THE INFLUENCE OF ABIOTIC AND BIOTIC DISTURBANCES ON THE PROTECTIVE EFFECT OF ALPINE FORESTS AGAINST AVALANCHES AND ROCKFALLS

VPLIV ABIOTSKIH IN BIOTSKIH MOTENJ NA VAROVALNI UČINEK ALPSKIH GOZDOV PRED SNEŽNIMI PLAZOVMI IN SKALNIMI PODORI

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ABSTRACT

Abiotic and biotic disturbances in alpine forests can reduce forest cover or change the structure of the forest and consequently reduce the protective effect of forest against natural hazards such as avalanches and rockfalls. In this review article, the effect of the main abiotic (forest fire, windthrow, ice break, snow break, avalanche and rockfall) and biotic (insects and pathogens) disturbances in protection forests are presented along with their potential influence on the protective effect of forest against avalanches and rockfalls. In general, natural disturbances negatively affect the protective effect of forest, especially in the case of large-scale and severe events, which in alpine areas are mostly caused by storms, bark beetle outbreaks, avalanches and forest fires. Climate change induced interactions between disturbances are expected to present challenges in the management of protection forests in the future.

Key words: natural disturbances, natural hazards, abiotic disturbances, biotic disturbances, protection forests, protective effect, stand parameters, rockfall, avalanche

IZVLEČEK

V gozdovih alpskega prostora lahko abiotske in biotske motnje vplivajo na porazdelitev in strukturo gozdov do te mere, da jim zmanjšajo varovalni učinek pred naravnimi nevarnostmi, kot so snežni plazovi in skalni podori. V članku je zato predstavljen pregled glavnih vplivov abiotskih (gozdnih požari, vetrolom, snegolom, žled, snežni plazovi in skalni podori) in biotskih (insekti in patogeni) motenj na varovalno in zaščitno funkcijo gozdov pred naravnimi nevarnostmi, vključno z veliko-površinskih dogodkov iz visoko jakosti poškodovanosti. Slednje so v alpskem prostoru najpogosteje posledica neviht, napada podlubnikov, snežnih plazov in gozdnih požarov. Podnebne spremembe in njihov vpliv na naravne motnje bodo v bodoče postale pomemben izziv pri upravljanju z gozdovi, ki opravljajo varovalno in zaščitno funkcijo.

Ključne besede: naravna motnja, naravne nevarnosti, varovalna in zaščitna funkcija gozda, varovalni učinek, sestojni parametri, skalni podor, snežni plaz

1 INTRODUCTION: NATURAL DISTURBANCES IN ALPINE FORESTS

1 UVOD: NARAVNE MOTNJE V ALPSKIH GOZDOVIH

In alpine areas, mountain forests provide important ecosystem services to society (De Leo and Levin, 1997; Baral et al., 2017). One of the fundamental objectives of long-term forest management in mountain forests is to mitigate natural hazards while maintaining other ecosystem services (Kräuchi et al., 2000; Brang et al., 2001; Brang et al., 2006; Sakals et al., 2006; Moos et al., 2017). Namely, forests can act as a protective barrier, absorbing and dissipating the kinetic energy of gravitational processes and reducing their onset probability (likelihood of initiation of a process), propagation probability (probability of spatial occurrence) and intensity (size and velocity) (e.g. Perret et al., 2004; Dorren et al., 2005; Dorren and Berger, 2005; Frehner et al., 2005, after Berger et al., 2013; Brang et al., 2006; Dupire et al., 2016; Moos et al., 2018).
Ecosystem management of mountain forests aims to maintain the integrity and stability of the forest ecosystem, mainly in terms of preserving the structure and function of the ecosystem over long periods of time (Dorren et al., 2004). Due to the constant evolution of mountain forests, forest functions do not remain constant, especially during transition phases where the protective effect is at its lowest because of non-optimal forest structure resulting from the aging of trees, breakdown of initial structure and abundance of pioneer species (Motta and Haudemand, 2000; Dorren et al., 2004; Dorren and Berger, 2006). The rate of transition is influenced by forest structure (which is in constant flux) (Dorren et al., 2004) and by the effects of natural disturbances (Peterson et al., 2000). Natural disturbances are defined as nonanthropogenic events that change the structure, composition and function of an ecosystem (White and Picket, 1985; Attiwill, 1994; Frelich, 2002). Due to natural disturbances in protection forest, the protective effect of forest against natural hazards can fluctuate over time and space and is thus difficult to quantify over longer time periods (e.g. Wehrli et al., 2006). The protective effect of forest is related to the ability of a forest stand to withstand disturbance without being altered (resistance), and to its adaptive and regenerative capacity (resilience) (Moos et al., 2017). The resilience and resistance of forest stands to natural disturbances, and consequently their capacity to protect against natural hazards, is strongly related to stand parameters that describe the structure of the forest (e.g. Cordonnier et al., 2008). The protective effect of forest against natural hazards is mainly related to stand structural parameters such as tree density, tree species composition, gap size, and diameter at breast height distribution (Wasser and Frehner, 1996; Bebi et al., 2001; Gauquelin et al., 2006, after Berger et al., 2013).

