Pregledni znanstveni članek / Review article

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 PLAZOVI IN SKALNIMI PODORI

Domen OVEN[1], Barbara ŽABOTA[2], Milan KOBAL[3]

(1) University of Ljubljana, Biotechnical Faculty, Department of Forestry and Forest Renewable Resources, domen.oven@bf.uni-lj.si
(2) University of Ljubljana, Biotechnical Faculty, Department of Forestry and Forest Renewable Resources, barbara.zabota@bf.uni-lj.si
(3) University of Ljubljana, Biotechnical Faculty, Department of Forestry and Forest Renewable Resources, milan.kobal@bf.uni-lj.si

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 nevarnostnimi, kot so snežni plazovi in skalni podori. V članku je zato predstavljen pregled glavnih vplivov abiotskih (gozdni požari, vetrolom, snegolom, žled, snežni plazovi in skalni podori) in biotskih (insekti in patogeni) motenj na varovalno in zaščitno funkcijo gozdov pred snežnimi plazovi in skalnimi podori. Naravne motnje na splošno negativno vplivajo na varovalni učinek gozda pred naravnimi nevarnostmi, še posebej v primeru veliko-površinskih dogodkov z visoko jakostjo 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

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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; Bebi et al., 2001). Mountain forests that are classified as direct and/or indirect protection forests provide protection against natural hazards such as rockfalls, avalanches, debris flows, shallow landslides and surface erosion. They occupy steep slopes at high elevations and play a crucial role in stabilizing slopes, thus providing protection for people, settlements and infrastructure (e.g. Schönenberger, 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. Klopčič 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- 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. Schönenberger, 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; Schneebeli 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.

2 MATERIALS AND METHODS

2 MATERIALI IN METODE

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.

3 THE PROTECTIVE EFFECT OF FOREST AGAINST AVALANCHES AND ROCKFALLS

3 VAROVALNI UČINEK GOZDA PRED SNEŽNIMI PLAZOVI IN SKALNIMI PODORI

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.

3.1 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 m^3) (Teich et al., 2012). In the case of large (> 1000 m^3) 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;

Berger et al., 2013). 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 and deciduous forest stands, runout distances are significantly greater compared to other evergreen coniferous 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 Zemljič, 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-Miklau 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 Zemljič, 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 Zemljič, 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 Zemljič, 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 podori

In the Alps, rockfalls most often occur as falling rocks with a volume between 0.5 and 5 m^3 (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 probability and intensity) are tree density, canopy gap length, diameter at breast height distribution, species composition, presence of trees in the release area, length of the forested part of the slope and surface roughness (Dorren et al., 2005; Stokes et al., 2005; Frehner et al., 2005, after Berger et al., 2013; Berretti et al., 2006, after Berger et al., 2013; Stokes et al., 2006; Gauquelin et al., 2006, after Berger et al., 2013; Brang et al., 2006; Bebi et al., 2009; Radtke et al., 2013; Dupire et al., 2016; Moos et al., 2017; Moos et al., 2018).

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 (NaiS, 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; Frehner 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 m^3) (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 m^3) and bigger blocks (> 0.5 m^3), 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 m^2/ha in the rockfall propagation area and ≥ 20 m^2/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 et al., 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 (Dorren 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 micro topography 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 position 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 VPLIV NARAVNIH MOTENJ NA VAROVALNI UČINEK GOZDA PRED SNEŽNIMI PLAZOVI IN SKALNIMI PODORI

4.1 Forest fires

4.1 Gozdni 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; Kashian 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 Vetrolom, žledolom in snegolom

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 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-

Fig. 1: Protection forest in the Trenta Valley after a storm. Fallen trees create obstacles for falling rocks, especially if they lie perpendicular to the slope. However, this enhanced protective effect disappears after the wood decays.

