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Impact of salvage logging on short-term natural regeneration in montane forests of the Alps after large windthrow events

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ABSTRACT

Wind disturbances are one of the main drivers of forest dynamics in Europe, shaping forest stands and modifying the ecosystem services provisioning. Salvage logging is often most common strategy adopted after a high-severity disturbance in managed stands. Understanding natural regeneration dynamics including their interaction with the logging operations, is crucial to understand how forests will be changing under a climate with increasing variability and to design adequate adaptive post-disturbance management strategies. In this study, we focused on 148 stands damaged by storm Vaia (2018). The aim was to analyze natural regeneration dynamics under different logging systems and to investigate influences of site characteristics and disturbance legacies on sapling growth and seedling emergence. The sampling protocol consisted of one transect per stand, perpendicular to one of the intact forest edges, and with a length of 80 m. Along the transect, we collected soil cover, natural seedling and sapling stem density, and deadwood quantity in four sample plots of 3 m radius each at distances of 0, 20, 40, and 80 meters from the edge (592 plots in total). Regeneration species composition was mainly driven by previous stand composition, with some exceptions depending on seed dispersal strategy. Distance from the edge significantly influenced seedlings and saplings occurrence in large gaps and affected the browsing damage percentage, together with deadwood presence. According to GLM's models, distance from the edge, elevation, and logging methods influenced seedling establishment. At the same time, species characteristics, edge structure, deadwood and logging damages significantly influenced pre-storm seedlings and saplings presence and health. In conclusion site factors, disturbance legacies, and logging strategies are key points to consider in post-disturbance management for a fast forest recovery.

1. Introduction

Under the ongoing global change, disturbances have become more and more frequent (Usbeck et al. 2010), and windstorms have been recognized as the most important disturbance affecting European forests, becoming the first responsible for stand damages and loss of canopy cover (Seidl et al. 2014; Gregow et al. 2017; Patacca et al. 2023). Climate modifications may make forests more vulnerable to disturbances and subsequent cascade and compound disturbances (Burton et al. 2020)): e.g., large severe windthrows usually lead to subsequent massive insect outbreaks. In addition, disturbance interactions can be amplified by drought spells, leading to further cascading processes (Seidl et al. 2017; Leverkus et al. 2021a). Focusing on mountain forests, such disturbance interactions could result in long-term effects, with partly dramatic consequences for ecosystem services (Romagnoli et al. 2023). For example, windthrow followed by bark beetle outbreak and amplified by exceptionally warm summer conditions can reduce mountain forests' productive and protective functions for decades due to slow regeneration processes at higher elevations (May et al. 2023). Seed germination and seedling establishment and survival have been described for long as crucial for the recovery of mountain forests, especially after a disturbance (Taeroe et al. 2019). Awareness rose that

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climate warming in forest openings may produce serious threats to regeneration processes (Von Arx et al. 2013; Zellweger et al. 2020). Under the ongoing and future climate scenarios, the regeneration of forests stands severely damaged by disturbances plays a key role in defining the future forest composition and structure, and their ability to face environmental modifications. Temperature increase is one of the biggest threats to European forests, especially in very sensitive ecosystems like mountain forests (Gobiet et al. 2014; Obojes et al. 2022). A closed canopy mitigates, to some extent, the effect of temperature increases (Dietz et al. 2020), instead, the lack of forest cover leads to a thermophilization of understory and forest species (Von Arx et al. 2013; Brice et al. 2019). After a disturbance, a new regeneration cohort consisting in different and better-adapted species could grow in damaged areas, and these modifications in species composition can persist after the disturbance (Dietz et al. 2020). In this sense, wind disturbances can potentially help adapt mountain forests to climate changes (Thom et al. 2020).

Most of the managed forests in Europe are traditionally salvage logged after large windthrows. The purposes can be multiple: to reduce economic losses by selling merchantable timber (Slyder et al. 2020), to safety issues (Lingua et al. 2023), to prevent pest outbreaks by performing sanitary loggings (Schroeder and Lindelöw, 2002), and to manage the landscape, especially in touristic areas. Three different management strategies can be adopted after windthrows: I) no intervention (passive): leaving all the deadwood and the damaged area as they are after the storm, without any intervention; II) salvage logging (active): total removal of damaged or uprooted trees; III) partial salvage logging and/or deadwood manipulation: removing only a certain percentage of damaged or uprooted trees and/or modify the disposition of deadwood for a different purpose (e.g. protecting from gravitative hazard, or sanitary logging) (Taeroe et al. 2019; Dobor et al. 2020b; Leverkus et al. 2021a). Different management strategies have shown to affect differently post-disturbance regeneration dynamics, in particular in relation to the seedlings surviving the disturbance that are very important in the first stage of forest recovery (Taeroe et al. 2019). Not harvesting and releasing a certain amount of deadwood on the site can help in creating favorable regeneration conditions and safe microsites (Leverkus et al. 2021b; Marangon et al. 2022). Different management strategies also influence ecosystem dynamics, modifying the biological legacies in forest stands (Morimoto et al. 2019; Dobor et al. 2020a), and, as a consequence, influencing forest regeneration structure and composition (Jonášová et al. 2010; Vodde et al., 2011; Kramer et al. 2014; Wohlgemuth et al. 2017).

Salvage logging operations can be executed using different harvest systems: highly mechanized systems, cable-yarding systems, and skidder and tractor systems. One system is preferable to another depending on site conditions, costs, safety, and overall impacts on the forest ecosystem. Nevertheless, salvage logging operations have a negative impact on regeneration sites, damaging saplings and regeneration microsites (Waldron et al. 2014), and eventually, modifying soil properties (Cambi et al. 2016). On the other hand, excessive quantities of deadwood, wood debris covering the soil or remnant ground vegetation (e.g. tall forbs), might reduce the available regeneration niches for seedlings, slowing the regeneration processes and potentially leading to a lower recovery rate in no-intervention areas (Wohlgemuth et al.,1990; Senf et al. 2019).

In the management of large windthrown areas, the dimension of the gaps is recognized to be a crucial variable for the timing and the dynamics of forest regeneration. The role of gaps in natural regeneration dynamics is well-known in forest ecology (Holeksa et al. 2012; Allen et al. 2012; Filicetti and Nielsen, 2022), transiently making available higher quantities of light, water, and nutrients for the seedlings (Grubb, 1977; Van Couwenberghe et al. 2011). Nevertheless, with increasing gap size and consequentially distance from living forest edges, seedling recruitment can be heavily delayed, which translates to late gap closure, eventually triggering various natural hazards (e.g., soil erosion, landslides, avalanche risk, rockfall) (White and Jentsch, 2001; Cordonnier et al. 2008). The dissemination strategy of each species can therefore influence gap filling processes. Indeed, anemochorous species cannot reach long distance from the seed tree (e.g. up to 80 m for Norway spruce (Kramer et al. 2006; Gratzer and Waagepetersen, 2018) while zoochorous species are not distance dependent so the colonization of the gap could be faster (Szwagrzyk et al. 2021).

Together with gap-induced dynamics, site factors play a central role in seedlings establishment and growth. Slope, aspect, temperature, water availability, and light intensity on the site are critical factors for forest regeneration dynamics (Kramer et al. 2014; Taylor et al. 2017; Marangon et al. 2022). These factors can be strongly influenced by a large variety of biological legacies. As reported before, deadwood and aspect of windthrown edges can strongly influence the solar radiation reaching the ground, modifying consequently temperature, humidity, transpiration, and nutrient availability in the microsites (Saxton and Rawls, 2006; Štícha et al. 2010; Marzano et al. 2013). Such modifications could affect the species composition, but at the same time provide new growing space and improve the growing condition for the already established saplings: light, in particular, is the most important driving factor for the regeneration established before the storm (Taeroe et al. 2019; Dietz et al. 2020).