Forest fires, windthrow, ice and snow break, drought, insects, pathogens and natural hazards themselves can influence the structure, composition and function of protection forests (e.g. Holtmeier, 2009; Kulakowski et al., 2012; Bebi et al., 2017; Seidl et al., 2014a; Seidl et al., 2017). Natural disturbance regimes are described as two-way interactions (Bebi et al., 2009) where disturbance affects forest structure and composition, and in return forest stand structure and composition also affect disturbance regimes. Forest cover and forest structure have been identified as factors influencing the frequency, severity and extent of natural disturbances (e.g. Klopcič et al., 2009; Seidl et al., 2011a; Kulakowski et al., 2011). The scale of natural disturbances in forest ecosystems can be divided into small-scale events (generally high frequency) and large-scale events (generally low frequency) (Coates and Burton, 1997; Dale et al., 2001). Both small-scale and large-scale events can be either low or high intensity. Small-scale events (around 2 hectares; e.g. Nagel and Diaci, 2006; Bartelt and Stöckli, 2001) create forest gaps or eliminate individual trees, and the forest in these areas can recover quickly since small gaps can be overgrown by the lateral in-growth of existing canopy trees (e.g. Schönberger, 2002; Zeibig et al., 2005). Large-scale events (> 10s of hectares; Nagel and Diaci, 2006), on the other hand, can eradicate thousands of hectares of forest (e.g. Bebi et al., 2017), alter the recovery of the tree layer for several decades and drastically change forest structure (Ulanova, 2000; Schneeberger and Bebi, 2004; Brang et al., 2006; Maringer et al., 2016a). The occurrence of large-scale disturbances is uncommon in alpine areas given the rarity of large continuous forests, the high small-scale variability in site conditions, large amount of summer precipitation, relatively cool temperatures, low density of fuel loads, and relative rarity of large-scale and intense meteorological events (e.g. winter windstorms, ice storms, wet snow events). Large-scale and severe events are rare regardless of vegetation conditions or climate (Brang et al., 2006; Lausch et al., 2011; Vacchiano et al., 2016), and in alpine areas they mainly occur in the form of windstorms, insect outbreaks and avalanches (in that order) (Bebi et al., 2017).

Interactions between natural disturbances can lead to a “cascading” or “synergistic” effect (Dale et al., 2001), resulting in unexpected changes in forest structure (Buma, 2015). Positive feedback between natural disturbances (e.g. drought and wind) occurs when one natural disturbance increases the probability of occurrence of another (Seidl et al., 2017), while in the case of negative feedback, susceptibility to subsequent disturbance is reduced (e.g. avalanches tracks that act as firebreaks) (Veblen et al., 1994; Germain et al., 2006; Bebi et al., 2017). Climate change is likely to influence the nature of disturbance regimes and their interactions, both in terms of frequency and intensity (Lindner et al., 2010, 2014; Seidl et al., 2011a, 2011b, 2017; Thom and Seidl, 2016).

Based on the presented issues, the aims of this article were to a) review the most relevant forest stand parameters that influence the protective effect of forest against avalanches and rockfalls and b) examine the effects of individual natural disturbances on those forest stand parameters.
The bibliographic research in this study was aimed at reviewing the relevant studies dealing with natural disturbances and their influence on protection forest stand parameters and the onset and propagation of avalanches and rockfalls in alpine areas. The research only included papers that were published in the form of scientific papers and project reports. In the first part of the analysis, the aim was to determine the main forest stand parameters that crucially influence the occurrence and frequency of avalanches and rockfalls. In particular, we focused on defining the optimal stand structure (Chapter 3). We also identified the main abiotic and biotic disturbances that are most likely to occur in alpine areas where avalanches and rockfalls are also considered to be among the abiotic disturbances (Chapter 4).

Combining the information on forest stand parameters and natural disturbances, we formed a matrix table connecting each disturbance type to individual forest parameters. In the following part of the study, we aimed at investigating how each disturbance type could potentially change individual forest stand parameters and thus the protective effect of forest against avalanches or rockfalls. Effects were classified as follows: positive, negative, negative or positive, unclear or no effect. The table with these interactions was partially built up based on the described interactions found in the literature review and partially based on the expected cause-effect relationships since few studies have focused on studying these interactions. The main findings are summarized in Chapter 4 and in Table 1 in Chapter 4.6., and in this summary the described changes in the protection function are presented only in the case of larger disturbance events (high severity events). However, as there is little or no literature on the direct influence of natural disturbances on the onset and propagation probability of avalanches or rockfalls, the findings in Table 1 are somewhat speculative.

Additionally, part of the literature study also included a discussion on how predicted changes to the climate could influence individual natural disturbance events and forest structure, namely through direct, indirect and mutual effects, and how it could directly affect the protective effect of forest against avalanches and rockfalls. We considered changes in temperature and precipitation regimes, wind, water limitations/surpluses, tree species distribution, and forest composition and structure. In the discussion section, we discuss the shortcomings of the main findings and provide forest management recommendations.

### 2 MATERIALS AND METHODS
#### 2 Materiali in Metode
After a natural disturbance event, forest stand structure may change, leading to a decrease or increase in the protective effect of the forest against avalanches or rockfalls. Therefore, the following chapter presents the main stand parameters that are the most relevant in optimizing the protective effect of forest against avalanches and rockfalls.

#### 3 The Protective Effect of Forest against Avalanches
##### 3.1 Varovalni učinek gozda pred snežnimi plazovi
Along with snow and topography characteristics, forest stand structure is one of the main factors influencing the occurrence of avalanches (Bebi et al., 2001; Holtmeier and Broll, 2018). The most relevant forest stand characteristics in terms of the hazard component of risk (onset probability, propagation probability and intensity) for avalanches are canopy cover, species composition, surface roughness, tree size, stem density, canopy gap size and diameter at breast height (DBH) distribution (Meyer-Grass and Schneebeli, 1992, after Rammig et al., 2006; Frehner et al., 2005, after Berger et al., 2013; Berretti et al., 2006, after Berger et al., 2013; Gauquelin et al., 2006, after Berger et al., 2013; Bebi et al., 2009; Moos et al., 2017). Forest has the most important mitigation role in release areas, where it serves the functions of stabilizing the snow pack and intercepting precipitation, while in avalanche tracks the effect of forest is limited to the lateral spreading and slowing down of smaller events (< 100 m³) (Teich et al., 2012). In the case of large (> 1000 m³) destructive events, the protective effect of forest is negligible (Viglietti et al., 2010).