Slika 1: Gozdovi, ki opravljajo varovalno in zaščitno funkcijo v dolini Trente po vetrolomu. Izruvana in polomljena drevesa zaustavljajo padajoče skale, še posebej če so debla usmerjena pravokotno na naklon. Povečani varovalni učinek zaradi motnje traja, dokler glive in drugi organizmi ne razkrojijo ležečega lesa.

est (Takeuchi et al., 2011; Feistl et al., 2014; Casteller et al., 2018). 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.

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 takih primerih ključno ponovno ocenjevanje nevarnosti proženja snežnih plazov).

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

4.6 Vpliv naravnih motenj na sestojne parametre

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

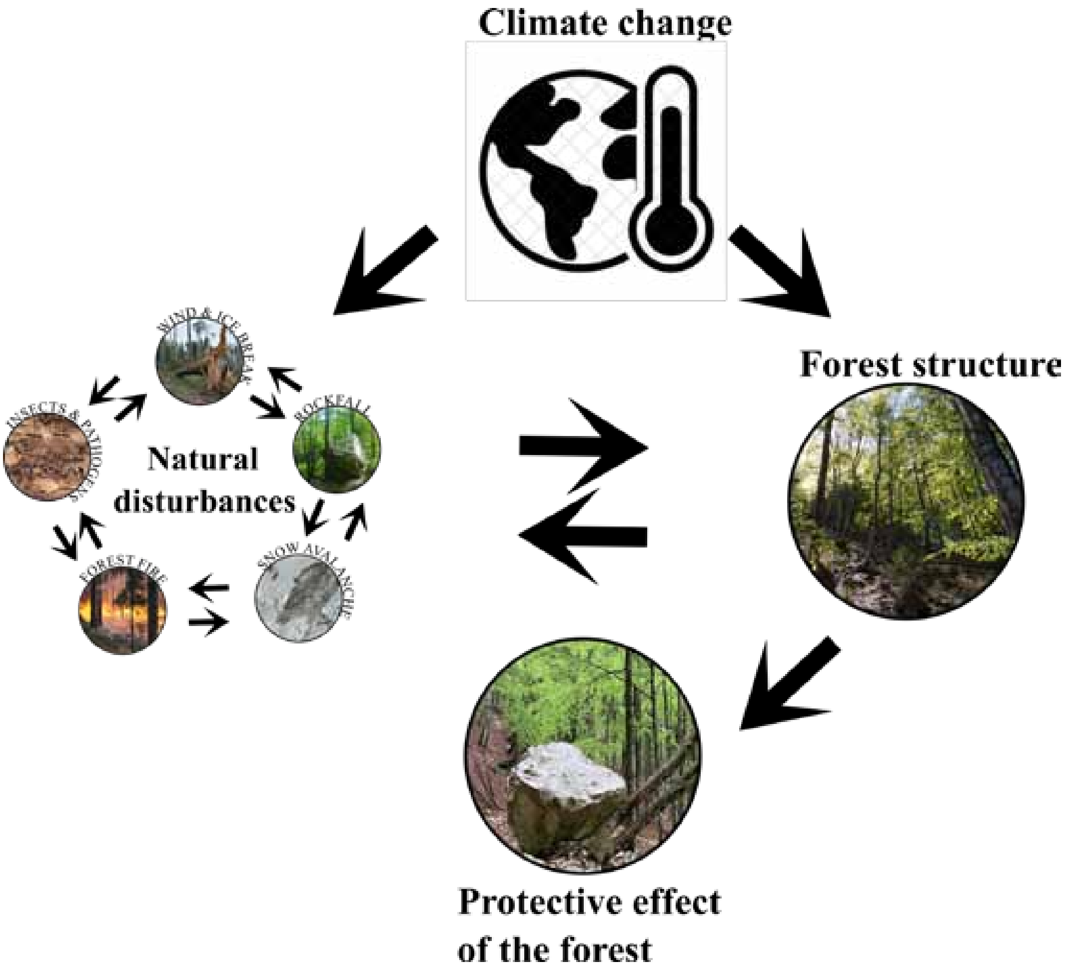

Fig. 3: Climate change can influence natural disturbances and forest structure through direct, indirect and mutual effects. Natural disturbances interact with each other and can change forest structure and composition. In turn, forest structure and composition influence natural disturbances regimes. All climate change influences, whether direct or indirect, change forest structure and composition, which directly influences the protective effect of the forest against avalanches and rockfalls.