The main objective of this paper was to analyze the post-windthrow short-term regeneration dynamics in areas damaged by the storm Vaia (2018) in Eastern Italian Alps after salvage logging operations with different harvesting systems and environmental conditions. We focused in particular on I) surveying the regeneration occurrence, both new and advanced regeneration, to assess any variation from the previous forest composition; II) assessing the importance of the distance from intact forests (edges with seed trees) serving for seed supply and of the local condition to seedlings establishment; III) assessing the importance of the regeneration established before the storm in the recovering of forest cover; IV) analyzing the influence of different harvesting systems on short-term regeneration.

2. Materials and methods

2.1. Study areas and field sampling

The study areas are located in the north-eastern Italian Alps, in the gaps and windthrown areas created by the storm Vaia in late October 2018, which struck the southern Alps, from the outer to the inner alpine range. The elevation ranges between 900 m a.s.l and 1942 m a.s.l. and the precipitation ranges between 600 mm in dry inner alpine areas and 3000 mm per year in the rainiest zones (Julian pre-Alps). In the upper areas above 1500 m a.s.l., snow cover is continuous at least during the winter months, with some exceptions on southern slopes. According to the Köppen system the climate ranges from oceanic (Cfb)/humid continental climate (Dfb) at lower elevation (1300 m a.s.l.) to subarctic (Dfc)/alpine (ET) at higher elevations (up to 2000 m a.s.l.) (Beck et al. 2018)

Forests damaged by the storm Vaia were composed mainly of Norway spruce (*Picea abies* (L.) H. Karst), mixed with silver fir (*Abies alba* Mill.), and beech (*Fagus sylvatica* L.) in particular at lower elevations. At higher elevations, larch (*Larix decidua* Mill.) and rowan (*Sorbus aucuparia* L.) were more abundant.

A total of 148 permanent monitoring areas were established in 2021 and 2022 (Fig. 1), located in the regions of Friuli Venezia-Giulia (20), Lombardia (11), Veneto (25), and the Autonomous Provinces of Trento (60), and Bolzano (32).

The adopted sampling protocol was consistent to previous studies conducted in Switzerland after storm Vivian (2000) and Lothar (1999) (Priewasser et al. 2013; Kramer et al. 2014), even thought it was slightly adapted to the local conditions and the objectives of this study.

The study areas were selected according to the following criteria: sites where salvage logging has been completed, located at a smooth

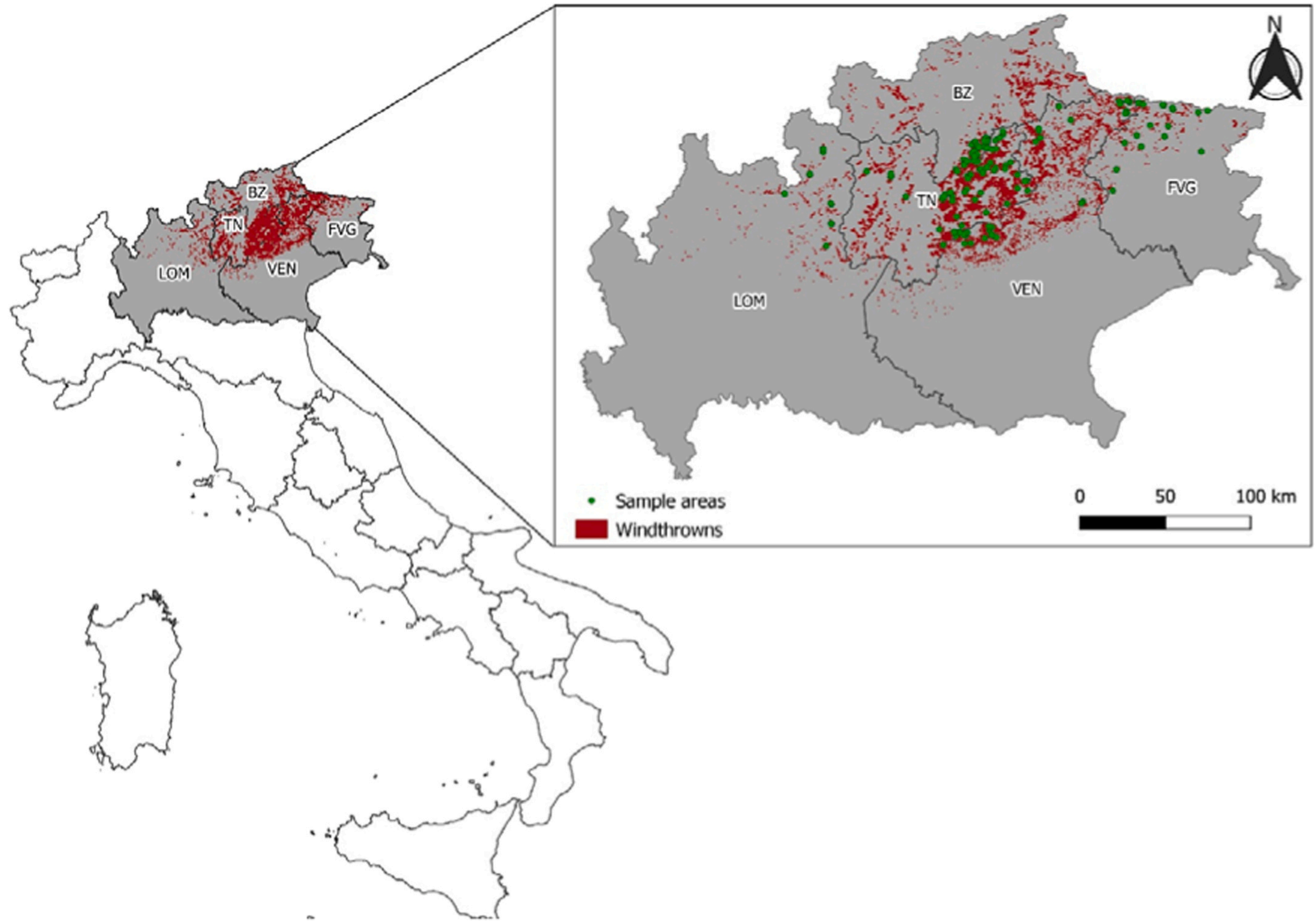

Fig. 1. Distribution of the 148 study areas in the northeastern regions of Italy (Regions of Friuli Venezia-Giulia - FVG, Lombardia - LOM, Veneto - VEN, and Autonomous provinces of Bolzano - BZ and Trento - TN).

slope with the same aspect across the windthrow area, with no other intervention planned, to avoid successive modifications to the site condition and morphology (e.g. soil restoration, other logging intervention, road constructions). Areas that presented sharp ridges, high cliffs, or an overly complex terrain morphology were excluded. Areas including stabilized road networks or other infrastructures were also avoided, while areas with exclusively logging corridors were accepted (Table 1*)*

Table 1
Variables recorded in each transect in every sample area.

Short name	Explanation	range
id_area	Identification code for each area	1–148
forest_type	Type of forest according to the classification of (Del Favero, 2004)(categorical)	15 types
elevation	Elevation above sea level (m a.s.l.)	900 – 1800 m
structure	Even- or uneven-aged forest (categorical)	Even-, uneven-aged
h_edge	Mean height of the standing trees in the windthrow edge (m)	10–30 m
slope	Degrees	0–35 °
aspect	Exposure of the slope derived from Digital Terrain Model (categorical)	N, E, S, W
treatment	Harvesting systems: Cable yarding systems (cy); winch tractor (wt); highly mechanized systems, e.g., harvester and forwarder (hf); more than one of the previous systems adopted together in the same area (mix). (categorical)	cy, wt, hf, mix

2.2. *Data collection*

In each study area, we defined four different circular plots along a 80 m transect, starting from the edge of the windthrown area and following a perpendicular direction (Fig. 2). The first plot was placed on the windthrown edge (distance 0), and the other ones were placed at 20, 40, and 80 m along the transect (distance 20, 40 and 80). The transect had to start from a well-defined edge, large enough to provide seeds for the regeneration processes (Priewasser et al. 2013; Kramer et al. 2014). Two types of transects were distinguished: horizontal transect (H), parallel to the contour lines, which could start from the left (HL) or the right (HR) to the edge; vertical transect (V), perpendicular to the contour lines, that could run uphill (VU) or downhill (VD). GPS position of the center of each plot was recorded using a GNSS receiver (multi-band RTK GNSS receiver EMLID Reach RS2, precision PPK H:5 mm+0.5 ppm, V:8 mm+1 ppm, recording period: 1 s).