Forest canopy cover influences the characteristics of the snow beneath it; in the forest, snow depth is lower than in open (non-forested) areas, and the density of snow is higher, meaning that forested areas are less prone to avalanches (Storck et al., 1999; Bründl et al., 1999; Mayer and Stöckli, 2006). Intercepted snow is more heterogeneous and thus prevents the formation of continuous weak layers (Mayer and Stöckli, 2006). Snow interception by the canopy is closely related to tree species composition (Bebi et al., 2009). Evergreen tree species are more efficient in intercepting snow and preventing it from gliding. However, *A. alba* and *P. abies* needles on the ground facilitate sliding and possibly increase avalanche activity (Viglietti et al., 2010;
In the case of smaller quantities of snow, deciduous trees can be suitable since more sunlight reaches the canopy floor and melts the snow, thus preventing gliding (Teich et al., 2012). In the case of large quantities of snow, the effect of canopy cover and tree species is negligible (Berger et al., 2013). In propagation areas, conifers are more effective than broadleaves or larch trees (Bebi et al., 2009). In larch propagation areas, conifers are more effective than deciduous species and mixed forests (Teich et al., 2012). In contrast to evergreen trees, leafless trees (deciduous trees and larch) have smaller effective crown areas and are more likely to survive powder avalanche blasts (Feistl et al., 2015). Thus, larch, deciduous trees and shrub canopy should be limited in release zones in favor of other conifers (Newesely et al., 2000; Viglietti et al., 2010; Berger et al., 2013). In areas where both avalanches and rockfalls occur, mixed forest provides the most effective form of protection (Stokes, 2006).

Surface roughness in release areas influences avalanche runout distances (Teich et al., 2012). High surface roughness (e.g. dead wood, logs, boulders) prevents the release of full-depth gliding avalanches since it provides stabilization of the snowpack and hinders the formation of continuous weak layers and provides mechanical support to the snowpack (Veitinger, 2015). No avalanche events have been reported with a surface roughness greater than 2 m (McClung, 2001; Veitinger, 2015). In the Alps it was observed that when farmers stopped cutting the grass on steep and open slopes, more avalanche events occurred due to the promotion of snow gliding conditions (Newesely et al., 2000; McClung and Schaerer, 2002). The presence of dead wood or staged terrain increases surface roughness and can prevent the gliding of snow cover, which also protects young plants from being uprooted (Puttalaz, 2010; Feistl et al., 2013). In order to promote surface roughness in the propagation area, lying tree stems should be left on the slope, and high stumps (1.3 m) should be left after cutting (Berger et al., 2013). With increasing snow accumulation, surface roughness decreases, resulting in potentially larger release areas (Veitinger, 2015; Veitinger and Sovilla, 2016).

Stem density affects both the frequency and magnitude of avalanche events since it locally increases air temperature and lowers the temperature gradient within the snowpack (Viglietti et al., 2010). Higher stem density decreases the onset probability in release zones and consequently limits their spatial extent. Recommended stem density in release areas of avalanches of low to moderate magnitude is 300 to 500 stems/ha on moderately steep slopes (30°), and 1000 to 2000 stems/ha on steeper slopes (40° or more) (Horvat and Zemljic, 1998). In order to reduce release propagation, the tree height in this area is recommended to be twice as high as the snow depth, and in the propagation area it is recommended that tree height is even higher (Rudolf-Milkau et al., 2015). The DBH of a tree affects avalanche propagation because trees with greater DBH present a greater mechanical obstacle. Trees with DBH ≥ 10 cm present a sufficient mechanical obstacle to limit the propagation of an avalanche (Horvat and Zemljic, 1998). Trees with DBH 6–10 cm can only marginally stabilize snowpack. Avalanches that are released in forest areas with larger mean DBH have longer runout distances (Teich et al., 2012). High stem density in combination with small diameters (< 15 cm) significantly reduces avalanche tracks (Teich et al., 2012), especially in the first 200 m.

Canopy gaps on slopes around 35° should not be wider than 50 m and should not be longer than 40 m (Horvat and Zemljic, 1998). Avalanches may release in gaps longer than 30 m (in the direction of the slope) and 15 m in the horizontal direction (Imbeck, 1987). Gaps within release and propagation areas are recommended to be < 15 m (Berger et al., 2013). The forest edge can increase the probability of release, especially in the case of coniferous forest, where greater quantities of snow accumulates at the forest edge. Snow that accumulates at the forest edge transforms more slowly and possesses different properties than (wet) snow under forest cover. Thus, a break in snow cover is more plausible at the forest edge (Horvat and Zemljic, 1998). Areas where division between forest and meadow coincide with a break into steeper terrain are especially dangerous (Pintar, 1968). Snow gliding is prevented by forest stands that are situated at the lower edge of gaps.

