a great influence on total seedling density, while bare soil emerged as the most important factor positively affecting Scots pine abundance (See Supplementary Material, Figs. S3.2 and S3.3). This finding aligned with the ecological needs of this species (Castro et al. 2005). We found coarse woody debris to be unrelated to seedling abundance, which is in contrast to what has been observed in other studies in the North-Western Italian Alps (Beghin et al. 2010; Marzano et al. 2013). This might be due to the overall sufficient presence of seed trees, even inside high severity patches, with the distance from seed sources seldom being a limiting factor in the Susa fire. Widespread seed availability likely reduced the importance of facilitation mechanisms on regeneration, such as those provided by shield objects like deadwood. However, where large stand-replacing fire patches are present, “safe-sites”, those with favorable microclimatic conditions created by deadwood, are fundamental for seedlings establishment and survival (Marzano et al. 2013). Unlike other studies, the presence of shrubs and herbaceous species after the Susa fire did not seem to strongly affect regeneration density yet, as assessed in the RF model. This indicates that competition had minimal importance during the first years after fire, even if interspecific competition is usually considered a key factor in the regeneration process (Nuñez et al. 2003). However, it is likely that the spreading of dense and continuous shrub or herbaceous layers in the area observed throughout the study period, will lead in the near future to an increase in competition for light and nutrients and to the death of those seedlings that are still growing under these layers.

3.4.4 Management implications

Our results provide implications for the management of mountain conifer forests affected by shifts in their fire regime and without specific fire-adaptive traits. Given the abundance of seedling regeneration in medium severity patches close to seed trees, we recommend leaving any potential seed source, including damaged individuals, to promote post-fire forest recovery. Survived trees, even with just a partially intact crown are crucial for post-fire seed dispersal. Their crown seed bank might compensate for the destroyed soil seed bank within medium- or high-severity patches. Therefore, our study demonstrates the importance of leaving any potential seed tree, even if damaged, however considering possible risks for people and infrastructures. The removal of damaged trees should be restricted to sensitive areas, where the fall of these individuals could pose a risk for humans or their assets. Salvage logging practices should be limited, since they can slow down or inhibit natural recovery processes, reducing regeneration density and influencing the specific composition and structure of future stands (Lerverkus et al. 2018a, b).

Proper planning and management of areas affected by a wildfire are often necessary, especially to define the actual need for intervention and organize appropriate and targeted measures. Active intervention should be devoted to those situations in which natural regeneration is unable to establish, for example in large high severity patches, or in areas that are likely to be affected by degradation phenomena, such as soil erosion, or where a decrease in the provision of ecosystem services and potential cascading disturbance effects are foreseen. In those contexts, where natural successional dynamics are delayed, it could be useful to adopt ANR approaches, such as removing competitive, non-woody species and grasses (Zahawi et al. 2013) or taking advantage of facilitation mechanisms. Methods like applied nucleation can be also implemented to accelerate natural dynamics. The use of applied nucleation can be envisaged in wide high severity patches where the seed rain from forest edges and green islands is insufficient. Spatial prioritization of *nuclei* location combined with ANR allows active restoration efforts to be implemented only in areas where natural regeneration is lacking or more prone to post-disturbance degradation phenomena, also resulting in lower costs compared to a traditional regular plantation. This follows within the framework of precise forest restoration (PFR) (Castro et al. 2021), aiming to improve planting (or seeding) efficiency, by focusing on site selection and preparation, postplanting care, and monitoring.

3.5 Conclusions

Our investigation of the Susa fire provided information on the spatial distribution and characteristics of short-term post-fire recovery after a large mixed severity event in Scots pine stands. These findings could be useful for informing land managers, helping them to enhance potential mitigation strategies in similar ecosystems. The most frequently applied restoration techniques applied after large fire events are often not up-to-date and suited to the ecological context and to the consequences of global change. More ecologically appropriate restoration approaches are needed as land managers increasingly request for restoration strategies and guidelines. The necessity of appropriate strategies is even more pressing in the case of sensitive ecosystems, where natural balances could be altered by changes in disturbance regimes, and human intervention can either facilitate ecosystem recovery or trigger further degradation phenomena. In this perspective, it is crucial to reconsider current post-disturbance policies to identify strategies that promote and maintain ecosystem functions of severely affected forests, whether through active or passive management.

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Supplementary Material

Year	Brillouin index		
	Unburnt to low severity	Medium severity	High severity
2018	0.25	0.62	0.50
2019	0.44	0.65	0.69
2020	0.68	0.90	0.72

Table S3.1*: Brillouin index values (0 to 1) according to fire severity classes in Susa fire (Susa Valley, Italy) in 2018, 2019, and 2020.*

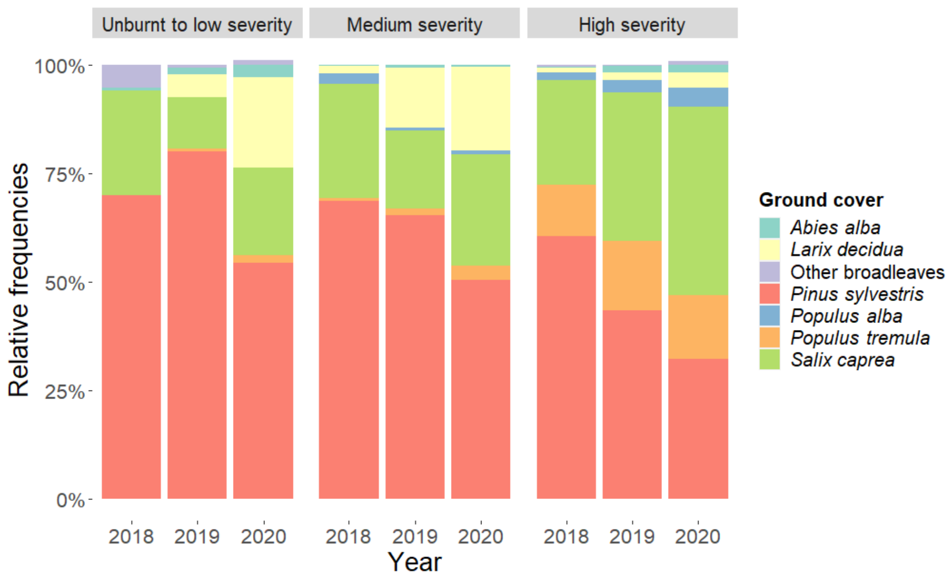

Fig. S3.1: *Proportion of seedlings of each tree species according to fire severity classes in 2018, 2019, and 2020 in the Susa fire (Susa Valley, Italy).*

