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Fire severity, residuals and soil legacies affect regeneration of Scots pine in the Southern Alps

Giorgio Vacchiano [a,*], Silvia Stanchi [b], Giulia Marinari [a], Davide Ascoli [a], Ermanno Zanini [b], Renzo Motta [a]

[a] Dipartimento di Scienze Agrarie, Forestali e Alimentari, Università degli Studi di Torino, Via da Vinci 44, 10095 Grugliasco (TO), Italy
[b] Università degli Studi di Torino:NatRISK - Research Centre on Natural Risks in Mountain and Hilly Environments, 10095 Grugliasco (TO), Italy

HIGHLIGHTS

- We analyzed fire legacies and regeneration in a Scots pine forest of the inner Alps.
- Legacies included surviving canopy, soil legacies and coarse woody residuals.
- Fire simulations showed critical heating of the topsoil under high severity fire.
- Fire decreased soil aggregate stability, organic matter and exchangeable cations.
- Pine seedlings established on poor, eroded soils, and were facilitated by residuals.

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ABSTRACT

Regeneration of non fire-adapted conifers following crown fires on the European Alps is often delayed or unsuccessful. Fire may limit establishment by eliminating seed trees, altering soil properties, or modifying microsite and soil conditions via disturbance legacies. However, the effect of soil legacies on post-fire establishment has rarely been discussed. We analyzed the abundance of Scots pine regeneration in a 257 ha wildfire in an inner-alpine forest. Our aims were (1) to model fire intensity at the soil surface and topsoil heating along a gradient of increasing fire severities; (2) to assess the differences in soil properties along the fire severity gradient; (3) to model the effect of disturbance and soil legacies on the density of pine seedlings. We reconstructed fire behavior and soil heating with the First Order Fire Effects Model (FOFEM), tested the effect of fire severity on soils by nonparametric distributional tests, and modeled seedling density as a function of site, disturbance and soil legacies by fitting a GLM following a variable selection procedure. Topsoil heating differed markedly between the moderate and high severity fires, reaching temperatures high enough to strongly and permanently alter soil properties only in the latter. High fire severity resulted in decreased soil consistency and wet aggregate stability. Burned soils had lower organic matter and cations than those unburned. Pine seedlings favored low-fertility, eroded, and chemically poor sites. Establishment was facilitated by the presence of coarse woody debris, but hampered by increasing distance from the seed source. These results suggest that in dry, inner-alpine valleys, fire residuals and soil legacies interact in determining the success of Scots pine re-establishment. High severity fire can promote favorable soil conditions, but distance from the seed source and high evaporation rates of bare soils must be mitigated in order to ensure a successful restoration.

1. Introduction

Scots pine (*Pinus sylvestris* L.) is the most widespread coniferous species in Europe, and the most widespread pine in the world (Mirov, 1967). At the dry, southern edge of its distribution, it is currently facing complex dynamics of decline and succession, which result from the interaction between environmental change, land use changes, and increased susceptibility to disturbance (Gimmi et al., 2010), including fire.

Fire regimes in Scots pine were described as moderate-severity (Agee, 1998). The species has been observed to resist multiple fires (Storaunet et al., 2013), and to regenerate successfully in low-frequency fire regimes, in both boreal and continental European forests (Fernandes et al., 2008; Hille, 2006; Niklasson and Granstrom, 2000), e.g., also following the application of prescribed burning (Hancock et al., 2009; Hille and den Ouden, 2004).

However, regeneration of Scots pine following high severity crown fires on the European Alps and in the Mediterranean mountains was often delayed or unsuccessful (Moser et al., 2010; Rodrigo et al., 2004). Many limiting factors have been identified, including limited seed dispersal distance (Vilà-Cabrera et al., 2011), short persistence of

* Corresponding author. Tel.: +39 0116705536; fax: +39 0116705556.
E-mail address: giorgio.vacchiano@unito.it (G. Vacchiano).