3.2 The protective effect of forest against rockfalls

3.2 Varovalni učinek gozda pred skalnimi padalci

In the Alps, rockfalls most often occur as falling rocks with a volume between 0.5 and 5 m³ (Berger et al., 2002; Dorren et al., 2005; Stoffel et al., 2005). Dorren et al. (2005) discovered that if rockfall activity is expressed as the number of rocks that surpass an area, the total number of such rocks will be 63 % lower in forested areas than in areas without forest. Moreover, forested slopes also decrease the bounce height (by 33 %) and velocity (by 26 %) of rocks. The most relevant forest characteristics in terms of the hazard component of risk (onset probability, propagation probabil-
It terms of forest structure, stands with high stem density and trees of similar age and diameter may have a maximum effect on reducing rockfall travel distances (Perret et al., 2004). Yet, it is difficult to maintain the optimum stage of forest stands (Dorren et al., 2005). A realistic upper limit of stem density in rockfall protection forests is 350 trees/ha with a mean DBH of 35 cm (NaI), 2003, after Perret et al., 2004; Gauquelin et al., 2006, after Berger et al., 2013); however, this strongly depends on the tree species and site characteristics. Although trees with larger DBH can dissipate the higher kinetic energy of rocks, the density of forest seems to be a more important factor in reducing rockfall propagation area and length than DBH itself (Dorren et al., 2004; Dorren et al., 2005; Frenhner et al., 2005, after Brang et al., 2006; Berretti et al., 2006, after Berger et al., 2013), especially for rocks of smaller diameters (from 13 to 45 cm) (Jahn, 1988). Not all simulation results concur with these findings, however Radtke et al., 2014 and Jancke et al. (2009) even suggest that a density of trees of between 5000 and 10000 per hectare (where stands are younger than 30 years) is sufficient to provide the best protection against blocks with diameters > 20 cm. Only extremely high stem density provides acceptable protection against very small blocks (> 0.25 m³) (Jancke et al., 2009; Radtke et al., 2013). On the other hand, the findings of Radtke et al. (2014) show that in coppice stands basal area and DBH are more important than stem density in the case of small (0.25-0.5 m³) and bigger blocks (> 0.5 m³), so they recommend a heterogeneous DBH distribution in coppice forest. The required stem density and mean stem diameter can be calculated based on the mean diameter of falling rocks, mean kinetic energy of the rocks, maximum length of the stopping zone and tree species (Dorren et al., 2005; Stokes et al., 2005; Brang et al., 2006). A high basal area should be maintained at the foot of the release area (Radtke et al., 2014; Dupire et al., 2016; Moos et al., 2017). With trees that have DBH ≥ 15 cm, basal area is recommended to be ≥ 25 m²/ha in the rockfall propagation area and ≥ 20 m²/ha in the rockfall deposit area (Bebi et al., 2009; Berger et al., 2013).

Gap size in the rockfall propagation area should be minimized. The maximum gap size should be around 1.5 times the height of the dominant tree (high forest < 40 m, coppice < 20 m) (Ancelin et al., 2006; Berger et al., 2013). Corridors in the rockfall propagation zone are areas with high rockfall activity that inhibits forest regeneration. In rockfall corridors forest can be artificially promoted so as to direct falling rocks towards “channels” (e.g. Kupferschmid Albisetti et al., 2003; Dorren et al., 2005; Berger et al., 2013). In this case, a 25 m band of high stem density forest should be located on either side of the corridor (Berger et al., 2013). The distribution of trees in the rockfall propagation area should be random, while in the deposition area coppice stands can also be effective in stopping rocks (Berger et al., 2013). The distance between the potential rockfall release areas and forest stands should be limited so that the kinetic energy of rocks is reduced and they can be stopped by the forest (Dorren et al., 2004; Berger et al., 2013). In the propagation area rockfall protection forest should be at least 200 m long in order to effectively stop rolling rocks (Berger et al., 2013).

In both rockfall release and propagation areas, broadleaved species are preferred in the forest stand as they are more resistant to rockfall impacts than coniferous species (Stokes, 2006). Thus, at least 30% of the thickest trees in the forest stand should be broadleaves (Stokes, 2006; Berger et al., 2013). Since they are the most resistant to rockfall impacts (Durren et al., 2005; Dorren and Berger, 2006), the regeneration of the following tree species should be promoted in rockfall protection forests (Berger et al., 2013): *Quercus petraea* L., *Fagus sylvatica* L. and *Acer pseudoplatanus* L. The forest stand should also be multilayered in order to provide long-term sustainable risk mitigation. Unstable trees in rockfall release areas can potentially increase rockfall probability due to the effect of wind on trees and roots, which can loosen cliffs and outcrops (Dorren et al., 2005).

High surface roughness reduces the kinetic energy of rocks and can change the paths of rockfalls. It influences the contact angles of rocks and changes rock movement from falling to rolling and sliding (Wang and Lee, 2010). Surface roughness represents the microtopography of the slope and obstacles on the slope that impede falling rocks (Dorren, 2016). In order to increase surface roughness in the propagation area in rockfall protection forests, it is recommended to promote dead wood, leave high stumps (1.3 m) and positioned logged trees perpendicular to the slope (Berger et al., 2013).
4 INFLUENCE OF NATURAL DISTURBANCES ON THE PROTECTIVE EFFECT OF FOREST AGAINST AVALANCHES AND ROCKFALLS

4.1 Forest fires

4.1.1 Gozdné požari

In general, the mortality of trees is high in the case of intense fires (i.e., crown fires), and trees with DBH < 35 cm are less resilient in the case of intermediate fires (Maringer et al., 2016b). Compared to Quercus robur L. and Quercus petraea (Matt.) Liebl, Castanea sativa L. and Fagus sylvatica L. are considered to be more susceptible to fire due to thin bark and poor resprouting capabilities (Conedera et al., 2010; Maringer et al., 2016a; Dupire et al., 2019). Larix decidua Mill. is highly resilient to mixed-severity (low, moderate, high) forest fires due to strong recruitment after fire (Moris et al., 2017). Abies alba Mill., Picea abies (L.) Karst., Pinus mugo Turra and Pinus cembra L. are fire sensitive species, whereas Pinus nigra Arnold and Pinus sylvestris L. can survive several surface fires of low to moderate intensity (Dupire et al., 2019). In forest stands with dense canopies, low-burning fires can turn into a high-intensity crown fire, leading to decreased canopy cover. This type of fire can kill large numbers of trees and decrease stem density (Graham and McCaffrey, 2003; Kashaian et al., 2005). When the majority of trees and understory vegetation is burned, surface roughness decreases, and if there is any forest remaining, it can be expected that the size of the gaps will increase. The consequences of low-severity fires in the F. sylvatica forests of the Southern Alps had almost the same protective effect against rockfalls as unburnt forest, whereas moderate- to high-severity fires greatly reduced the protective effect for the next 10 to 30 years after the fire (Dupire et al., 2016). Due to the abundant growth of post-fire colonizers and scarcity of seed-producing trees, poor regeneration of F. sylvatica can postpone the reestablishment of protection forest by a couple of decades (Ascoli et al., 2013; Maringer et al., 2016a, 2016b, 2016c). Forest fires will reduce the protective effect of forest against avalanches since i) there is lower interception of snow leading to increased snow gliding; ii) stand density decreases, meaning that the forest will not be able to stop avalanches; and iii) gap sizes within forest stands will increase, resulting in new potential release areas. A similar conclusion can be drawn for rockfall protection forest: i) as tree density potentially decreases in both release and propagation areas, fewer rocks are stopped by trees; ii) gap length can increase, leading to rocks with higher kinetic energy that are not able to be stopped by trees; and iii) surface roughness decreases, which means that there are fewer obstacles that could stop rocks.