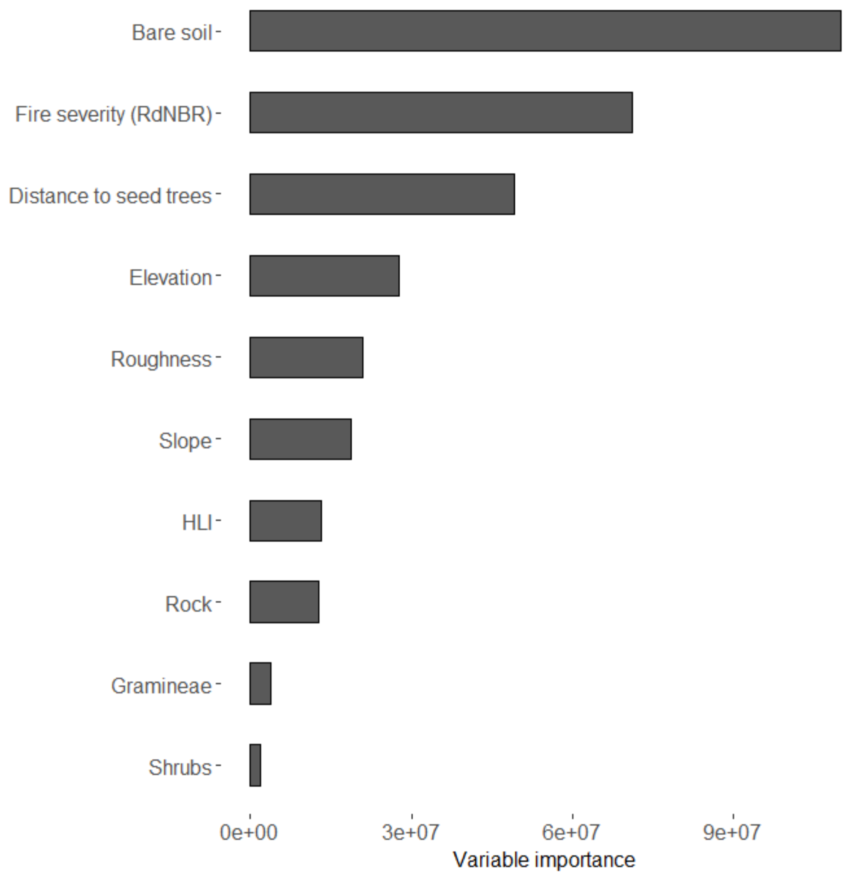

Fig. S3.2: *Variable importance (vimp) for Scots pine density (seedlings number ha*$^{-1}$*). The plot details vimp ranking for the regeneration density baseline variables, from the largest (bare soil) at the top, to the smallest (shrubs) at the bottom. Vimp measures are shown using bars to compare the scale of the error increase under permutation. Only the first 10 variables are shown.*

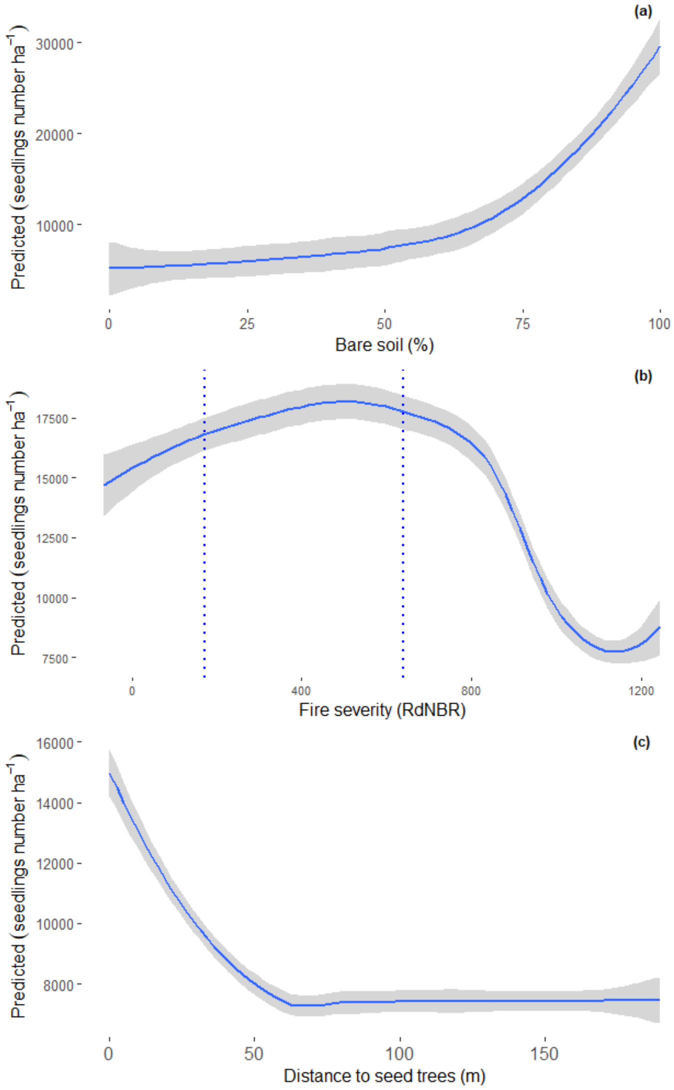

Fig. S3.3: *Partial dependence plots from RF of Scots pine density for the three main driver variables: (a) bare soil, (b) fire severity, (c) distance to seed trees. A partial dependence plot shows the effect of a particular predictor on the response variable after integrating the effect of the rest of predictors. The blue line indicates the average value over individual marginal effects of the variables, while the grey ribbon indicates the standard deviation of individual marginal effects. (b) Dotted vertical lines indicate thresholds for severity classes (Morresi et al., 2022).*

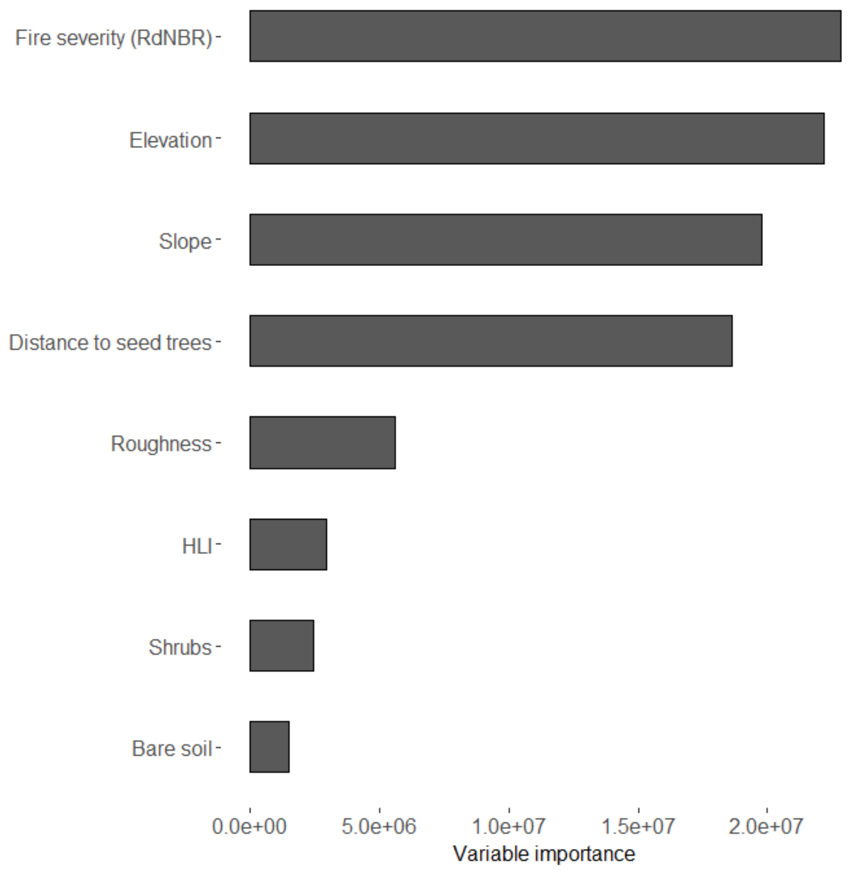

Fig. S3.4: *Variable importance (vimp) for broadleaf density (seedlings number ha^{-1}). The plot details vimp ranking for the regeneration density baseline variables, from the largest (fire severity) at the top, to the smallest (bare soil) at the bottom. Vimp measures are shown using bars to compare the scale of the error increase under permutation. Only the first 8 variables are shown.*