Slika 3: Podnebne spremembe lahko vplivajo na naravne motnje in strukturo gozda prek direktnih, indirektnih in vzajemnih učinkov. Naravne motnje imajo medsebojni vpliv in lahko spremenijo strukturo in zgradbo gozda. Hkrati pa lahko struktura in zgradba gozda vplivata na režim naravnih motenj. Vsi učinkih podnebnih sprememb, bodisi direktni bodisi indirektni, lahko spremenijo strukturo gozda in tako vplivajo na varovalni učinek gozda pred snežnimi plazovi in skalnimi podori.

Table 1: Influence of natural disturbances on forest stand parameters of protection forest against a) avalanches and b) rockfalls. Different effects on the protection function of forest against avalanches are indicated as follows: (+) positive effect (increase), (-) negative effect (reduction), (0) no effect, (?) effect unclear.

Preglednica 1: Vpliv naravnih motenj na sestojne parametre gozdov, ki varujejo pred a) snežnimi plazovi in b) skalnimi podori. V preglednici so predstavljeni učinki naravnih motenj na sestojne parameter z vidika varovalnega učinka pred snežnimi plazovi: (+) pozitiven učinek, (-) negativen učinek, (0) brez učinka, (?) učinek neznan.

avalanches / *snežni plazovi*

Stand parameter *Sestojni parameter* → Natural disturbance *Naravna motnja* ↓	canopy cover *sklep sestoja*	species composition *vrstna sestava*	surface roughness *hrapavost površja*	tree size relative to snow depth *velikost drevesa glede na debelino snežne odeje*	stem density *gostota dreves*	gap size *velikost vrzeli*	DBH distribution *debelinska struktura*
forest fire *gozdni požar*	-	-	-	-	-	-	-
windthrow *vetrolom*	-	-	+	-	-	-	-
ice and snow break *žledolom in snegolom*	-	-	+	-	-	-	-
avalanches *snežni plazovi*	-	-	+	-	-	-	-
rockfalls *skalni podori*	-	-	+	-	-	-	-
insects *insekti*	-	-	0, +	-	-	-	-
pathogens *patogeni*	-	-	?, 0	-	-	-	-

rockfalls / *skalni podori*

Stand parameter *Sestojni parameter* → Natural disturbance *Naravna motnja* ↓	trees in release areas *drevesa v območju proženja*	species composition *vrstna sestava*	surface roughness *hrapavost površja*	length of the forested part of the slope *dolžina pobočja poraščena z gozdom*	stem density *gostota dreves*	gap length *velikost vrzeli*	DBH distribution *debelinska struktura*
forest fire *gozdni požar*	-, 0	-	-	-	-	-	-
windthrow *vetrolom*	-, 0	-	+	-	-	-	-
ice and snow break *žledolom in snegolom*	-, 0	-	+	-	-	-	-
avalanches *snežni plazovi*	-, 0	-	+	-	-	-	-
rockfalls *skalni podori*	-, 0	-	+	-	-	-	-
insects *insekti*	-, 0	-	0, +	-	-	-	-
pathogens *patogeni*	-, 0	0, -	0, -	-	-	-	-

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 at., 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; Jactel 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 DISSCUSSION

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 particular 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 natural disturbances depends on i) the scale and intensity of the natural disturbance, ii) the resistance and resilience of the forest stand and iii) post-disturbance management (Bebi et al., 2015). In order to sustain a robust protective effect in the face of natural disturbances, the management of protection forest should increase forest resilience and elasticity by favoring species and structural diversity (e.g. mixed forest), adequate regeneration and the presence of coarse woody debris (Brang and Lässig, 2000; Brang, 2001; Jactel et al., 2017).