4.2 Windthrow, ice and snow break

4.2.1 Vetrološki, žledoloski in snegoloski

Windthrow and ice and snow break can result in the breakage of branches, tree tops and trunks, and also in the uprooting of trees (Nykänen et al., 1997; Bragg et al., 2003). In general, the survival rate of trees with low to moderate or even severe damage is high (Irland, 1998; Coons, 1999), although post-event disturbance agents such as insect outbreaks negatively influence survival rates (Bragg et al., 2003; Köster et al., 2012). Large-scale events can demolish entire forest stands and thus completely destroy the protection function of the forest (Schönenberger, 2002). Within forest stands, gap sizes increase, resulting in new potential avalanche release areas (Coates and Burton, 1997) and a reduction in the length of the forested part of the slope, potentially increasing rockfall deposit areas. In the case of dispersed damage and low-intensity windthrows, ice and snow breaks can improve the protective effect against avalanches and rockfalls in even-aged forest (Frey and Thee, 2002) due to increased surface roughness (lying logs, stumps) (Figure 1) and because of the shift in structure due to an increase in light and nutrient availability, which favors pre-regeneration (e.g. Collet et al., 2008; Kramer et al., 2014). Lying logs and stumps can in the first 10 to 30 years after the disturbance (Kupferschmid Albisetti et al., 2003; Wohlgemuth et al., 2017) act as barricades against avalanches (Frey and Thee, 2002) and rockfalls (Kupferschmid Albisetti et al., 2003). Harvesting trees leads to less forest cover and tree density, diminishing the protective effect of the forest (Brang et al., 2006). Compared to forest fires, windthrow and ice and snow break usually leave an intact tree regeneration layer and an abundance of downed logs (Franklin et al., 2002), which is favorable in terms of the protective effect (Maringer et al., 2016a). The susceptibility of tree species to uprooting or steam breakage varies. Tree species with shallow roots (P. abies), lower stand density and high height/diameter are especially prone to wind damage (Meunier et al., 2002; Quine and Gardiner, 2007; Klopčič et al., 2009; Schmidt et al., 2010; Albrecht et al., 2010; Pukkala et al., 2016; Díaz-Yáñez et al., 2019).

4.3 Avalanches

4.3.1 Snežni plazovi

Smaller avalanches that flow through forest can break, uproot and overturn trees, while large avalanches can even destroy large tracts of mountain for-
The damage potential of avalanches that have larger amounts of tree debris (e.g. branches, stumps, lying logs etc.) is higher due to the increase in high-density mass within the avalanche. On the other hand, the presence of dead wood increases the surface roughness and prevents snow gliding (Putallaz et al., 2010; Feistl et al., 2013). Stand density and tree height in protection forest are reduced due to avalanche activity (Patten and Knight, 1994; Kulakowski et al., 2006). Avalanche loading and tree strength are the factors that influence the degree of forest destruction (Feistl et al., 2014). Stem breakage due to avalanche activity is influenced by tree size, with smaller trees tending to bend under the snow pressure, while larger trees easily break (Johnson, 1987). Species composition may change after an avalanche event, resulting in a change from coniferous to mixed forest and thus lower interception of snow, higher snow accumulation and higher onset probability of snow avalanches (Veblen et al., 1994; Bebi et al., 2009). On the avalanche track, small short-lived trees and shrubs (Acer, Salix, Betula, Alnus) are often established (Holtmeier and Broll, 2018) because of their higher stem flexibility (Johnson, 1987). In the case of powder avalanches, taller trees are more susceptible to avalanche damage (Bebi et al., 2009). Due to the decreased canopy cover, tree size and stem density, the interception of snow is decreased, leading to a higher probability of snow gliding and the inability of the forest to stop small avalanche events (Newesely et al., 2000). Increased avalanche activity also results in increased gap sizes and non-forested areas. Subsequently, the risk of rockfall activity in these areas may also increase (Wasser and Frehner, 1996; Feistl et al., 2014).

4.4 Rockfalls
4.4 Skalni podori

Small-scale rockfalls damage individual trees, while larger events can demolish larger forest stand areas. The main types of tree damage due to rockfalls in forest are stem wounds, uprooting, partial fracture or complete breakage of the stem, and tree top break-off (Dorren et al., 2005; Dorren and Berger, 2005; Stokes et al., 2006). As a consequence of tree rooting, rockfall activity might lead to the formation of rockfall paths that follow the slope direction. In these areas avalanche activity might also increase (avalanches within the forest). This leads to channelization and greater frequency of rockfall activity and thus larger impacts on trees. The velocity of rocks in non-forested areas increases, leading to larger impacts on trees and to a state where trees cannot stop them due to their higher kinetic energies. Injuries due to impacts can eventually result in tree death, which can lead to lower stand density, increased gap sizes and reduced length of the forested part of the slope. Since broadleaved trees are more resistant compared to coniferous trees, it is more
likely that a reduction in coniferous trees can occur on rockfall slopes (Stokes et al., 2005, 2006). Surface roughness can increase in the case of uprooted trees, fallen trunks or tree tops (Schönenberger et al., 2005), which are additional barriers in the forest that can stop rocks or reduce their kinetic energy.