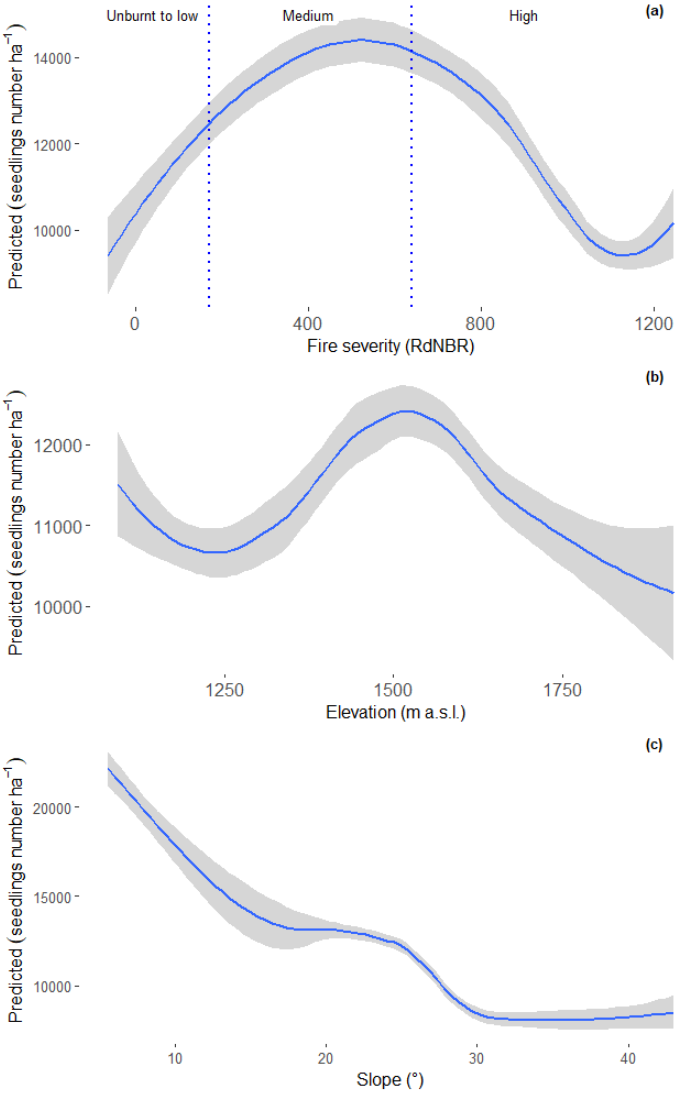

Figure S3.5: *Partial dependence plots from RF of broadleaf regeneration density for the three main driver variables: (a) fire severity, (b) elevation, (c) slope. A partial dependence plot shows the effect of a particular predictor on the response variable after integrating the effect of the rest of predictors. The blue line indicates the average value over individual marginal effects of the variables, while the grey ribbon indicates the standard deviation of individual marginal effects. (b) Dotted vertical lines indicate thresholds for severity classes (Morresi et al., 2022).*

Chapter 4

Modelling 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 regeneration dynamics. Applied nucleation (AN) could be a valuable active restoration approach for promoting natural regeneration in forest ecosystems affected by extreme disturbance events since it improves seed availability and microsite conditions.

Objectives

The study aimed to investigate the potential outcomes of a set of AN 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

wildfire in 2005 and post-fire salvage logging that amplified ecosystem degradation and dampened natural regeneration.

Methods

We assessed the main drivers guiding post-fire natural recovery and identified suitable sites for regeneration through a machine learning correlative model (Bayesian Additive Regression Tree, BART), using the occurrence of natural regeneration as a response and several environmental variables (e.g., topography, wind direction, and distance from seed trees) as predictors. We predicted the probability of regeneration presence at the landscape scale with a spatial resolution of 10 m under the current situation (wildfire followed by salvage logging) and a set of AN scenarios characterized by an increase in the density of *nuclei*, since distance from seed trees emerged as the most important driver for natural regeneration. Starting from the current situation, we reclassified the prediction raster into a binary map of intervention priority (priority vs. non-priority pixels), using the probability value that maximized the model accuracy (true skill statistic; TSS) as threshold. Areas 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 regeneration processes.

Conclusions

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

Keywords: Applied nucleation, Ecological restoration, Natural regeneration, Post-fire management, Regeneration drivers, Scots pine, Spatial modelling

4.1 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 Nation 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 on the ecological consequences of active post-fire interventions due to their potential implications on ecosystem recovery (Alayan et al. 2022). Many nature-based solutions, that consist in 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). However, post-fire management in most forest ecosystems is still mainly focused on salvage logging, often followed by artificial plantation, even though the ecological consequences of this practices negative impacts of this practice 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 challenges 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 US

Rocky Mountains), with a reduction in regeneration density, shift in species distribution and delay in post-fire recovery due to the lack of specific fire-adaptive traits (Tapias et al. 2004; Stevens-Rumann 2017). Moreover, mountain conifer stands are already experiencing a contraction of their range because of direct climate change effects, such as the increased frequency of drought periods and the rise of mean temperature, which are hindering natural 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 (i.e., a general increase of xeric broadleaves such as downy oak (*Quercus pubescens* Willd.) in the Alps)), or a transition towards shrubland or grassland, which can be accelerated by the effects of altered fire regime on post-fire regeneration (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.) are able to promptly 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). The alterations in post-fire regeneration dynamics (i.e., reduction in regeneration density, shift in species distribution and delay in post-fire recovery), sometimes further worsened by post-fire interventions (i.e., salvage logging) 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 mostly affected by direct and indirect effects of global change. Indeed, the increase in the 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 wildfires (Pausas and Keeley 2021). Moreover, the widespread land abandonment that occurred in the marginal mountain areas of the Mediterranean region resulted in a large forest cover gain on traditionally managed land (i.e., meadows, pastures, and crops), with a consequent fuel build-up associated to an increase in fire risk (Mantero et al. 2020).

A proper diagnosis of 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 been often 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. Conversely, taking advantages of natural regeneration could be ecologically sound and economically feasible, but must be weighed against edaphic conditions and disturbance characteristics (Holl et al. 2020; Di Sacco et al. 2021). Natural 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 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 in planting small groups of trees, called *nuclei*, that have the potential to restore forest cover within a highly disturbed site both through the 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 temperature and moisture conditions, reducing wind disturbance, and improving soil quality (Rey Benayas et al. 2008; Corbin and Holl 2012). Despite the challenges that can arise from AN application (i.e., need of greater supervision of planting crews), this technique seems to be promising in cost-benefits terms (Rey Benayas et al. 2008; Corbin and Holl 2012).

An accurate planning is thus crucial for a successful AN application and should consider the characteristics of the surrounding landscape and the influence of some technical parameters, such as the 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 restoring tropical forests (Corbin and Holl 2012; Zahawi and Augspurger, 2006; Holl et al. 2020). Some authors observed that small *nuclei* (i.e., < 64 m²) might not be able to improve microsite conditions in terms of shadow, 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, although not thoroughly studied, and its effect depends on 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). AN is a relatively recent and promising technique that has been mainly 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 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 regeneration presence. This is particularly important for those situations where natural 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., lacking of fire-related traits; Mantero et al. 2023).

The aim of this study was to investigate the main drivers influencing post-fire 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 and a consequent salvage logging. Specifically, we wanted to (i) evaluate post-fire regeneration 16 years after the wildfire; (ii) assess drivers of post-fire recovery; (iii) define intervention priorities for active restoration based on the probability of post-fire natural regeneration presence; (iv) define the most effective AN scenario through modeling. We focused primarily on Scots pine and European aspen 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 regeneration.

4.2 Materials and methods

4.2.1 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). The 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). The 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* Miller,) Norway spruce (*Picea abies* (L.) H. Karst.), downy oak, European aspen, and birch (*Betula pendula* Roth.). In March 2005 a high severity wildfire affected the area, burning about 257 ha (Fig. 4.1). In a large part of the burned area (160 ha; 62%) the wildfire showed a stand-replacing behavior, leading to the complete mortality of the previous Scots pine stand. 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 deadwood was removed from the sites, with the only exception of small branches, which were piled up. Some management units were however left unsalvaged, with complete deadwood retention, allowing for comparison between the two treatments.