In this article the influence of abiotic and biotic disturbances on the protective effect of forest against avalanches and rockfalls is assessed indirectly, through changes in forest stand structure (e.g. gaps length, stem density) and forest cover. While our understanding of the influence of each individual disturbance on the ecosystem may be relatively well understood, the relationship between the onset and magnitude of different disturbance events of different origin (abiotic or biotic) remains understudied (with the possible exception of bark beetle outbreaks after abiotic disturbance - e.g. Kulakowski and Veblen, 2007; Seidl et al., 2011b; Simard et al., 2011; Temperli et al., 2013; Bebi et al., 2017). Both negative and positive feedback between disturbances may become important factors to consider in the future (Buma, 2015; Bebi et al., 2017). Researching cascading effects between disturbances could be done by integrating data on natural disturbances into risk analysis and coupling forest dynamics models with natural hazard models in order to better understand the protective effect of forest in the face of disturbances (Maroschek et al., 2015; Moos et al., 2017).

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. Varovalni učinek gozdov pri zmanjšanju pojavljanja in širjenja naravnih nevarnosti je v glavnem odvisen od sestojne zgradbe gozda. Ekosistemsko upravljanje varovalnih in zaščitnih gozdov stremi k ohranjanju odpornosti in stabilnosti ekosistema, večinoma v smislu vzdrževanja strukture in funkcije ekosistema. Abiotske in biotske motnje so naravni proces v alpskih gozdovih, njihov vpliv pa se najbolj jasno kaže v spremenjeni strukturi in funkciji gozdnih ekosistemov. Zaradi delovanja abiotskih in biotskih motenj je spremenjen varovalni učinek gozda pred snežnimi plazovi in skalnimi podori. V tem preglednem članku je predstavljen vpliv glavnih abiotskih (gozdni požari, vetrolom, snegolom, žled, snežni plazovi in skalni podori) in biotskih (insekti in patogeni) motenj na varovalni učinek gozdov 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 vrzeli, 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. sestojnega parametra). Vse obravnavane naravne motnje negativno vplivajo na varovalni učinek pred skalnimi podori z vidika spremembe gostote sestoja, dolžine vrzeli, 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, velikosti vrzeli 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 snežnimi plazovi. Ugotovitve, predstavljene v članku, so zaradi neraziskanosti vplivov pomanjkljive in v določenem delu hipotetične, saj manjkajo študije, ki bi preučevale 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 na frekvenco kot jakost naravnih motenj. Za upravljanje z gozdovi, 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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9 REFERENCES

9 VIRI

Albrecht A., Hanewinkel M., Bauhus J., Kohnle U. 2010. How does silviculture affect storm damage in forests of south-western Germany? Results from empirical modeling based on long-term observations. European Journal of Forest Research, 131: 229–247.

Alpine strategy for adaptation to climate change in the field of natural hazards. Developed by the Platform on Natural Hazards of the Alpine Convention PLANALP. Bern, Switzerland: 20 p.

Ancelin P., Barthelon C., Berger F., Cardew M., Chauvin C., Courbaud B., Descroix L., Dorren L., Fay J., Gaudry P., Gauquelin X., Genin J.R., Joud D., Loho P., Mermin É., Plancheron F., Prochasson A., Rey F., Rubeaud D., Wlérick L. 2006. Guide des sylvicultures de montagne: Alpes du Nord françaises. Gestion des territoires - CemOA: 136 p.

Ascoli D., Castagneri D., Valsecchi C., Conedera M., Bovio G., 2013. Post-fire restoration of beech stands in the Southern Alps by natural regeneration. Ecological Engineering, 54: 210–217.

Attiwill P.M. 1994. The disturbance of forest ecosystems: The ecological basis for conservative management. Forest Ecology and Management, 63: 247–300.

Axelson J.N., Alfaro R.I., Hawkes B.C. 2010. Changes in stand structure in uneven-aged lodgepole pine stand impacted by mountain pine beetle epidemics and fires in central British Columbia. Forestry Chronicle, 86: 87–99.