4.5 Insects and pathogens

4.5 Insekti in patogeni

Bark beetle outbreaks can change the composition and structure of forest stands and can alter the protective effect against avalanches and rockfalls. Tree mortality due to bark beetle outbreaks increases with greater stand density smaller DBH and tree height (Axelson et al., 2010). Bark beetles cause a decrease in canopy bulk. Needle loss reduces canopy interception, increases light transmission and wind speeds, alters snow accumulation and melting, and changes the microstructural properties of the subcanopy snowpack, leading to greater avalanche activity (Pugh and Small, 2012; Winkler et al., 2014). However, not all studies confirm this, as even standing dead trees provide sufficient interception (Teich et al., 2019). Species composition in avalanche protection sites might change drastically due to the high mortality of coniferous species and shift to more mixed and deciduous forest (Heurich, 2001; Stokes, 2002). High tree mortality decreases stand density, leading to new and larger forest gaps (Maroschek et al., 2015). This can result in the occurrence of new avalanche release areas and can reduce the protective effect of forest in avalanche propagation areas (Figure 2). In the case of rockfalls, decreased forest stand density and the length of forested area will also reduce the protective effect of forest by increasing rockfall runout lengths, and with new gaps, potential new release areas will be exposed. Surface roughness does not change significantly in the case of bark beetle outbreaks; however, dead trees eventually fall, resulting in snagfall, which increases surface roughness (Wohlgemuth et al., 2017). Leaving unharvested trees after other natural disturbance events (e.g. windthrow, ice and snow break, avalanche events) risks beetle infestation, which usually kills any remaining trees (Wermelinger, 2004) and can result in the bark beetle outbreak spreading to the undisturbed part of the protection forest.

Disease can kill trees or predispose them to mechanical failure (Franklin et al., 1987; Berryman, 1988). Tree mortality due to root rot disease (Heterobasidion

![Fig. 2: Reduction in forest cover after bark beetle outbreak and salvage logging above the Dovje settlement (NW Slovenia) could lead to new snow avalanche release areas. Risk assessment after the natural disturbance event is crucial in such cases.](image)

![Slika 2: Zaradi napada podlubnika in sanitarne sečnje se je zmanjšala pokrovnost z gozdom nad naseljem Dovje (SZ Slovenija), kar lahko vodi k potencialno novim območjem pojavljanja snežnih plazov. Po naravnih motnjah je v teh primerih ključno ponovno ocenjevanje nevarnosti proženja snežnih plazov.](image)
spp., *Armillaria* spp.) in protection forest results in potentially higher onset probabilities and wider spatial span of avalanches and rockfalls, with the creation of larger and longer gaps in the forest canopy, a decline in tree cover and elimination of larger trees (Newesely et al., 2000). Trees affected by root rot or other fungi are also more susceptible to windthrow (Papaik et al., 2005; Gonthier et al., 2012; Garbelotto and Gonthier, 2013), which can further expand gap sizes or lengths. Mainly coniferous trees are attacked by root rot, which shifts species composition towards broadleaves, leading to greater onset probability of avalanches, although this can also prevent the propagation of rockfalls. Snow fungi increase tree species mortality, especially near the tree line, reducing forest cover and promoting snow gliding. Due to the absence of vegetation and reduced surface roughness, avalanches can develop greater velocities in longer paths without obstacles, resulting in larger avalanches (Schneebeli and Bebi, 2004).

### 4.6 Influence of natural disturbances on forest stand parameters

After a natural disturbance event, the protective effect of forest is altered, leading to either an increase or decrease in the protection function. In some cases one natural disturbance event can positively or negatively affect, or have either no effect or an unclear effect on, the protection function of forest stands (Table 1). The scale of the natural disturbance event is a crucial factor in altering the protection function. Small-scale natural disturbance events might not be as important in altering the protection function of forest against avalanches.
and rockfalls as large-scale events, which can have potentially devastating consequences.

5 INFLUENCE OF CLIMATE CHANGE ON NATURAL DISTURBANCES

5 VPLIV PODNEBNIH SPREMEMB NA NARAVNE MOTNJE

In the future, interactions between natural disturbances are expected to be influenced by climate change, which is expected to affect the frequency and intensity of natural disturbances (Lindner et al., 2010, 2014; Seidl et al., 2011b, 2017; Thom and Seidl, 2016). Climate change is expected to have a number of direct, indirect and mutual effects on natural disturbances and stand structure (e.g. Seidl et al., 2017), which could affect the protection function of forest against natural hazards (Schumacher and Bugmann, 2006) (Figure 3). For example, warming temperatures and reduced precipitation could trigger drought periods that would predispose trees to bark beetle outbreaks. Any potential bark...
beetle outbreak would affect forest cover (creating larger canopy gaps) and snowpack characteristics, potentially leading to an increase in avalanche formation and risk (e.g. Maroschek et al., 2015).