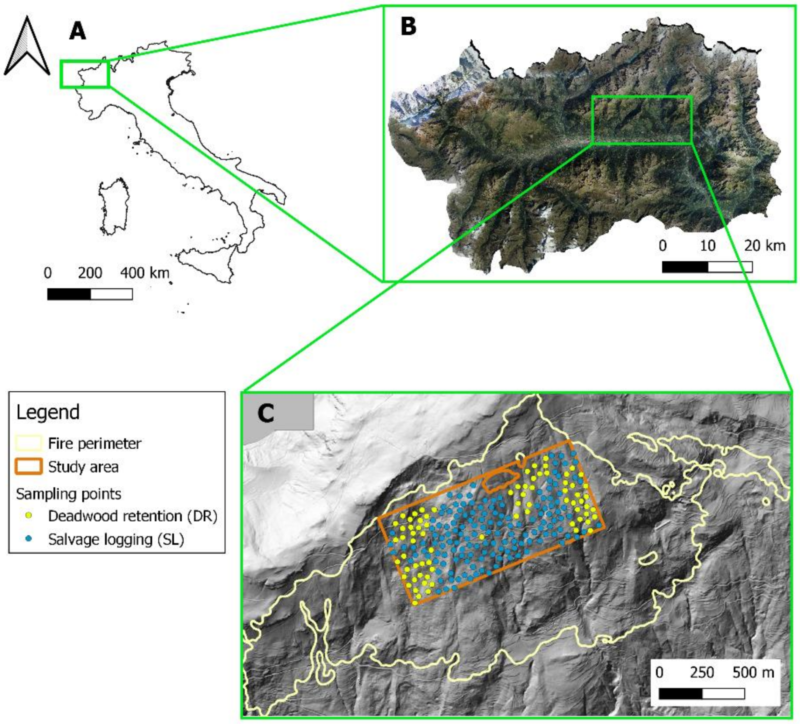

Fig. 4.1: *Location of the study area within **A** Italy, **B** Aosta Valley region, and **C** perimeter of the 2005 wildfire with location of the 223 plots used to assess regeneration pattern. Plots within salvage logging areas (SL) are marked in blue and plots within deadwood retention areas (DR) in yellow.*

4.2.2 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 regeneration. We collected regeneration data in autumn 2021. We established 223 plots (density~3 plots ha^{-1}) with a 6 m radius and a minimum distance of 40 meters from each other through a random sampling design created in a GIS environment (QGIS 3.16). 75 plots were in DR areas, while 148 plots were located in SL areas (Fig. 4.1). 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 regeneration, and ground cover data by visually estimating the percent cover (to the nearest 5%) of herbs, forbs, bare soil, litter, shrubs, coarse woody debris (CWD), and rocks. CWD was divided into piles of branches resulting from salvage logging operations (CWD_piles) and sparse logs (CWD_log).

4.2.3 Regeneration patterns

We assessed regeneration dynamics in the study site 16 years after the fire based on regeneration species composition, density, and ground cover. We analyzed Scots pine density based on the distance to the nearest seed tree (threshold: 50 m) to check for a relationship between distance from seed trees and regeneration abundance. We chose this threshold according to literature evidence (Debain et al. 2007; Vilà-Cabrera et al. 2011; Mantero et al. 2023). We applied Kruskal-Wallis test by rank to test for significant differences between Scots pine density in plots closer than 50 m to the nearest seed tree and further. We analyzed ground cover based on the two different post-fire treatments (SL and DR).

4.2.4 Drivers of forest regeneration

We used the presence/absence of Scots pine and European aspen across the 223 plots as response variable and a set of environmental drivers as covariates (Table 4.1). We used 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, terrain position index, and Euclidean distance to gullies. Since aspect is a circular variable, we converted it into eastness (sin(aspect)). 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 v. 7.8.2. 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 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 modelling 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). 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).

Variable	Category	Species of application	Original spatial resolution (m)	Unit	Data source
Elevation		Ps, Pt	2	m	DTM
Slope		Ps, Pt	2	°	DTM
Roughness		Ps, Pt	2	m	DTM
Eastness	Topography	Ps, Pt	2	-	DTM
Terrain rudgeness index		Ps, Pt	2	-	DTM
Topographic position index		Ps, Pt	2	-	DTM
Distance to gullies		Ps, Pt	2	m	DTM
Wind effect		Ps, Pt	2	-	DTM
Wind effect 10 m	Climate	Ps, Pt	2	-	DTM
Wind exposition		Ps, Pt	2	-	DTM
Distance to seed trees	Vegetation	Ps, Pt	1	m	CHM

Table 4.1: *Environmental and regeneration variables included in the BART model for assessing the main drivers of Scots pine and European aspen presence.*

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 of the reliability and the transferability of a model. We used a block spatial cross-validation through the package `blockCV` to retrieve the most unbiased estimate of autocorrelation (Valavi et al. 2018).

We measured the variable importance to select the most important drivers of 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` to see how the principal environmental variables influenced the presence/absence of Scots pine and European aspen.

4.2.5 Management scenarios

We predicted the probability of regeneration 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; Shönenberger et al. 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 regeneration probability and the extent of high intervention priority areas according to nucleation density. We then positioned the *nuclei* in the entire area, regardless of the regeneration presence probability, to see the possible outcomes of a random AN (extensive approach). All the analyses were conducted using `R version 4.2.2` (R Core Team 2022).

4.3 Results

4.3.1 Regeneration patterns

The mean 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 (149 ± 19 seedlings ha^{-1}, 10%), 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 6% of the total regeneration density (See Supplementary Material, Fig. S4.1, Table S4.1).

Regeneration showed different spatial patterns within the study area. In particular, we found significant differences for the density of Scots pine according to the distance from seed trees. The first 50 m close to seed trees showed a significantly higher Scots pine seedling density (269 ± 81 seedlings ha^{-1}) than plots located farther away from seed trees (48 ± 7 seedlings ha^{-1}; Kruskal Wallis test, $P < 0.05$).

The most important ground cover was shrubs in both treatments (44% in SL and 43% in DR), followed by Gramineae (35% in SL and 34% in DR). SL plots were characterized by a low 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. S4.2). The other ground cover classes were similar between SL and DR areas.

4.3.2 Drivers of forest regeneration

The BART model with the highest accuracy was the one with a spatial resolution of 10 meters. The accuracy values of the model according to a 5-fold spatial block cross-validation are reported in the Supplementary Material (Fig. S4.3). 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 of pine seedling (i.e., modeled) was higher than observed. The variable importance plot (VIMP) ranked all the predictors of the BART model according to their influence on Scots pine presence, showing that distance from seed trees was the most important factor, followed by eastness, and distance to gullies (See Supplementary Material, Fig. S4.4). 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. 4.2). The maximum probability to find Scots pine seedlings was found 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.

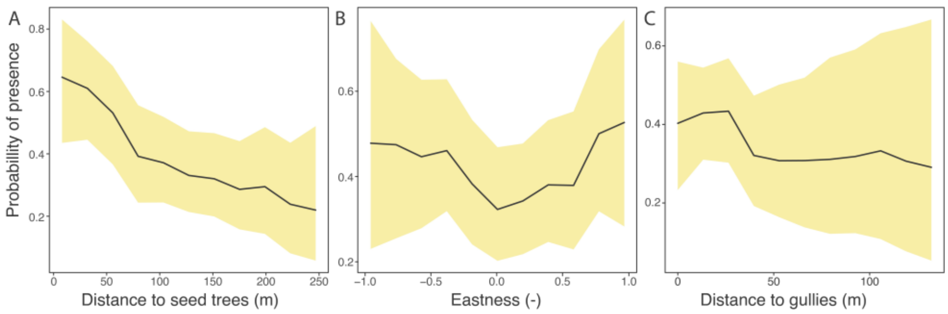

Fig. 4.2: *Partial dependence plots of the three principal drivers of Scots pine regeneration presence generated by single-instance Bayesian additive regression trees implementation:* ***A*** *distance to seed trees,* ***B*** *eastness,* ***C*** *distance to gullies. Y axes represents the probability of Scots pine seedlings presence. Yellow area represents 95% confidence interval.*

Similarly to Scots pine, also models for European aspen had 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. S4.5). 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 spatial prediction to be accurate. In this case, the low accuracy was mostly related to type-II errors (Specificity = 0.64), meaning that aspen was present also where the model predicted its absence.