Each circular plot had a radius of 3 m, where we counted the tree species per vertical category depending on height: trees below 20 cm (seedlings), trees between 20 cm and 150 cm (saplings), and trees above 150 cm (surviving trees). Seedlings were counted in a subplot with a radius of 50 cm tangent to the main plot, positioned on the right along the transect direction, with the center located 3.5 m from the center of the plot. Saplings and surviving trees were sampled within the 3 m radius plot. Deadwood within the plot with a diameter larger than 15 cm and length more than 50 cm was recorded only for its part laying within the sample area. For each transect we recorded the forest edge height, structure of the standing forest edge, treatment, and soil cover; while

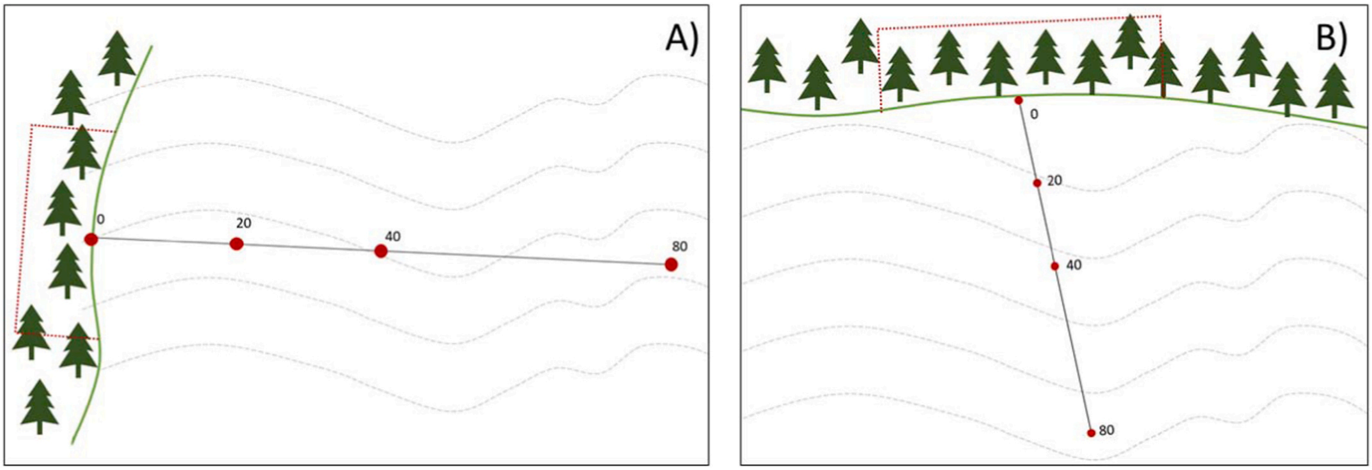

Fig. 2. The two types of transect in the protocol: A) horizontal transect (H), parallel to the contour lines, that can be on the left (HL) or on the right (HR) of the edge (head facing upslope); B) vertical transect (V), perpendicular to the contour lines, that can run uphill (VU) or downhill (VD). On each transect, we set four circular plots at distances of 0, 20, 40, and 80 m from the edge. The red dotted lines represent the standing forest on the edge where the stand characteristics (mean height, species composition, structure, forest type) were recorded, measuring 20×40 m.

using GIS software we derived the slope, aspect and elevation from a DTM (Regione Veneto 2019).

All the data were organized in different datasets, with specific IDs for the area, plot, and single trees, reporting all the variables explained in Table 2. To perform the analysis on trees of different ages, subsets of main dataset were defined by height classes, i.e. seedlings, saplings and surviving trees. For each class, we estimated the age class considering as post-storm the seedlings or saplings younger than three years, and as pre-storm the seedlings or saplings older than three years. We perform only general descriptive analysis on surviving trees to describe the current stand situation, without including this category in the stem densities analysis.

We applied Pearson correlation and linear models to predict stem density based on distance from the edge, both for all seedlings and for the most represented species (Norway spruce, rowan, silver fir, beech, larch); ANOVA, and post-hoc Tuckey test were used to test differences in stem density regarding different treatments, distance to the edge, and height classes (seedlings or saplings). Wilcoxon test was performed to test any significant difference in stem density regarding seedlings or saplings categories, treatment, and distance from the edge. Chi-squared test was performed to test significant differences in stem density between different plots (i.e., distance from the edge), substrate, height class, age class, and treatment.

To evaluate the influence of explanatory variables on stem density, both pre- and post-storm, we employed Generalized Linear Models, including aspect as a random factor (GLM family = Poisson, using packages lm and lme4 on Rstudio Bates, 2015) (Table 3). We excluded the models with highly intercorrelated variables. Models were ranked according to the Akaike Information Criterion (AIC) for the goodness of fit. Operations between datasets and statistical analysis were performed using the software R (RStudio team, 2022).

Table 3
Dependent and explanatory variables adopted in the models, collected at transect level and included in the analysis at plot level.

DEPENDENT VARIABLE	EXPLANATORY VARIABLE
Density (n/ha, n)	Distance from edge/**plot** (m, 0,20,40,80) **Elevation** (m a.s.l.) **Exposition** (N, S, E, W) **Slope** (°, yes/no) **Treatment** cable yarding (cy), harvester and forwarder (hf), mix of the previous two (mix), winch tractor (wt) **Deadwood** (m^3/ha, plot) **Structure** (even/uneven-aged) **Edge height** (m) **Soil cover** (type) only for total transect, not for a single plot **Seedling/sapling age** (established pre/post-storm)

3. Results

3.1. Overall results

The study areas were almost evenly distributed regarding aspect, with 46 areas on north exposed slopes (29 %), 42 on south exposed slopes (27 %), 39 on west and 29 on east exposed slopes (25 % and 19 %, respectively). Mean slope was 8.52°, with most of the areas below

Table 2
Variables assessed for trees and deadwood in each plot along the transects, according to vertical height classes.

Variable	Description	Seedlings < 20 cm	Saplings 20–150 cm	Surviving Trees > 150 cm	Deadwood
species	The tree species	name	name	name	name
dbh	Diameter at 1.30 m			cm	cm
height	Height of the tree			m	
length	Length of deadwood				cm
age_class	On field estimation of the regeneration age. New regeneration: three years old or younger, post-storm; advanced regeneration: older than 3 years, pre-storm.	pre/post	pre/post	pre/post	
substrate	The growing substrate: deadwood or soil	soil/ deadwood	soil/ deadwood	soil/ deadwood	
trees	Number of trees counted	n	n	n	
browsing	Browsing damage to the apex or to the branches		yes/no	yes/no	

the third quartile (14.75°). During the field campaign, 3143 trees were sampled in total across all vertical categories, with 698 seedling stems, 2130 sapling stems, and only 315 stems of surviving trees. Most of the trees were present at the forest edge (distance 0, 1114 individuals), and frequency decreased along with increasing distance from the edge: 809 trees at distance 20, 612 trees at distance 40, and 608 trees at distance 80. Norway spruce was the most frequent species (1151 individuals), followed by rowan (768), silver fir (336), beech (314), larch (113), goat willow (*Salix caprea* L.) (69), silver birch (*Betula pendula* Roth.) (65), hazel (*Corylus avellana* L.) (52), sycamore maple (*Acer pseudoplatanus* L.) (42), aspen (*Populus tremula* L.) (34), and Scots pine (*Pinus sylvestris* L.) (29). Other woody species were less frequent (< 20 individuals per species, less than 1 %) (Fig. 3 and Fig. 4). Stem densities slightly decreased with elevation (Pearson correlation $P = -0.12$, $p<0.05$).