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viable seeds in the soil (Nyman, 1963), competition or allelopathy by herbs or sprouters (Hille and den Ouden, 2004), loss of micorrhiza associated to pine regeneration (Bastias et al., 2006; Curlevski et al., 2011; Kipfer et al., 2011), and unfavorable water balance due to high soil evaporation (Castro et al., 2004; Vacchiano et al., in press). Most of these factors depend on fire type (e.g., crown vs. surface-fire), fire intensity, (i.e., the energy release from organic matter combustion per unit volume, times the velocity at which the energy is moving [kW m^{-2}]), and fire severity, i.e., tree mortality and soil organic layer consumed (Keeley, 2009).

Fire legacies are living organisms, e.g., seed trees ("residuals" sensu Pickett and White, 1985), dead organic matter (e.g., logs), and physical structures (e.g., exposures of mineral soil) that remain after the disturbance (White and Jentsch, 2004). Legacies play a key role in facilitating regeneration establishment, increasing plant growth, and promoting ecosystem functioning, e.g., in terms of nutrient availability, diversity and abundance of microsites, soil respiration and biotic community functioning, in many Mediterranean, temperate, boreal and tropical forest ecosystems throughout the world (e.g., Beard et al., 2005; Castro et al., 2012; Griffin and Turner, 2012; Marañón-Jiménez et al., 2013a; Marañón-Jiménez and Castro, 2013; Peterson and Leach, 2008).

Similarly, soil legacies are the degree to which soil properties and functions are modified following a disturbance (Baer et al., 2012). Fire can affect a wide range of soil properties both at the surface and along the profile (Bento-Gonçalves et al., 2012), such as organic matter (OM) pools (González-Pérez et al., 2004), aggregate stability (Mataix-Solera et al., 2011), nutrient content (Neary et al., 1999), and water repellency (Doerr et al., 2010). Many of these issues are applicable quite widely around the world (e.g., Bogorodskaya et al., 2011; Covington and Sackett, 1990; Granged et al., 2011; Jordán et al., 2011; Mallik et al., 1984; Mills and Fey, 2004; Wan et al., 2001). The magnitude and temporal extent of fire-induced changes in soil properties is related to the duration and depth of soil heating (Table 1).

Table 1
Effects of fire on soil at different temperatures (thresholds used in the text are in bold).

Temperature (°C)	Effects	Source
40–70	Protein degradation and death of living cells	Precht et al. (1973)
48–54	Dehydration or death of roots	Hare (1961)
70–90	Death of seeds	Martin et al. (1975)
80–90	Death of micorrhiza	Pattinson et al. (1999)
60–120	**Death of soil microbes**	Neary et al. (1999)
127	Soil sterilization	Raison (1979)
175–200	Potential increment in soil hydrophobicity	DeBano (1981)
220–380	**Incipient soil structural degradation**	Soto et al. (1991)
200–315	Incipient distillation of soil organic matter	Neary et al. (1999)
200–400	N volatilization	Neary et al. (1999)
270–300	Disruption of soil hydrophobicity	DeBano (1981)
300	Complete consumption of organic horizons	Neary et al. (1999)
460–700	Loss of hydroxyl groups from clay minerals	Giovannini et al. (1988)
450	Complete consumption of soil organic matter	Neary et al. (1999)
500	Dehydroxilation of minerals	Neary et al. (1999)
600	Oxidation of metallic bonds	Mataix-Solera and Guerrero (2007)
600	Sharp increase in sand, decrease silt and clay	Ketterings et al. (2000)
760	K volatilization	Weast (1988)
774	P volatilization	Weast (1988)
800	S volatilization	Weast (1988)
880	Na volatilization	Weast (1988)
980	Permanent alterations in clay minerals	DeBano et al. (1977)
1107	Mg volatilization	Weast (1988)
1000	Degradation of carbonates	Rabenhorst (1988)
1240	Ca volatilization	Weast (1988)

In order to sustain the flow of ecosystem services provided by the mountain forest, e.g., protection from gravitational hazards and recreation, rapid restoration of forest cover is often desired following catastrophic disturbances (Dorren et al., 2004). However, when temperatures able to alter soil properties are reached (e.g., 60 °C for the destruction of the microbial pool, and 220 °C for incipient structural degradation), soil resilience, i.e., the capability to recover after severe stress (Seybold et al., 1999), may be compromised (Certini, 2005), potentially delaying or preventing the establishment of tree regeneration.