The variable importance plot (VIMP) ranked all the predictors of the BART model according to their influence on European aspen presence, showing that elevation was the most important factor, followed by wind exposition, and slope (See Supplementary Material, Fig. S4.6).

As indicated by the partial dependence plots of the three most important variables (See Supplementary Material, Fig. S4.7), the highest probability to find aspen regeneration decreased with increasing elevation and reached a maximum on steep slope (40°). The maximum probability to find European aspen regeneration was found for wind-shadowed area, decreasing with increasing exposition to wind.

4.3.3 Management scenarios

Presence probability ranged from 0.06 to 0.90 within the fire perimeter with a mean value of 0.51± 0.18 and the highest values were in the outer part of the area (Fig. 4.3a). 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. 4.3b). We reclassified the probability raster of Scots pine regeneration 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. 4.3c).

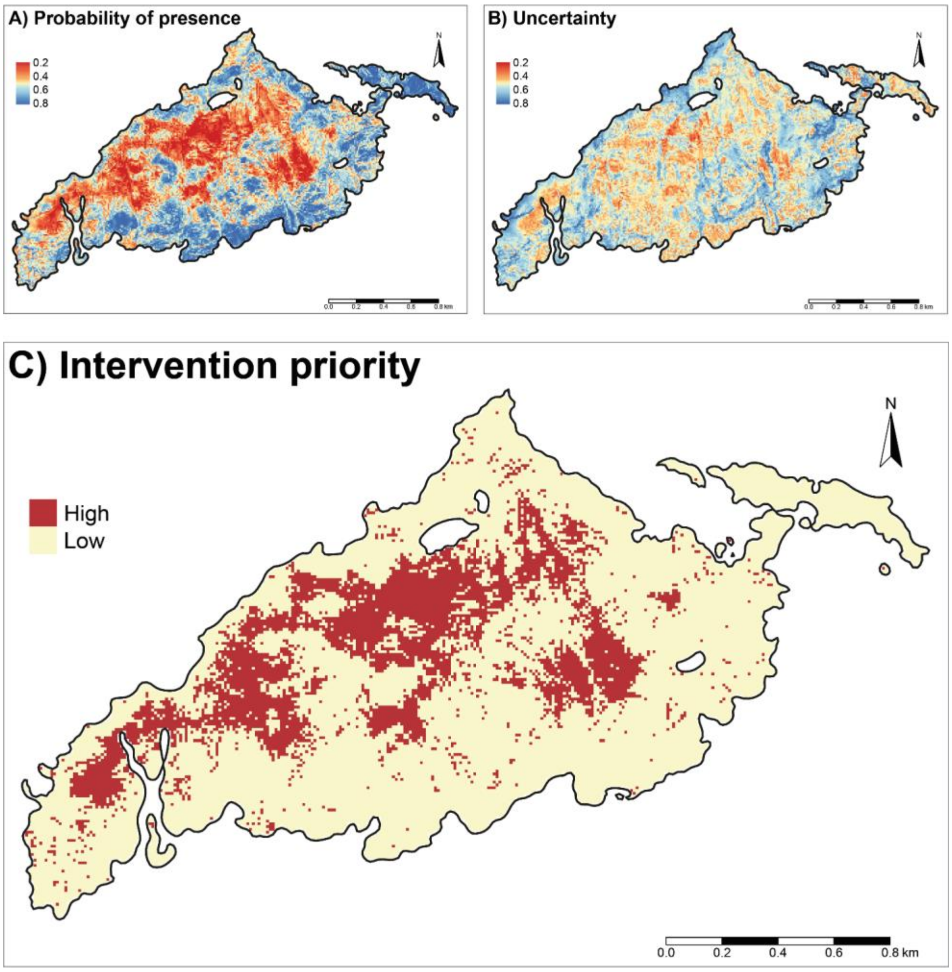

Fig. 4.3: ***A*** *Probability of presence of Scots pine seedlings according to the BART model,* ***B*** *probability uncertainty based on the 5th and 95th percentile,* ***C*** *binary map of intervention priority according to the threshold that maximized the model TSS (= 0.37).*

We observed that the probability of presence of Scots pine seedlings 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. 4.4).

However, their relationship was not linear, neither for the patchy approach nor for the extensive approach (Fig. 4.4). The 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 regeneration presence probability, while the extensive approach is more effective for higher *nuclei* densities (Fig. 4.4a). 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. 4.4b). 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 current extent of high intervention priority area (Fig. 4.4b).

The mean regeneration 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 the extensive approach respectively (Fig. 4.4a). 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 the extensive approach respectively (Fig. 4.4b). The effectiveness of the two approaches was comparable for *nuclei* density values between 0.4 and 0.65 *nuclei* ha^{-1} (Fig. 4.4; See Supplementary Material, Fig. S4.8).

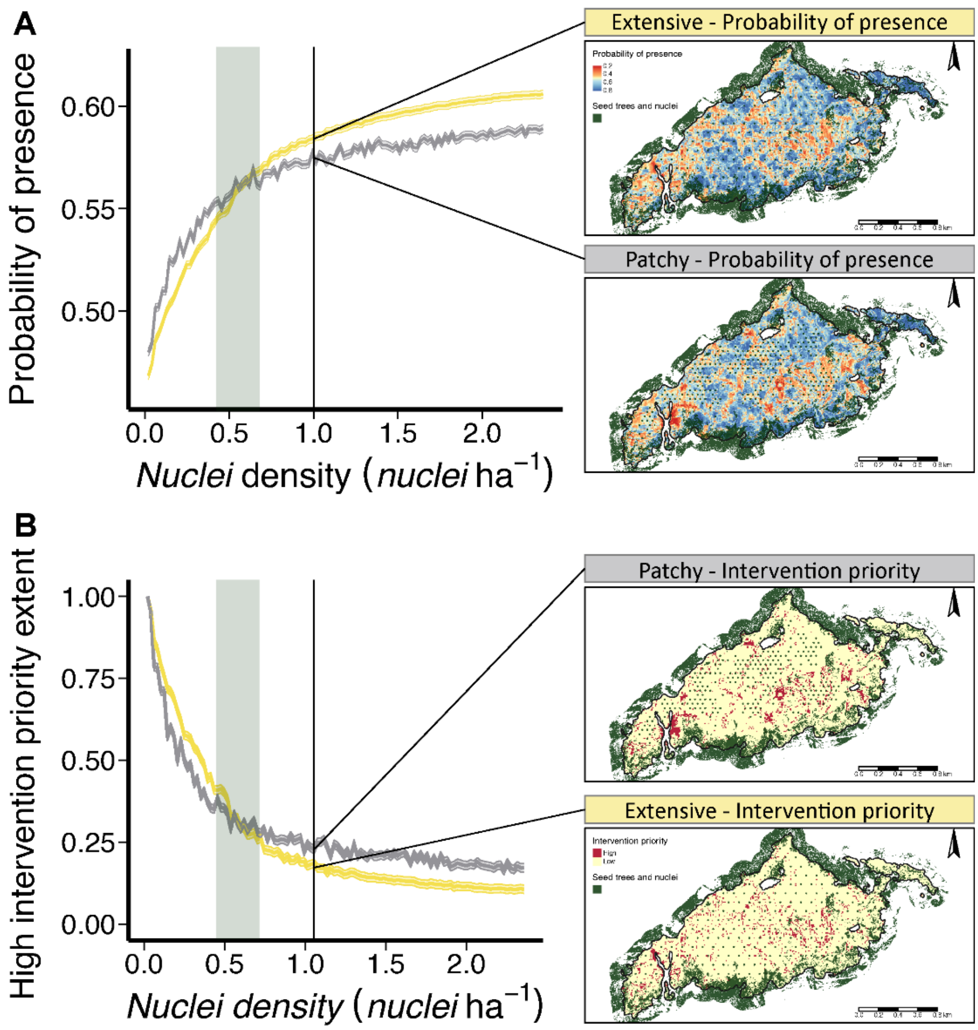

*Fig. 4.4: trends of **A** probability of presence of Scots pine regeneration according to the increasing nuclei density with standard error, **B** extent of high intervention priority areas with standard error. The yellow line represents the extensive approach, while grey line represents the patchy approach. On the right we reported probability of presence and intervention priority maps corresponding to an illustrative nuclei density of 1 nucleus ha^{-1}. The green band corresponds to the nuclei density values where the slope of the response variable decreases abruptly (See Supplementary Material, Fig. S4.9).*

4.4 Discussion

Improving our knowledge on spatial patterns and drivers of seedling regeneration in areas affected by stand-replacing wildfires and subsequent salvage logging is essential to plan effective management strategies. We proposed a correlative modeling approach at a mesoscale to detect areas where to prioritize active post-fire management due to scarcity of post-fire natural regeneration.