Of the 3143 trees, 392 (12.5 %) were browsed on the apex or lateral branches. Most of them were in the height class 20–150 cm (Fig. 5a). Among the different surveyed species *Salix spp.*, *Sorbus spp.*, *Populus spp.*, downy birch (*Betula pubescens* Ehrh.) and green alder (*Alnus alnobetula* (Ehrh.) K. Koch.), emerged as the most palatable species with more than 25 % of the individuals being browsed (Fig. 5b).

3.2. Seedlings (< 20 cm)

Seedling number, density, and species distribution are different compared to the general results. In this case, we found 698 seedlings, with an average density of 57709 stems/ha. The highest stem density was found at the forest edge (distance 0, 85992 stems/ha), then at 40 m (distance 40, 45393 stems/ha), 20 m (distance 20, 35332 stems/ha), and 80 m (distance 80, 32320 stems/ha). Norway spruce is the species that occurs more frequently (9126 n/ha), followed by silver fir (2946 n/ha), beech (774 n/ha), rowan (580 n/ha), larch (516 n/ha), Scot's pine (236 n/ha), silver birch (236 n/ha), and sycamore maple (172 n/ha). For the other species, the stems per each species are less than 1 % of the total.

Stem density shows significant differences between the different age classes (Wilcoxon test, $p<0.05$), with most of the seedlings established after the storm (post-storm; < 3 years old). We found significant differences in the seedlings density between those established on bare soil and those established on deadwood (637 vs 61; chi-squared test, $p<0.05$), with most of the seedlings established on bare soil. Significant differences were also found in seedling stem density grown on slopes with different aspects (chi-squared test, $p<0.05$). We found a significant decreasing trend in the seedling stem density with the increasing distance from the forest edge (chi-squared test, $p<0.05$). For seedlings, elevation was not a significant factor, except for the beech, which presence was negatively correlated with elevation (Pearson correlation $P = -0.63$, $p<0.05$). The two-way ANOVA and the Tuckey post-hoc test both confirmed such a significant difference ($p<0.05$) (Fig. 6b). A significant difference in seedling stem density was also found under different treatments (cy, hf, mix, wt, Table 1; chi-squared test, $p<0.05$). However, the two-way ANOVA and the Tuckey post-hoc test both do confirm such a significant difference ($p<0.05$).

The GLMs showed that the only significant factor influencing seedling stem density is the distance from the edge (ANOVA type 3, $p<0.05$; mod1, Table 4). If aspect was considered as a random factor (mod2, Table 4), elevation, treatment hf (harvester and forwarder), and treatment wt (winch and tractor) emerged to have a positive influence on stem number, beyond the distance from the edge that had a negative influence ($p<0.05$). According to ANOVA type 3 analysis treatment, the distance of the plots from the forest edge and elevation significantly influenced seedling stem density ($p<0.05$).

3.3. Saplings (20–150 cm)

Considering saplings, plot density and species abundance differs from the patterns of the total regeneration. In this case, we counted 2130 saplings in total, with an average density of 2634 stems/ha. The highest tree density was found at 20 m (distance 20, 3066 stems/ha), then 40 m (distance 40, 2655 stems/ha), 80 m (distance 80, 2466 trees/ha), and at forest edge (distance 0, 2314 stems/ha). Rowan is the species that occurred most frequently (15851 n/ha), followed by Norway spruce (11936 n/ha), beech (5484 n/ha), silver fir (3591 n/ha), larch (1742 n/ha), goat willow (1376 n/ha), silver birch (1010 n/ha), hazel (817 n/ha), sycamore maple (709 n/ha). For the other species, numbers of individuals per species were less than 1 % of the total. Fig. 7.

Stem density for pre- and post-storm established saplings did not differ (Wilcoxon test, $p>0.05$). In contrast, stem densities of saplings established in pre-storm uneven-aged forests were significantly higher than those in even-aged forests (Wilcoxon test, $p<0.05$). Significant differences in stem densities were also found regarding substrate (2020 stems on soil and 101 stems on deadwood; Chi-squared test, $p<0.05$), regarding different slope aspects (Chi-squared test, $p<0.05$), and distance to the edge (decreasing from distance 20 to distance 80; Chi-squared test, $p<0.05$). This distance-related decrease in saplings stem density was not confirmed by both a two-way ANOVA and a Tuckey post-hoc test ($p>0.05$) (Fig. 6b). Saplings stem density was overall

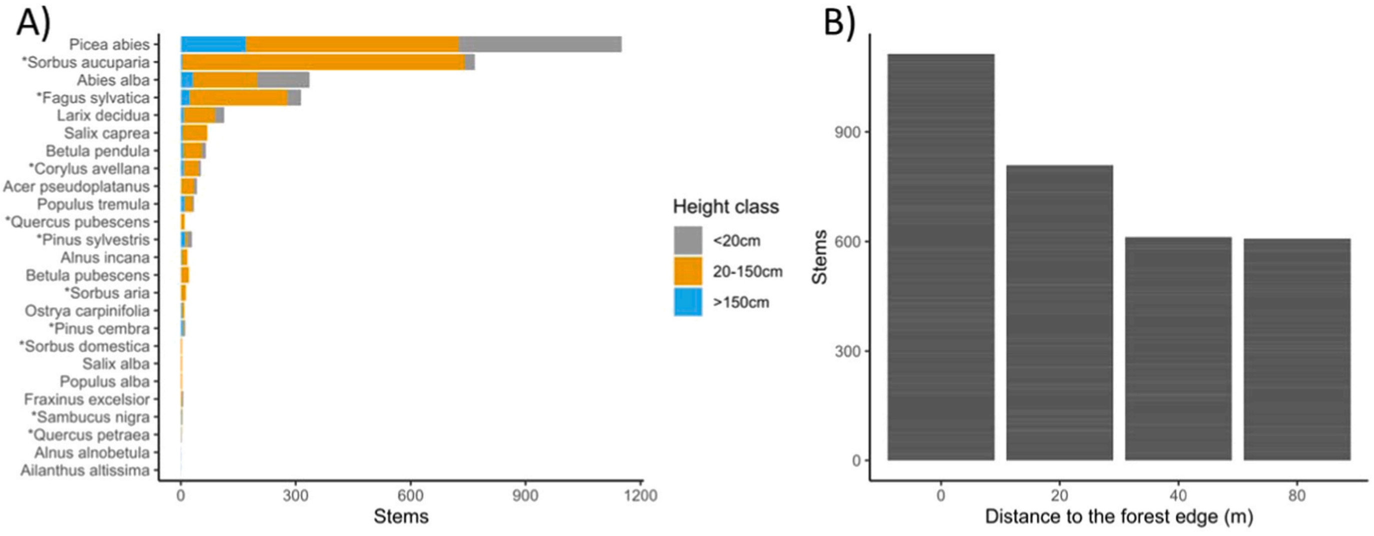

Fig. 3. A) Number of trees sampled per species, considering all plots, stacked by height classes. Asterisks indicates species adopting zoochorous seed dispersal strategy B) Number of trees arranged by distance to the forest edge.