Both disturbance and soil legacies are influenced by fire severity, and can alter the microsites available for plant regeneration (Leverkus et al., 2012; Marañón-Jiménez et al., 2013b; Marzano et al., 2013; Schimmel and Granstrom, 1996). However, the role of soil legacies on post-fire regeneration (e.g., Giardina and Rhoades, 2001; Lynham et al., 1998) has not been adequately enquired, particularly for Scots pine. In the view of expected increases in fire activity due to global changes, particularly in the Alpine region (e.g., Ascoli et al., 2013; Moser et al., 2010), a better knowledge of Scots pine regeneration dynamics after fire is needed to plan for a successful post-fire restoration.

We analyzed pine regeneration five years since a stand-replacing fire in a dry, inner-alpine Scots pine forest. Our aims were: (1) to model fire intensity at the soil surface and the amount and duration of soil heating along a gradient of increasing fire severity; (2) to assess the differences in chemical and physical soil properties of along the fire severity gradient; and (3) to assess the effect of increasing fire severity on pine regeneration by modeling the influence of disturbance residuals and soil legacies on the density of pine seedlings.

2. Materials and methods

2.1. Study area

The study area is located in central Valle d'Aosta, an inner valley of the south-western Alps. Fire regime here is characterized mainly by late winter-early spring fires (cause of ignition: 95% anthropogenic; 5% natural). Surface fires usually start at the bottom of the valley and spread up to the top of the mountain, often originating crown fires in conifers due to the low moisture content of live foliage during the dormant season. Wildfires are small in size (average = 8 ha); however, the 70% of the burned area is due to sporadic but relatively large (>20 ha) wildfires. This fire regime is common to several inner alpine valleys (Moser et al., 2010; Zumbrunnen et al., 2011) and reflects the influence of fire suppression policies adopted throughout the alpine region (Ascoli et al., 2013; Pezzatti et al., 2013).

The study site is a human-caused wildfire that occurred on 12th March 2005 in the municipalities of Nus and Verrayes (45°76′40″ N, 7°49′32″ E) and burned 257 ha of forest vegetation. The fire perimeter lies on a moderately steep (33 to 45%), southerly-exposed slope, at elevations ranging between 1190 and 1870 m a.s.l. The bedrock consists of colluvial sediments rich in ophiolite and schist. Soils are mostly Entisols (Stanchi et al., 2013a) with a sandy texture, moderate rock fragment content (3–15%), and a typical sequence of O–A–C horizons. No diagnostic horizons are detectable.

Mean annual temperature is 5.6 °C, and mean annual precipitation is 750 mm (Marzano et al., 2013). February is the driest month, coinciding with the main peak of the fire season. The south-facing slopes of central Valle d'Aosta experience a high fire risk (Cesti and Cerise, 1992). Additionally, dry and warm katabatic winds blowing across the region (Wastl et al., 2013) may decrease air and fuel moisture, increase winter air temperatures, and sustain the spread of ensuing flame fronts.

The fire burned through a mature, even-aged conifer forest, dominated by Scots pine (77% basal area on average) with mixed larch (*Larix decidua* Mill.: 15%) and spruce (*Picea abies* Karst.: 7%), and sporadic broadleaves (1%), such as downy oak (*Quercus pubescens* Willd.), aspen (*Populus tremula* L.), birch (*Betula pendula* Roth.) and ash (*Fraxinus*