4.4.1 Regeneration patterns and drivers

In the Bourra site, Scots pine regeneration density was still low over a decade after the wildfire and the low recovery rate was mainly related to the high 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 regeneration establishment in the area (Marzano et al. 2013; Marcolin et al. 2019). 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 (Marzano et al. 2013; Marcolin et al. 2019).

Regeneration density was mainly 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 severity of the event, it is likely that the seed 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 seedlings also appeared to be mostly located on upper gully banks. Given the predominant southern exposure of the areas, better microclimatic conditions for Scots pine seedlings 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 seedlings were not found in gully bottoms and flat areas because aspen formed dense stands in those topographic conditions. Aspen presence was also correlated to elevation, because its recolonization started from pre-existing groups located in the lower part of the area.

4.4.2 Applied nucleation modeling

The analysis of the current situation highlighted low probability of presence of Scots pine seedlings in the core area of the site. Since the disturbance was characterized by a homogeneous high severity, very few seed trees survived within the fire perimeter. Therefore, most of the seeds came from the surrounding forest edges and were not able to penetrate into the inner part because of the low seed dispersal ability of the species. Considering that post-fire 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 abundance).

The great false positive and false negative rates of the Scots pine and aspen model, respectively, can be interpreted as an evidence of dampened ecosystem conditions after post-management practices. The high rate of false positives in 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 seedling abundance of Scots pine 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 AN *nuclei* spatial distribution. For a density of nuclei higher than 1 *nucleus* ha^{-1}, the slope of the probability of presence of Scots pine seedlings 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 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 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) could 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.

4.4.3 Management implications

In post-fire environments where passive 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. An appropriate planning is key to avoid excessive costs (e.g., widespread planting) and maximize 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 regeneration dynamics are slow due, for example, 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 reasonable time. Conversely, when seed trees are located nearby, it could be more effective to assess natural regeneration presence and abundance and evaluate the possibility of facilitating its development, rather than just planting (Holl et al. 2020).

This approach allows to detect priorities 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 seedlings might include favorable topographic features and shelters from snow cover, grazers, and water runoff. The importance of CWD in facilitating seedling 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 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 be implemented also to restoration projects in mountain forests ecosystems, given the current changes in fire regime and the difficulties in post-fire dynamics 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 policymaker and stakeholders as a tool for planning precise and effective active interventions to restore disturbed stands.

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Supplementary Material

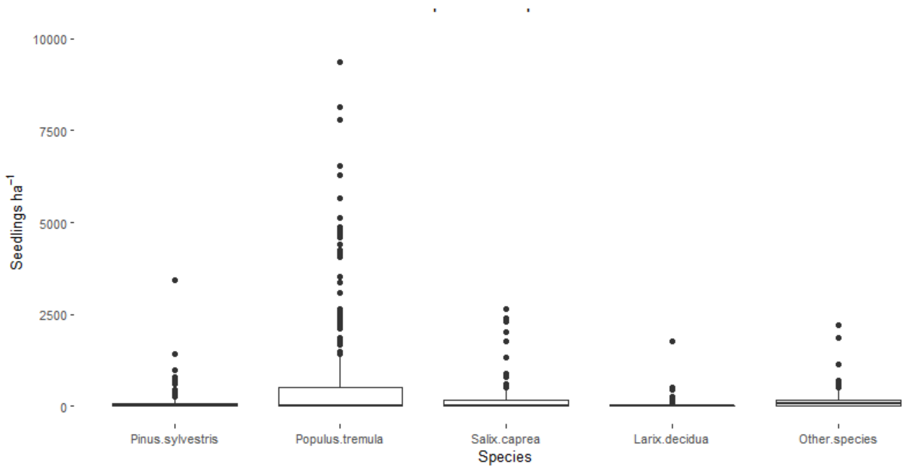


Fig. S4.1: *Boxplot of the main regeneration species in 2021.*

	Total density (Stems ha^{-1})	***Pinus sylvestris* (Seedlings ha^{-1})**	***Populus tremula* (Stems ha^{-1})**	***Salix caprea* (Stems ha^{-1})**	***Larix decidua* (Seedlings ha^{-1})**	**Other species (Stems ha^{-1})**
Mean	1527	94	1103	149	32	148
SE	173	19	167	25	9	17

Table S4.1: *Density (seedlings ha^{-1}) and standard error (SE) of the main regeneration species.*

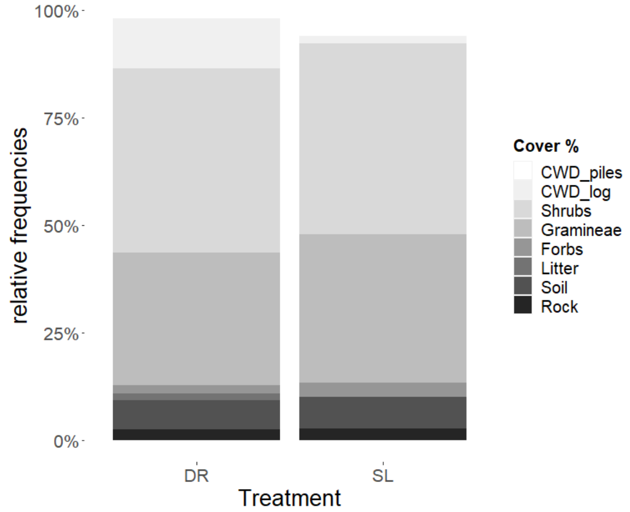


Fig. S4.2: *Ground cover percentage divided per treatment: deadwood retention (DR) and salvage logging (SL).*

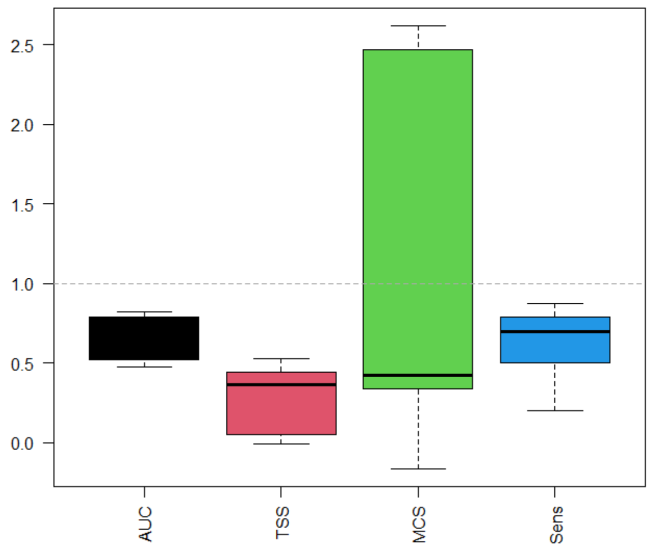


Fig. S4.3: *Accuracy values of BART model for Scots pine presence according to a 5-fold spatial block cross-validation.*