Due to climate change, the occurrence, duration and intensity of strong winds is expected to increase (Peltola et al., 2010; Usbeck et al., 2010; Donat et al., 2011), as is the frequency of forest fires due to lower fuel moisture (Williams and Abatzoglou, 2016). Also expected to increase are fuel availability (e.g. via wind or insect disturbance) (Seidl et al., 2017; Harvey et al., 2013), ignition (due to lightning activity; Conedera et al., 2006) and the duration and intensity of water deficit (Cook et al., 2014). Snow related forest damage is expected to decrease in the future due to a reduction in specific weather events and an increase in temperature. However, shorter periods of frozen soil and changes in forest structure (e.g. increasing pole stage stands and h/d ration) may increase susceptibility to snow break (Peltola et al., 2010; Hlasny et al., 2011; Bebi et al., 2017). Climate change will most likely affect the distribution range and increase the frequency of insect outbreaks (Volney and Fleming, 2000; Lange et al., 2006; Netherer and Schopf, 2010; Jacel et al., 2012; Sturrock et al., 2011; Weed et al., 2013; Seidl et al., 2014b; Maroschek et al., 2015; Seidl et al., 2017), especially due to the interaction between increasing temperatures and insect biology (Rouault et al., 2006; Battisti et al., 2005; Netherer and Schopf, 2010; Evangelista et al., 2011; Temperli et al., 2013; Maroschek et al., 2015). The higher frequency of abiotic events also provides better conditions for insect and pathogen outbreaks (Rouault et al., 2006; Netherer and Schopf, 2010). It is expected that bark beetle outbreaks could be especially influential at higher elevations because of aging P. abies stands (Seidl et al., 2009) and the formation of new P. abies habitat (Hlasny et al., 2011). However, climate change will probably cause ambiguous consequences with different species responses (Harrington et al., 2001; Netherer and Schopf, 2010). The success and performance of insect species will likely depend on the quality of the ecosystems and the effect of climate change in different bioclimatic regions (Netherer and Schopf, 2010).

Disturbance regimes that are influenced by temperature-related variables will have the highest importance at higher altitudes and in boreal zones and coniferous forest (Seidl et al., 2017). In addition, climate change might remove or relocate the barriers that limit present species ranges (Robinet and Roques, 2010) and influence their distribution ranges (Volney and Fleming, 2000; Lange et al., 2006; Netherer and Schopf, 2010). The expected shift in the geographic distribution of trees due to increasing mean temperatures will probably influence the magnitude and frequency of rockfalls and avalanches, mainly because of the progression of trees towards upper slopes (Lindner et al., 2010; Stoffel and Huggel, 2012; Berger et al., 2013). New forest cover could cover release areas and increase overall surface roughness, consequently increasing the protective effect of mountain forests (Lindner et al., 2010; Berger et al., 2013).

Overall, climate change is likely to significantly affect protective forest composition and structure by affecting plant species competitiveness and distribution (e.g. Lexer et al., 2002). On the other hand, besides a change in distribution of vegetation, ice, snow and permafrost zones could be altered under abrupt changes in climatic patterns, resulting in increased erosion and altering slope stability (Kraüchi et al., 2000). A change in rockfall slope stability has already been attributed to the warming and thawing of the permafrost and retreating glaciers (Stoffel and Huggel, 2012; Ravanel et al., 2017). Decreases in snow precipitation, snow depth and snow cover duration have already been observed, and these factors are crucial in avalanche formation (Castebrunet et al., 2014). Warming temperatures will result in a reduction in dry snowpack and an increase in wet snowpack, which will result in decreased avalanche activity in spring and an increase in wet-avalanches in winter (Castebrunet et al., 2014).

In conclusion, under the influence of climate change, alterations in the frequency and magnitude of natural hazards is expected, mainly due to changes in precipitation regimes, forest structure, temperatures, the freeze thaw cycle and snowpack characteristics (e.g. Beniston, 2001; Lindner et al., 2010; Stoffel and Huggel, 2012; Alpine strategy for ..., 2013; IPCC, 2014; Seidl et al., 2011a; Berger et al., 2013; Castebrunet et al., 2014). A shifting natural disturbance regime in the future will most likely influence the structure and dynamics of protection forest, with forest cover, species composition and gap size being particularly affected. This will consequently affect the protection function of mountain forest ecosystems and present the need for protection forest managers to reevaluate risks in altered ecosystems.

6 DISCUSSION
6 RAZPRAVA

In this article the influence of natural disturbances on the forest protective effect against avalanches and rockfalls is presented. The main findings of this article are summarized in Table 1, where the influence of par-
Ticular disturbance types on forest stand parameters is shown. However, there are multiple shortcomings regarding Table 1. Firstly, the results are presented individually, while the mutual effects between parameters, where one stand parameter influences another, are not discussed. In addition, the findings present the immediate effects of the disturbance event on stand structure. The characteristics of each presented stand parameter should remain more or less the same for approximately five to ten years after the event, at least to the point when decay breaks down dead wood, regeneration is established or new disturbance events occur. There should also be some constraints regarding the application of the findings of this paper to specific cases, especially because the main findings in Table 1 are generalized and are not fully derived from studies due to the lack of studies assessing risk after a disturbance event (e.g. Wohlgemuth et al., 2017). The outcome of a particular disturbance event on an individual forest stand parameter may vary and can be unpredictable, especially if we account for the fact that natural disturbance affects multiple stand parameters, and that there are synergistic effects between multiple stand parameters. As stated in Chapter 3, the vulnerability of a stand is strongly related to stand parameters. For example, the change in surface roughness after windthrow should be different in P. abies dominated stands than in F. sylvatica dominated forest due to their different vulnerability/susceptibility to windthrow. In addition, we could also account for other sites or weather characteristics. For example, after a windthrow event, surface roughness can be relatively high due to broken branches and trunks; however, freshly fallen snow after windthrow can cover the majority of the obstacles, reducing surface roughness and leading to greater onset probability of avalanches. A depth of freshly fallen snow of between 30 and 50 cm can be critical for the initiation of moderate avalanches (Schweizer et al., 2003).

The influence of natural disturbance on forest parameters was also discussed only for high severity events. The vulnerability of forest to low severity events may be minimal and limited. For example, the forest protective effect remained the same after low severity forest fire (Maringer et al., 2016a). Low to moderate severity snow or ice breaks produce a large amount of dead wood and leave many surviving trees, and the protective effect of such a stand can be even greater than before the event. Low severity forest disturbances can even be beneficial due to pre-regeneration capabilities (Kramer et al., 2014), which can produce more diverse stands in the future (Wohlgemuth et al., 2017). Diverse forest stands are especially desirable in protection forest management because their resistance and resilience are greater compared to those of even-aged mono-species stands (Brang, 2001; Frehner et al., 2005, after Berger et al., 2013; Jactel et al., 2017).