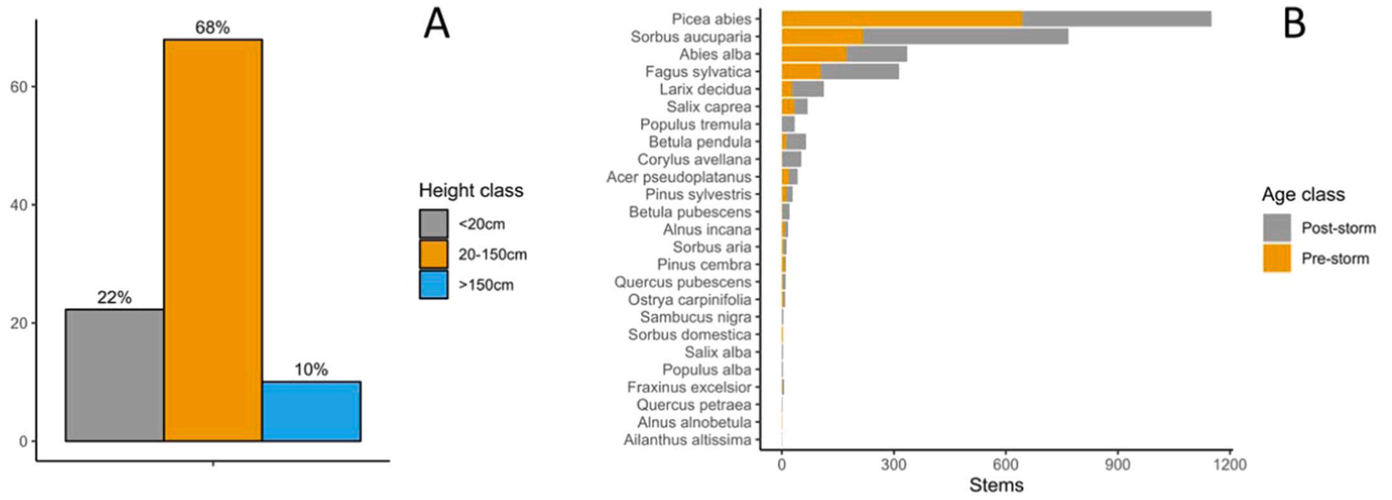

Fig. 4. A) Proportion of surveyed trees divided according to the height class. B) Trees per age class divided per species.

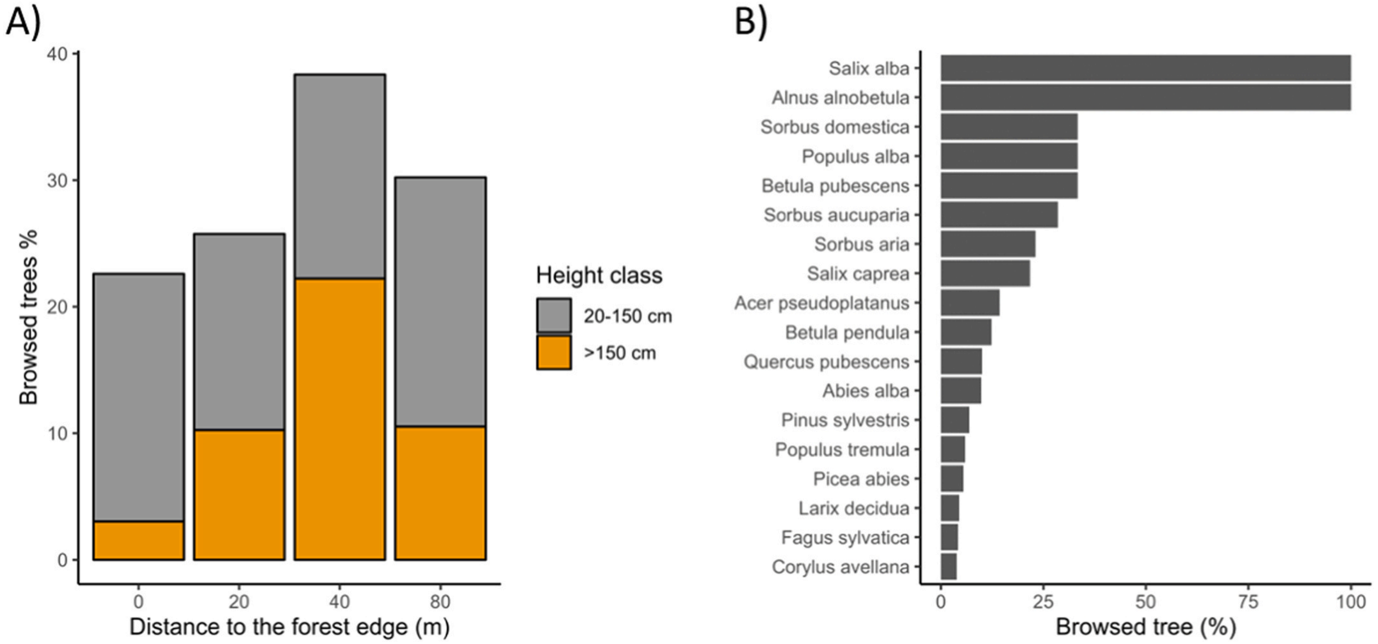

Fig. 5. a) Seedlings and saplings damaged by browsing at different distances from the windthrown edge, grouped per height class. b) Percentage of trees browsed by species.

slightly negatively correlated with elevation (Pearson correlation, P = −0.14, p<0.05), but there it is visible a clear decreasing trend (Fig. 8). Regarding single species correlation, only beech presence was significantly and negatively correlated with elevation (Pearson correlation, P = −0.35, p<0.05).

In GLM models, the even-aged structure of the bordering forest and elevation emerged to be the significant factors influencing the sapling stem density (mod3 Table 5, ANOVA type3, p<0.05). Considering aspect as a random factor, elevation, treatment, presence of deadwood, and distance from the edges resulted in a significant effect on saplings stem density (mod4, Table 5). Shorter distance from the edge influenced saplings stem density positively (p<0.05) while elevation and deadwood influenced negatively stem density (p<0.05 and p<0.05, respectively). Mixed treatment affected densities positively. According to ANOVA type 3 analysis, elevation, deadwood, and treatment significantly influenced saplings stem density (p<0.05).

3.4. *Surviving trees (>150 cm)*

We counted 315 trees grouped as surviving trees. Norway spruce was the most represented species (170 stems), followed by silver fir (32). Other species accounted for less than 1 % of the total. Most of the trees have been found at distance 0 (230 stems, 73 % of the total, Fig. 9), then the number of trees decreased from 20 m to 80 m (39 stems 12 %, 27 stems 9 %, 19 stems 6 % respectively). Most of the trees were the ones survived to the storm and were part of the forest edge (mean DBH = 21 cm, mean height = 14 m).

4. Discussion

Many factors affect forest regeneration after a severe disturbance, such as windthrows. The species composition of the previous forest exerts a pivotal influence on the regeneration dynamics, actively shaping the composition and structure of the future forest stands. After the 2018

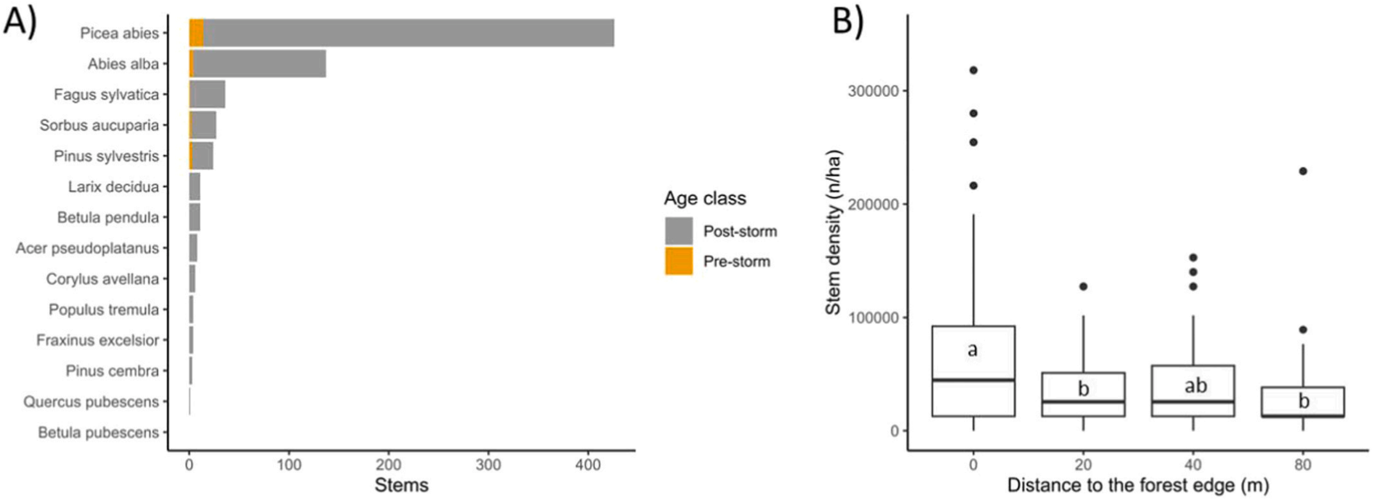

Fig. 6. *A) Stems per species divided* into seedlings established before the storm (pre-storm; > 3 years) or after the storm (post-storm; < 3 years). B) Different seedling stem densities (height < 20 cm) at different distances from the windthrown edge. Different letters indicate significant differences according to post-hoc Tuckey tests.