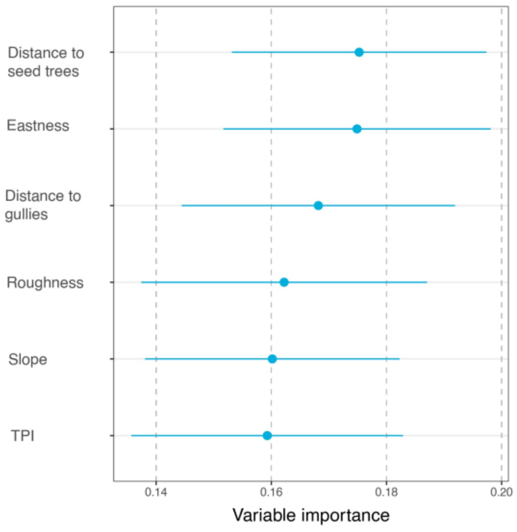


Fig. S4.4: *Variable importance plot (VIMP) of the BART model for Scots pine presence. Variable importance is measured in BART models by counting the number of times a given variable is used by a tree split across the full posterior draw of trees (Carlson, 2020). The most important variable is distance to seed trees, followed by eastness, and distance to gullies.*

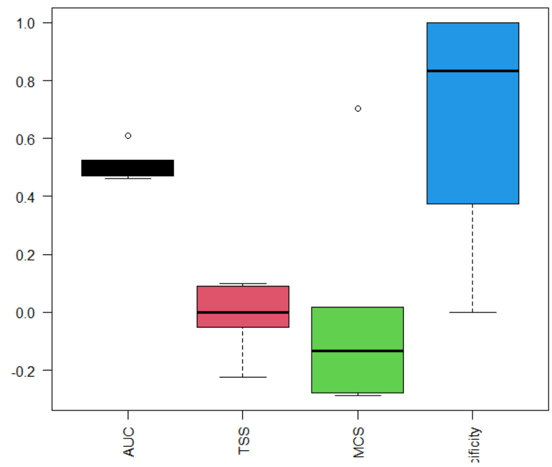


Fig. S4.5: *Accuracy values of BART model for aspen presence according to a 5-fold spatial block cross-validation.*

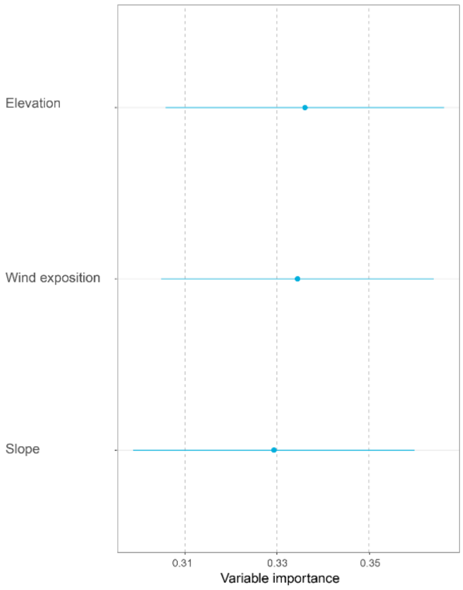


Fig. S4.6: *Variable importance plot (VIMP) of the BART model for European aspen presence. Variable importance is measured in BART models by counting the number of times a given variable is used by a tree split across the full posterior draw of trees (Carlson, 2020). The most important variable is elevation, followed by wind exposition and slope.*

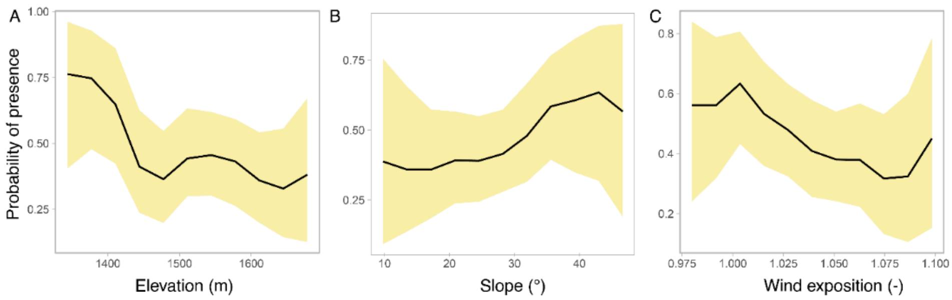


Fig. S4.7: *Partial dependence plot of the three principal drivers of European aspen regeneration presence generated by single-instance Bayesian additive regression trees implementation:* ***A*** *elevation,* ***B*** *slope,* ***C*** *wind exposition. Y axes represents the probability of Scots pine seedlings presence. Yellow area represents 95% confidence interval.*

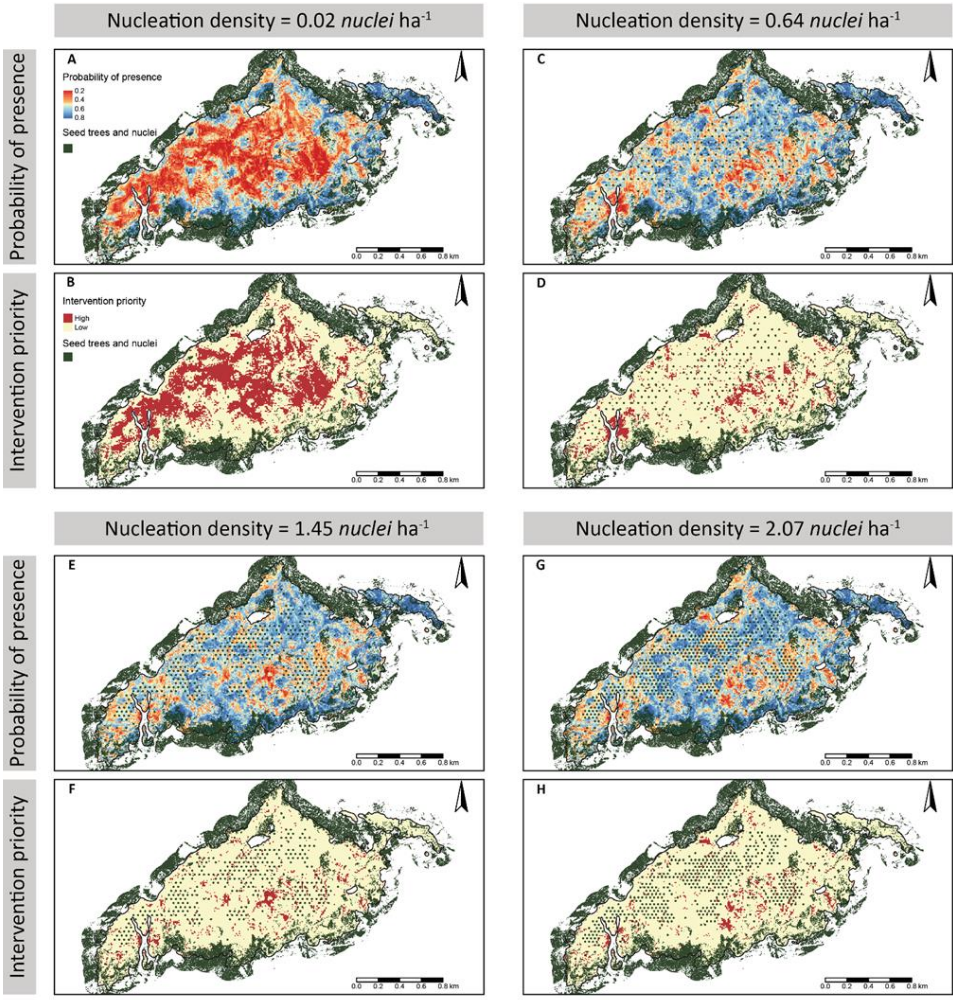
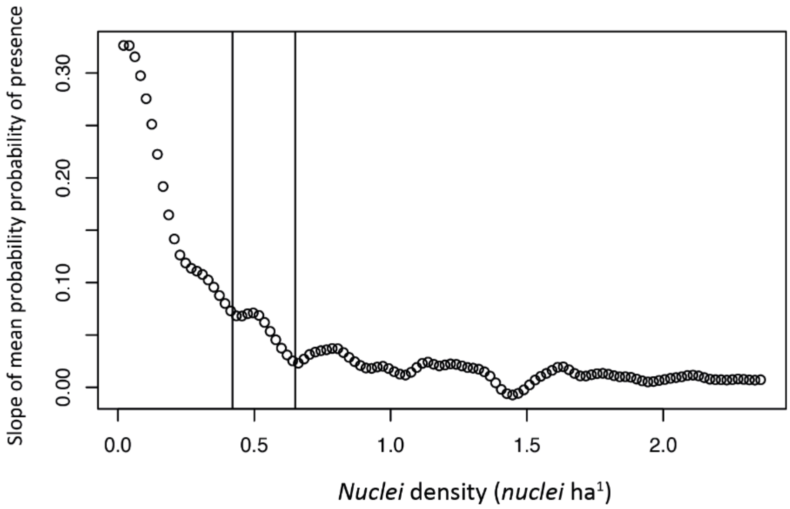