Post-disturbance management usually consists of salvage logging and planting. Risk assessment is rarely done after a disturbance event (e.g. Wohlgemuth et al., 2017). Therefore, after a disturbance event, a new assessment of the protective effect of forest should be done, and in cases where forest cover has been completely removed, afforestation plans or technical solutions that offer protection against natural hazards should be considered (Schönenberger and Wasem 1997; Schönenberger, 2002; Maringer et al., 2016a; Wohlgemuth et al., 2017). After a disturbance event, the protective effect of the forest is altered and can result in higher avalanche and rockfall risk due to advanced wood decay and log breakage (Frey and Thee, 2002). Leaving unharvested trees after a disturbance event promotes surface roughness. On other hand, these trees represent a source for bark beetle outbreaks and forest fires (Wermelinger, 2004; Brang et al., 2006). This is particularly specific to attacks of Ips typographus L. on disturbed Norway P. abies stands, which usually kill any remaining trees (Heurich, 2001). The breakage of logs in unharvested (felled) trees is species specific, where the durability of P. abies and A. alba is greater compared to that of F. sylvatica or B. pendula (Stokes, 2002). On the other hand, harvesting trees leads to less forest cover and tree density, reducing the protective effect of the forest (Brang et al., 2006). Although major damage to the forest as a consequence of natural disturbance impairs the protective function of the forest, this is not the case for the first 10 to 30 years after stand destruction (Kupferschmid Albisetti et al., 2003; Wohlgemuth et al., 2017) since lying or broken trees may act as a barricade against avalanches (Frey and Thee, 2002) or rockfall because they enhance surface roughness (Kupferschmid Albisetti et al., 2003).

Factors influencing seedling establishment (e.g. site conditions, competing understory vegetation) after a disturbance event seem to be especially important (Kramer et al., 2014) since they can hinder regeneration for a few decades (Wohlgemuth et al., 2017) and prevent the establishment of adequate forest structure and its protective capacity. Therefore, post-disturbance management influences the quantity of dead wood and the regeneration capacity of stands, which further affects the recovery of the protection function (Wohlgemuth et al., 2017).

In conclusion, the protective effect of a forest stand against avalanches and rockfalls under the influence of
7 SUMMARY
7 POVZETEK

Pomembna ekosistemska storitev alpskih gozdov je varovalna in zaščitna funkcija pred naravnimi nevarnostmi, kot so snežni plazovi, skalni podori, zemeljski plazovi in poplave. V tem preglednem članku je predstavljen vpliv glavnih abiotičnih (gostujoči požari, vetrolom, snegolom, žled, snežni plazovi in skalni podori) in biotičnih (insekti in patogeni) motenj na varovalni učinek gozov pred snežnimi plazovi in skalnimi podori. Vpliv naravnih motenj je predstavljen v povezavi s spremembo sestojnih parametrov (delež gozda, vrstna sestava, hrapavost površja, gostota sestoja, velikost vrzel, debelinska sestava), ki so najbolj pomembni pri preprečevanju pojavljanja in širjenja snežnih plazov in skalnih podorov. Sprememba parametrov je predstavljena s petstopenjsko lestvico z vidika varovalnega učinka gozda (oz. sesto-jnega parametra). Vse obravnavane naravne motnje negativno vplivajo na varovalni učinek pred skalnimi podori z vidika spremembe gostote sestoja, dolžine vrzel, debelinske strukture in dolžine pobočja, poraslega z gozdom. Vpliv naravnih motenj na vrstno sestavo in hrapavost površja ni povsod enoznačen z vidika varovalnega učinka gozda pred skalnimi podori. Vse obravnavane naravne motnje imajo negativen vpliv na varovalni učinek gozda pred snežnimi plazovi z vidika spremembe gostote sestoja, dolžine vrzel in debelinske strukture. Vpliv naravnih motenj na sestojni sklep, vrstno sestavo, hrapavost površja in velikosti dreves v primerjavi z globino snega ni povsod enoznačen z vidika varovalnega učinka gozda pred skalnimi plazovi. Ugotovitve, predstavljene v članku, so zaradi nenaziskanosti vplivov pomanjkljive in v določenem delu hipotetične, saj manjšajo študije, ki bi preučevalo neposreden vpliv naravnih motenj na verjetnost pojavljanja in širjenja skalnih podorov in snežnih plazov. Ugotovitve so posplošene, zato avtorji odsvetujejo neposredno uporabo ugotovitev na konkretnih primerih. Vseh dejavnikov, ki vplivajo na spremembo varovalnega učinka gozda, zaradi delovanja naravnih motenj v okviru članka ni mogoče analizirati. Glavne pomanjkljivosti ugotovitev so neupoštevanje naravnih motenj šibkih do srednjih jakosti, neupoštevanje vzajemnega vpliva sestojnih parametrov, neupoštevanje časovne komponente, neupoštevanje odpornosti različnih gozdnih združb, neupoštevanje kaskadnega vpliva med naravnimi motnjami. V prihodnosti je moč pričakovati spremenjene vzorce naravnih motenj, delno zaradi vpliva podnebnih sprememb na sestojne parametre, delno zaradi neposrednega vpliva podnebnih sprememb, tako da na frekvenco kot jakost naravnih motenj. Za upravljanje z gozdi, ki opravljajo varovalno in zaščitno funkcijo, bo še posebej pomembno preučiti povezave med naravnimi nevarnostmi in njihov vpliv na varovalni učinek gozda pred naravnimi nevarnostmi.
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