Table 4

Results of the GLM (mod1) and GLMER (mod2). Bold font indicates significant values (p<0.05). Seedling density = seedling stem density per plot, evenaged_structure = the structure of the forest edge where is located at distance 0, elevation = elevation of the site, distance20-40–80 = the distance from the forest edge, h_edge = mean height of the trees on the forest edge, substrate_soil = soil as germination substrate, pre_storm = seedlings established before the storm, treatment_hf = high mechanize logging systems, treatment_wt = wich and tractor logging system, treatment_mix = both of the previous treatment adopted in the same site, deadwood = deadwood volume in each plot.

mod1						
Dependent variable		**estimate**		**Std. Error**	**t value**	**Pr(>|t|)**
seedling density	(Intercept)	1.2314	±	3.1342	0.393	0.6948
	evenaged_structure	0.6482	±	0.8510	0.755	0.4514
	elevation	0.0003	±	0.0018	0.168	0.8665
	distance_20	**-2.5773**	±	**0.9012**	**-2.860**	**0.0047**
	distance_40	-1.6959	±	1.0724	-1.581	0.1155
	distance_80	**-2.8142**	±	**1.0788**	**-2.609**	**0.0098**
	h_edge	0.0899	±	0.0584	1.538	0.1257
	substratesoil	0.6489	±	1.1986	0.541	0.5889
	pre_storm	-1.9376	±	1.3143	-1.474	0.1421
mod2						
Dependent variable		**estimate**		**Std. Error**	**z value**	**Pr(>|t|)**
seedling density	**(Intercept)**	**0.9632**	±	**0.3569**	**2.699**	**0.0070**
	elevation	**0.0005**	±	**0.0002**	**2.552**	**0.0107**
	treatment_hf	**0.3784**	±	**0.1117**	**3.389**	**0.0007**
	treatment_mix	0.0425	±	0.1828	0.233	0.8160
	treatment_wt	**0.4002**	±	**0.1949**	**2.053**	**0.0401**
	deadwood	-0.0024	±	0.0026	-0.933	0.3510
	distance_20	**-1.0271**	±	**0.1155**	**-8.894**	**<0.001**
	distance_40	**-0.9039**	±	**0.1336**	**-6.768**	**<0.001**
	distance_80	**-1.1772**	±	**0.1446**	**-8.141**	**<0.001**

storm Vaia in north-eastern Italian Alps, Norway spruce is the most abundant regenerating tree species. The substrate and the distance from the forest edge are two other factors playing important roles in post-disturbance regeneration dynamics. Seed dispersal from "green islands" is fundamental for post-disturbance regeneration dynamics (Van Couwenberghe et al. 2010; Mantero et al. 2023), even though it is limited by the extent of damaged areas, since in very large high-severity patches seed rain is not able to reach the furthest sites, making the forest recovery process slower (Battaglia et al. 2008). Site conditions such as aspect, slope, and elevation influence the presence of seedlings, making even more important the role of microsites in creating favorable conditions for seedlings establishment and growth. Different logging systems influenced seedling occurrence, increasing in the short-term seedling stem densities when logging operations exposed more mineral soil (e.g. using heavy machinery).

4.1. *Drivers of regeneration*

4.1.1. *Species and stand structure*

After large disturbances and under ongoing climate changes scenario, species composition in the regeneration layer plays an important role in shaping future forests and defining their resistance and resilience to future disturbances (Nagel et al. 2006; Cerioni et al. 2022). One of the most important drivers in determining species composition in regenerating forests is the composition of the former forest stand (Manso et al. 2019), confirming the importance of ecological memories as driver of forest succession (Johnstone et al. 2016). After the storm Vaia (2018) in the northeastern Italian Alps at elevations from 1200 to 1700 m a.s.l., Norway spruce is the most abundant regenerating tree species, which reflects the abundant availability of seeds of the most widespread stand-forming tree species in the region of the windthrown areas. The seed supply is provided by intact trees forming the standing forest edge and survived trees inside the area affected by the disturbance (Van

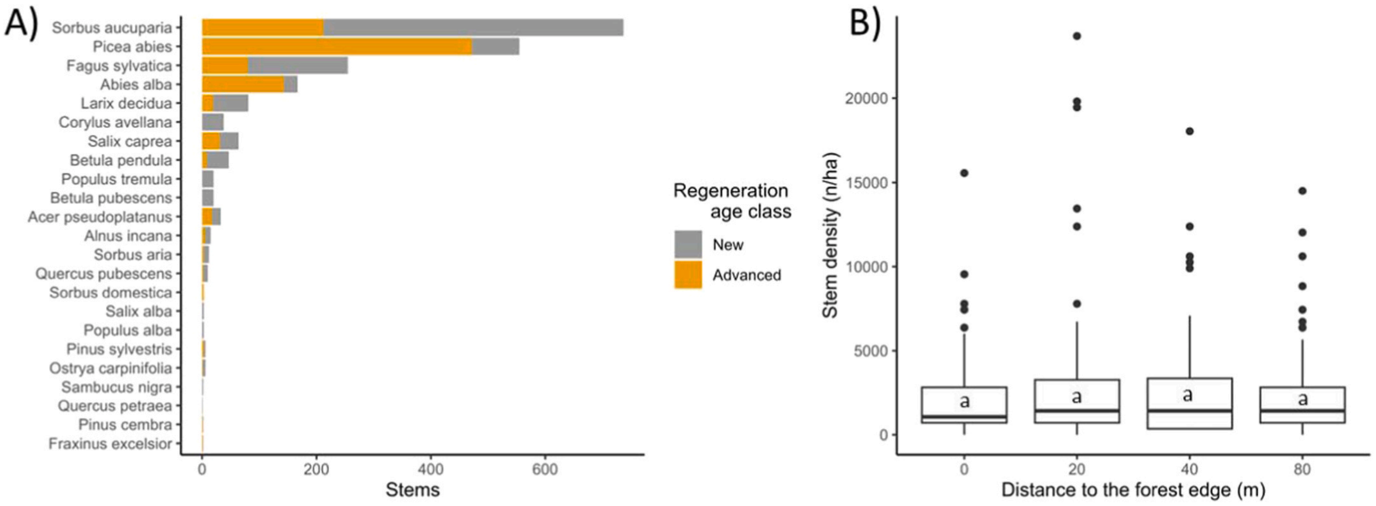

Fig. 7. A) Stems per species, distinguished by saplings established pre-storm (< 3 years) and post -storm (< 3 years). B) Different sapling stem densities at different distances from the windthrown edge. Different letters indicate significant differences according to post-hoc Tuckey tests.