Fig. S4.8: *Probability of presence (**A**, **C**, **E**, **G**) and intervention priority maps (**B**, **D**, **F**, **H**) according to four different scenarios of AN obtained through the patchy approach.*

A



B

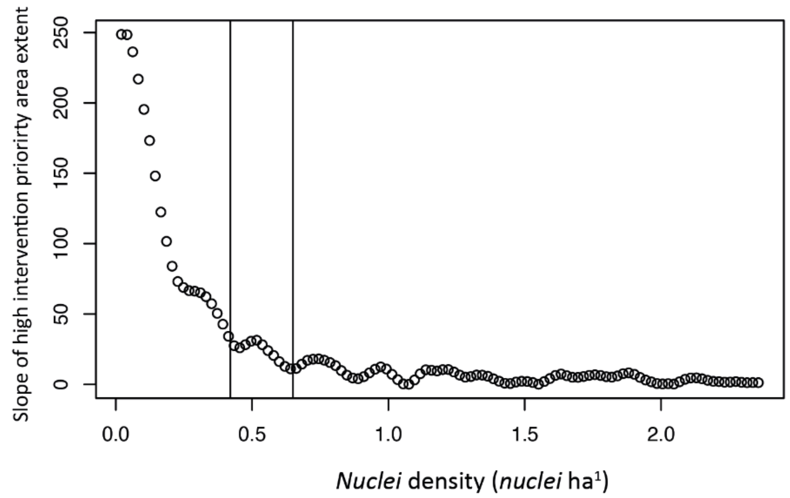


Fig. S4.9: *Curve representing the first derivative of* ***A*** *the mean probability of Scots pine seedling presence and* ***B*** *the extent of high intervention priority area according to nuclei density value obtained through the function* `sm.spline` *of the R package* `pspline`*.*

Chapter 5

Conclusions

The consequences of global changes on disturbance regimes and the potential impacts of disturbance alteration on forest ecosystems have been analyzed within the chapters of this thesis. In particular, I focused on the post-fire dynamics of mountain conifer stands, considering the alterations of disturbance regimes (chapter 2), potential impacts on forest ecosystems (chapter 3), and possible solutions to mitigate consequent degradation phenomena (chapter 4).

The research carried out during the PhD program started from a global systematic review on the effects of land abandonment on forest disturbance regimes, aiming to fill the existing gap of knowledge highlighted in previous studies (e.g., Haddaway et al., 2014). The literature review revealed interactions between land abandonment and disturbance regimes, as well as significant biases in terms of research locations and type of disturbance. Most studies were located in Europe, especially in the Mediterranean area, and analyzed the effects of land abandonment on wildfire regimes. The reason for the scientific attention devoted to this phenomenon is mostly due to the importance that wildfires play in these ecosystems and to the high rate of rural depopulation that Southern Europe experienced starting from the XIX century, leading researchers to focus on the ecological consequences of this exodus. The increase in wildfire frequency, size, severity, and risk that arose from most studies, acting together with post-fire climatic conditions, have the potential to impair post-fire recovery in ecosystems characterized by a low resilience to severe wildfires. This calls for monitoring of land abandonment evolution over time. Moreover, the low number of articles dealing with land abandonment interactions with disturbances other than wildfires, together with the scarcity of quantitative assessments revealed importance gaps of knowledge that need to be filled. Another issue that should be addressed in future studies regards the effect of the cessation anthropogenic disturbances related to agriculture, such as the intensive use of pesticides, machinery, or irrigation.

The third chapter focused on the effects of wildfire regime alterations on a sensitive mountain forest ecosystems, aiming to examine the patterns and drivers of post-fire forest recovery in a stand dominated by Scots pine, a species lacking fire-related traits and particularly vulnerable to fire regime alterations. This study wanted to provide useful management insights for policymakers to plan post-fire management strategies in the light of the new potential fire regime conditions. This objective was pursued through the analysis of the spatial distribution and characteristics of short-term post-fire recovery dynamics after a large mixed severity event. The analysis of post-fire regeneration drivers pointed out the importance of seed trees, that emerged as one of the main factors affecting regeneration density. Therefore, while planning post-fire management strategies, especially in areas that experienced high temperature at the soil level and located far away from the forest edge it is fundamental to leave on site any potential seed source, including damaged individuals, to promote natural post-fire forest recovery. The abundance of regeneration in medium severity areas underlined the natural resilience of these ecosystems in presence of ecologically appropriate disturbance regimes, with the logical consequence that active intervention should be limited to situations characterized by a reduction in natural regeneration dynamics and a risk of triggering degradation phenomena (i.e., large high severity patches). In those contexts where natural successional dynamics are hindered, it could be useful to adopt natural regeneration (NR) approaches, like Assisted Natural Regeneration (ANR) or Applied Nucleation (AN).

The aim of the research described in the fourth chapter was to investigate the potential outcomes of a set of AN scenarios in a mountain forest ecosystem of the Northwestern Italian Alps (Aosta Valley) dominated by Scots pine. The area was affected by a large stand-replacing wildfire in 2005 and subsequent post-fire salvage logging operations that increased ecosystem degradation and dampened natural regeneration, as assessed in previous studies conducted in the area (Marzano et al. 2013; Marcolin et al. 2019). The probability of regeneration across the landscape was predicted under the current situation and a set of applied nucleation (AN) scenarios. The simulations showed the positive effects of AN and the importance of site selection for plantation. Indeed, both the density and position of *nuclei* influenced the probability of presence of forest regeneration. This work is the first AN simulation in temperate mountain ecosystems to our knowledge, and it requires further field experiments and cross-scale integration to consider favorable microsites at a finer scale. Moreover, this approach might be an efficient nature-based solution in the light of current changes in fire regimes and the difficulties in natural post-fire recovery that those stands are experiencing.

Although the last two studies allowed to face important post-fire management issue and obtain useful management implication, they are limited to a landscape scale. Upscaling the analyses to the regional scale and encompassing sites with differences in fire severity, species composition, post-fire management, and environmental conditions could increase their generalizability. Moreover, the results of the AN simulations should be empirically validated with field experiments. Finally, there is a need for further cross-scale integrations considering the importance of microsites for effective plantation (e.g., favorable topographic features and shelters from snow cover, grazers, and water runoff).

In conclusion, this PhD thesis investigated disturbance regime alteration and post-fire forest regeneration dynamics in mountain conifer forests of the European Alps. The research has also explored the potential of nature-based solutions (i.e., applied nucleation) for promoting post-fire forest recovery and enhancing the ecological resilience of conifer forests in the face of increasing disturbances severity and frequency. The results highlighted that understanding the complex interactions between disturbances, forest structure, and post-disturbance processes is fundamental to plan effective post-disturbances management strategies. This thesis contributes to the knowledge base necessary for effective management and conservation of conifer forests in the European Alps in the context of ongoing global change.

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