Baral H., Wanggi J, Bhatta L.D., Phuntsho S., Sharma S., Paudayl L., Zarandian A., Sears R., Sharma R., Dorji T., Artati Y. 2017. Approaches and tools for assessing mountain forest ecosystem services. (Working Paper, 235). Bogor, Indonesia, CIFOR: 21 p.

Bartelt P., Stöckli V. 2001. The influence of tree and branch fracture, overturning and debris entrainment on snow avalanche flow. Annals of Glaciology, 21: 209–216.

Battisti A., Stanstny M., Netherer S., Robinet C., Schopf A., Roques A., Larsson S. 2005. Expansion of geographic range in the pine processionary moth caused by increased winter temperatures. Ecological Applications, 15, 6: 2084–2096.

Bebi P., Kienast F., Schönenberger W. 2001. Assessing structures in mountain forests as a basis for investigating the forests dynamics and protective function, Forest Ecology and Management, 145, 1–2: 3–14.

Bebi P., Kulakowski D., Rixen C. 2009. Snow avalanche disturbances in forest ecosystems - State of research and implications for management. Forest Ecology and Management, 257, 9: 1883–1892.

Bebi P., Putallaz J., Frankhauser M., Schmid U., Schwitter R., Gerber W. 2015. Die Schutzfunktion in Windwurfflächen. Swiss Forestry Journal, 166: 168–176.

Bebi P., Seidl R., Motta R., Fuhr M., Firm D., Krumm F., Condera M., Ginzler C., Wohlgemuth T., Kulakowski D. 2017. Changes of forest cover and disturbance regimes in the mountain forests of the Alps. Forest Ecology and Management, 338: 43–56.

Beniston M. 2001. The effect of global warming on mountain regions: A Summary of the 1995 report of the Intergovernmental Panel on Climate Change. In: Global change and protected areas. Visconti G., Beniston M., Ianovelli E.D., Varba D. (eds.). (Advances in Global Change Research). Dordrecht, Springer: 155–185.

Berger F., Quetel C., Dorren L.K.A. 2002. Forest: a natural protection mean against rock- falls, but with which efficiency? In: Proceedings of the International Congress. Interpravent 2002 in the Pacific Rim - Matsumoto, Japan. Congress Publication, 2: 815–826.

Berger F., Dorren L., Kleemayr K., Maier B., Planinšek Š., Bigot C., Bourrier F., Jancke O., Toe D., Cerbu G. 2013. Eco-enginerring and protection forests against rockfalls and snow avalanches. In: Management strategies to adapt alpine space forests to climate risks. Cerbu G. (ed.). InTech. https://www.intechopen.com/books/management-strategies-to-adapt-alpine-space-forests-to-climate-change-risks/eco-engineering-and-protection-forests-against-rockfalls-and-snow-avalanches (24.03.2019)

Berryman A.A. (ed.). 1988. Dynamics of forest insect populations: patterns, causes, implications. (Population Ecology). Pullman, Washington State University, Springer: 604 p.

Bragg D.C., Shelton M.G., Zeide B. 2003. Impacts and management implications of ice storms on forests in the southern United States. Forest Ecology and Management, 186: 99–123.

Brang P., Lässig R. 2000. Restoring protection against natural hazards in European mountain forests after wind disturbance: how much human interference? In: Conference: XXI IUFRO World Congress, Kuala Lumpur, 1, 7–12: 327–338.

Brang P. 2001. Resistance and elasticity: Promising concepts for the management of protection forests in the European Alps. Forest Ecology and Management, 145: 107–119.

Brang P., Schönenberger W., Ott E. 2001. Forests as protection from natural hazards. In: The Forest Handbook Vol. 2. Evans J. (ed.). Oxford, Blackwell Science: 53–81.

Brang P., Schönenberger W., Frehner M., Schwitter R., Thormann J.-J., Wasser B. 2006. Management of protection forests in the European Alps: an overview. Forest Snow and Landscape Research, 80, 1: 23–44.