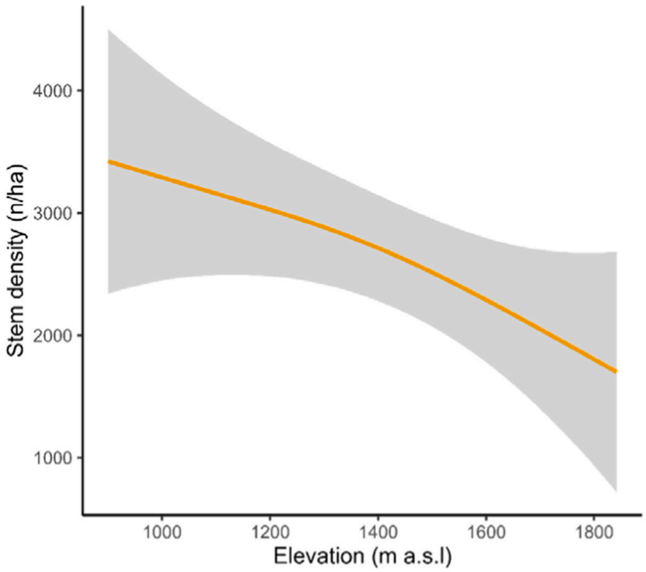

Fig. 8. Elevation versus sapling (20–150 cm) stem densities. According to the Pearson correlation, there is a slightly negative correlation ($P = -0.14$, $p<0.05$). The shaded area represents the 95 % confidence interval.

Couwenberghe et al. 2010; Mantero et al. 2023). Even uprooted trees served as seed sources for the first year. Dissemination from the green islands is a crucial element of post-disturbance regeneration dynamics in the few years after the disturbance (Romme et al. 2011; Fidej et al. 2016; North et al. 2019), but at the same time, it is strongly limited by the extension of damaged areas. According to the literature, the maximum seed dispersal distance for Norway spruce is between 30 and 60 m (Kramer et al. 2006, 2014; Gratzer and Waagepetersen, 2018). In central areas of large windthrow patches characterized by a limited initial seed dispersion through wind, the occurrence of young seedlings from anemochorous species with comparatively weighty seeds (e.g., Norway spruce) and autochorous species can be attributed to the dissemination of seeds by trees that have suffered substantial or complete damage due to windthrow. Zoochorous species such as rowan (mostly dependent on the presence of perches) are less limited by distance from seed trees but often need exposed mineral soil for germination (Milne-Rostkowska et al. 2020). Plant functional traits and habitat preferences are the main reasons explaining why after windthrows, sporadic or early seral species can be observed, like the presence of bird-spread rowan in mountain forests (Fidej et al. 2018) or the rapid spread of species like aspen, silver birch and *Salix* spp. especially in central Alpine valleys (Vodde et al. 2010; Moser et al. 2010). Similarly, resprouting is another strategy for some species to respond to higher light transmission (e.g., beech or willow) and enabling them to eventually escape from the competition with shrubs and herbaceous layers. Nevertheless, young resprouts can be heavily damaged by logging operations and forced to resprout again after the intervention (Leverkus et al. 2021b).

4.1.2. *Aspect and elevation*

Seedlings' presence can be strongly influenced by site conditions, like aspect, slope, and elevation. Most of the areas in our study have a northern exposure, which creates better conditions for the regeneration of shade-tolerant species, with lower temperatures and higher soil moisture, due to less desiccation. Natural regeneration is less abundant at higher elevations due to harsher environmental conditions (e.g. shorter vegetation time) and narrower regeneration niches (Wohlgemuth et al. 2008; Kramer et al. 2014; Stroheker et al. 2018). Most of the surveyed species are in their elevation optimum (especially Norway spruce, larch, silver fir, and beech), thus elevation itself is not a significant factor in determining post-storm stem density. For pre-storm seedlings and sapling, the trend is toward a decrease in stem density as altitude increase (Fig. 8), but such a trend cannot be entirely attributed to elevation alone because of the presence of competing tall herbs and the reduced number of mast years (Mencuccini et al. 1995; Wohlgemuth et al. 2017).

4.1.3. *Substrate and facilitation*

After disturbances like stand-replacing windthrows and subsequent salvage logging operations, soil is the most represented substrate for seedling establishment as widely discussed (Taylor et al. 2017; Kern et al. 2019). New deadwood is too fresh and not decayed enough to become a suitable substrate for seed germination. Depending on climatic conditions, lying logs start becoming suitable for seedling establishment after twenty to forty years after tree death (Robert et al. 2012; Konôpka et al. 2021). After windthrows, "*pit and mound*" micro-topographical features represent a suitable substrate since most of the seedlings tend to establish on bare soil in the mounds (Bormann et al. 1995; Ulanova, 2000; Vodde et al. 2015; Macek et al. 2017), taking advantage of the exposed mineral soil and nutrients released by the logging residues, the longer vegetative period (less snow cover) and less water stagnation especially on lower slopes. However, establishing on bare soil could lead to a higher short-term mortality, since there are no mitigating factors

Table 5
Results of the GLM (mod3) and GLMER (mod4). Bold font indicates significant values ($p<0.05$). Sapling stem density = sapling density per plot, evenaged_structure = the structure of the forest edge where is located at distance 0, elevation = elevation of the site, distance20-40–80 = the distance from the forest edge, h_edge = mean height of the trees on the forest edge, substrate_soil = soil as germination substrate, pre_storm = saplings established before the storm, treatment_hf = high mechanize logging systems, treatment_wt = wich and tractor logging system, treatment_mix = both of the previous treatment adopted in the same site, deadwood = deadwood volume in each plot.

mod3						
Dependent variable		**estimate**		**Std. Error**	**t value**	**Pr(>|t|)**
Sapling density	**(Intercept)**	**4.3832**	**±**	**1.0431**	**4.202**	**<0.001**
	evenaged_structure	**-1.4817**	**±**	**0.2555**	**-5.799**	**<0.001**
	elevation	**-0.0016**	**±**	**0.0006**	**-2.582**	**0.0100**
	distance_20	0.6323	±	0.3478	1.818	0.0694
	distance_40	0.2755	±	0.3551	0.776	0.4381
	distance_80	0.0815	±	0.3455	0.236	0.8137
	h_edge	0.0095	±	0.0155	0.613	0.5399
	substrate_soil	0.4407	±	0.4857	0.907	0.3644
	pre_storm	0.1995	±	0.2464	0.810	0.4184
mod4						
Dependent variable		**estimate**		**Std. Error**	**Z value**	**Pr(>|t|)**
Sapling density	**(Intercept)**	**2.8777**	**±**	**0.2056**	**13.998**	**<0.001**
	elevation	**-0.0008**	**±**	**0.0001**	**-5.791**	**<0.001**
	treatment_hf	0.0310	±	0.0640	0.484	0.6286
	treatment_mix	**0.2763**	**±**	**0.0710**	**3.543**	**<0.001**
	treatment_wt	-0.3162	±	0.1994	-1.586	0.1127
	deadwood	**-0.0028**	**±**	**0.0011**	**-2.647**	**0.0081**
	distance_20	**0.1958**	**±**	**0.0768**	**2.550**	**0.0108**
	distance_40	0.1050	±	0.0808	1.301	0.1934
	distance_80	0.0941	±	0.0775	1.213	0.2250

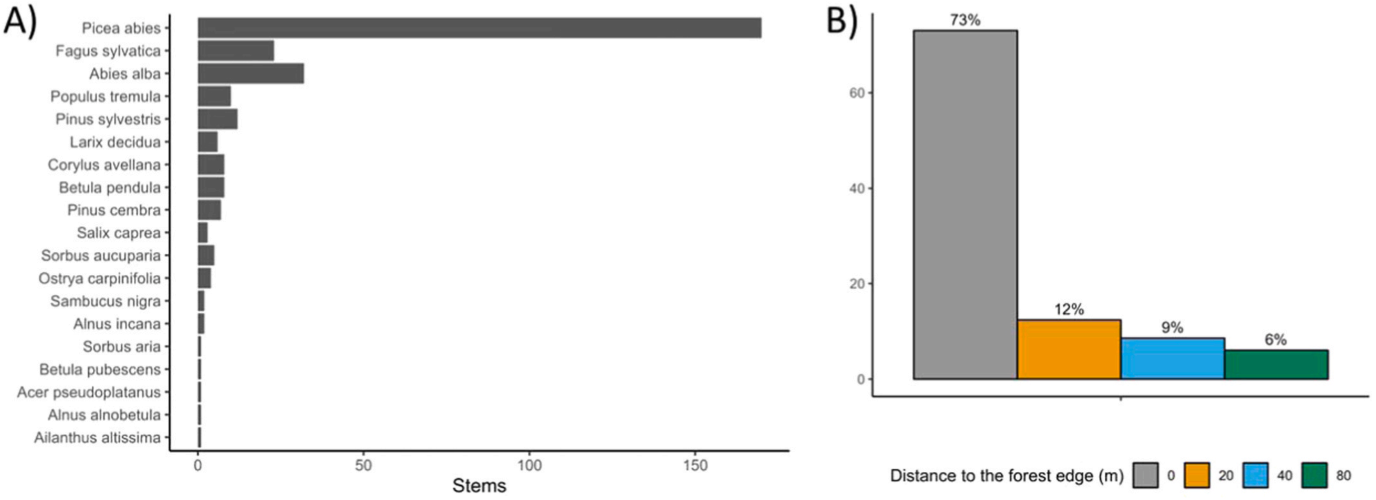

Fig. 9. A) Stems of surviving trees per species. B) Percentage distribution of stems of surviving trees found in each plot at different distances from forest edge (0, 20, 40, 80 m respectively).

and the seedlings' establishment microsite is more exposed (Castro et al. 2011; Macek et al. 2017; Marangon, 2023). Only few seedlings have been found on logging tracks where compacted soil does not allow seedlings' establishment and root penetration (Ampoorter et al. 2011). In disturbed areas, post-disturbance regeneration tends to cluster in favorable microsites, like around deadwood (Wild et al. 2014) and other biological legacies (Holeksa et al. 2012). Disturbance legacies contribute to create heterogeneity at microsite level, shaping suitable microsite environmental conditions by protecting seedlings and saplings from desiccation and promoting seedlings establishment and growth. That contributes to mitigate environmental stressors and protect seedling and saplings from browsing or mechanical damages (Marangon et al. 2022).

4.1.4. *Distance from the forest edges*

Distance from the edge is a relevant parameter to consider after such large disturbances. In our case study, distance from the edge resulted as significant factor to influence seedling densities in the short term. Wind-dispersed tree species with relatively heavy seeds (i.e. conifers) are not able to reach large distances from seed trees, and in particular, the maximum distances ranged from 20 m for beech and silver fir to a maximum of 60 m for Norway spruce and other coniferous species (Kramer et al. 2006; Gratzer and Waagepetersen, 2018). Considering an 80 m buffer from living forest edges, an area larger than 2 ha can be critical for seeds dispersal. In this case, the regeneration dynamics could be slower for species with heavy seeds, while for bird-dispersed species (e.g. rowan) seedling stem density increases in the short-term right after the disturbance (Wagner et al. 2010; Szwagrzyk et al. 2021). In our study, distance influenced seedling stem density significantly, but at the same time, there is still a good density of Norway spruce in the far (40 m, 80 m) plots. This suggest that the seeds recruited during the tree falling could be an important resource for seedling establishment.

4.1.5. *Time of establishment*

After large highly severe disturbances like windstorms, intact seed trees are rare, and younger trees would still need a few years until maturation and first dissemination. Most of the regenerating trees were saplings, that could have been established right after the storm (e.g. mainly broadleaves like rowan or coniferous like larch) or a few years before the storm (e.g. most of the coniferous species or broadleaves like hazelnut or birch). As they were originally located under a canopy or dominant layer, these trees survived the wind disturbance as well as the following salvage logging activities. Furthermore, they can take advantage of the protection of the laying logs as a favorable microsite to adapt to the new bright conditions and start with amplified growth in the next season (De Chantal et al. 2005; Thom et al. 2022). Seedlings represented the 22 % of the counted trees (693 trees, Fig. 4a) and consisted mainly of Norway spruce with slow growth rates compared to other species, mainly post-storm established seedling and saplings (< 3 years, Figs. 6a and 7a, respectively). Fast-growing broadleaves like rowan and other pioneer species like larch, take advantage of higher light transmission in post-disturbance environment and can easily escape from the competition of tall herbs and shrubs (Vodde et al. 2010). Since severe disturbances widely reduce the dominance of mature trees (Wohlgemuth et al. 2002a), the future forest strongly depends on survived pre-storm seedlings and sapling and later on new arriving seedlings (Bače et al. 2012; Wild et al. 2014).

4.1.6. *Harvesting systems*

Different salvage logging approaches and strategies seem to influence wood debris quality and distribution (Udali et al. 2023) together with the regeneration dynamics (Li et al. 2023), in particular short-term seedlings establishment and survival. Soil perturbation by logging systems (skidder or harvester track, soil exposure due to erosion or heavy machinery passages, etc.…) exposes a higher portion of bare ground, which actually emerged to be a favorable substrate for seedling establishment (Wohlgemuth et al., 2002b), if not highly compacted. According to the results of our study, salvage logging operations conducted with harvester and forwarder or skidder tractors, disrupt ground surface and post-storm established seedling or saplings leading to an increase in tree species regeneration in the understory a few years after the disturbance similarly to what has been reported in the literature (Michalová et al. 2017; Slyder et al. 2020; Konôpka et al. 2021). In no-intervention areas, regeneration could be difficult because of the mulching effect of deadwood (Leverkus et al. 2021a). In large areas highly damaged by salvage logging operations and with no deadwood or other legacies able to favor seedlings' establishment and survival (Marangon et al. 2022), seedlings and saplings are partially lacking because of the high shrub density and/or dense vegetation cover (Palm et al. 2022), since soil is not mulched by woody debris (Konôpka et al. 2021). Using mixed salvage logging methods, i.e. combining different logging methods to harvest the same area (e.g. harvester and cable yarding systems), can slightly affect the seedlings establishment in the short-term, since the heavy damages are reduced due to the cumulated advantages of different logging strategies. According to (Wohlgemuth et al., 2002b; Kramer et al. 2014; Morimoto et al. 2019), the difference in seedling stem densities between harvested and untouched areas could start to be compensated after 10 years.

5. Conclusion

Selecting the most effective post-disturbance management techniques requires careful monitoring of the dynamics of forest regeneration following severe and extensive disturbance. Short-term regeneration species abundance is mainly driven by previous stand composition, but with a higher proportion of bird dispersed species. In the post-disturbance management, emphasis should be put on the protection and facilitation of seedlings and saplings – established both pre and post-disturbance – as an element of resilience. In this regard, choosing the logging or post-disturbance management strategy is crucial to minimize the damages to the seedlings or saplings. Short-terms regeneration dynamics showed to be influenced by the distance from the forest edge, especially in large damaged area. In this case, active forest restoration practices are a valid option, especially in productive stands, for landscape purposes or protection forests. Even so, a mixture of the two strategies, salvage logging and no-intervention, should be considered, diversifying the management locally, and making sure to avoid a compound effect summing up negative impacts of each strategy, especially damaging seedlings and saplings established before the storm, which is crucial in the short term and in large areas to restore forest cover. Lastly, taking advantage of micro-topography and biological legacies to cluster seedlings and saplings around such elements can be an effective strategy for maximizing restoration success and enhancing forest adaptive capacity by exploiting the characteristics of tree species diversity.

CRediT authorship contribution statement

Emanuele Lingua: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Claudio Betetto:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Data curation. **Thomas Wohlgemuth:** Writing – review & editing, Visualization, Validation, Supervision, Formal analysis, Data curation. **DAVIDE MARANGON:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Enrico Tomelleri:** Writing – review & editing. **Luca Cadez:** Writing – review & editing, Validation, Software, Methodology, Investigation, Data curation. **Giorgio Alberti:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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