Bründl M., Schneebeli M., Flühler H. 1999. Routing of canopy drip in the snowpack below a spruce crown. Hydrological Processes, 13: 49–58.

Buma B. 2015. Disturbance interactions: Characterization, prediction, and the potential for cascading effects. Ecosphere, 6: 1–15.

Castebrunet H., Eckert N., Giraud G., Durand Y., Morin S., 2014. Projected changes of snow conditions and avalanche activity in a warming climate: the French Alps over the 2020-2050 and 2070-2100 periods. The Cryosphere, 8, 5: 1673–1697.

Casteller A., Häfelfinger T., Cortés Donoso E., Podvin K., Kulakowski D., Bebi P. 2018. Assessing the interaction between mountain forests and snow avalanches at Nevados de Chillán, Chile and its implications for ecosystem-based disaster risk reduction. Natural Hazards and Earth System Sciences, 18: 1173–1186.

Coates K.D., Burton P.J. 1997. A gap-based approach for development of silvicultural systems to address ecosystem management objectives. Forest Ecology and Management, 99: 337–354.

Collet C., Piboule A., Leroy O., Frochot H. 2008. Advance *Fagus sylvatica* and *Acer pseudoplatanus* seedlings dominate tree regeneration in a mixed broadleaved former coppice-with- standards forest. Forestry, 81: 135–150.

Conedera M., Cesti G., Pezzatti G.B., Zumbrunnen T., Spinedi F. 2006. Lightning induced fires in the Alpine region: an increasing problem. In: Fifth International Conference on Forest Fire Research. Vegas D.X. (ed.). University of Coimbra: 1–9.

Conedera M., Lucini L., Valese E., Ascoli D., Pezzatti G. 2010. Fire resistance and vegetative recruitment ability of different deciduous trees species after low- to moderate-intensity surface fires in southern Switzerland. In: Proceedings of the VI International Conference on Forest Fire Research: 14 p.

Coons C.F. 1999. Effect of ice storm damage and other stressors on sugar bush health and sap productivity - literature review and synthesis. In: Eastern Ontario Model Forest Information Report: 91 p.

Cook B.I., Smerdon J.E., Seager R., Coats S. 2014. Global warming and 21st century drying. Climate Dynamics, 43: 2607–2627.

Cordonnier T., Courbaud B., Berger F., Franc A. 2008. Permanence of resilience and protection efficiency in mountain Norway spruce forest stands: a simulation study. Forest Ecology and Management, 256, 3: 347–354.

Dale V.H., Joyce L.A., Mcnulty S., Ronald P., Matthew P.A., Flanningan M.D., Hanson P.J., Irland L.C., Lugo A.E., Peterson C.J., Simberloff D., Swanson F.J., Stocks B.J., Wotton B.W. 2001. Climate change and forest disturbances: Climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. BioScience, 51, 9: 723–734.

De Leo G.A., Levin S.A. 1997. The multifaceted aspects of eco- system integrity. Conservation Ecology, 1, 1. http://www.consecol.org/vol1/iss1/art3/ (11. 09. 2019)

Díaz-Yáñez O., Mola-Yudego B., González-Olabarria J.R. 2019. Modelling damage occurrence by snow and wind in forest ecosystems. Ecological Modelling, 408: 1–10.

Donat M.G., Leckebusch G.C., Wild S., Ulbrich, U. 2011. Future changes in European winter storm losses and extreme wind speeds inferred from GCM and RCM multimodel simulations. Natural Hazards and Earth System Sciences, 11: 1351–1370.

Dorren L.K.A., Berger F., Imeson A.C., Maier B., Rey F. 2004. Integrity, stability and management of protection forests in the European Alps. Forest Ecology and Management, 195, 1–2: 165–176.

Dorren L.K.A., Berger F. 2005. Stem breakage of trees and energy dissipation during rockfall impacts. Tree Physiology, 26: 63–71.

Dorren L.K.A., Berger F., Hir C., Mermin E., Tardiff P. 2005. Mechanisms, effects and management implications of rockfall in forests. Forest Ecology and Management 215: 183–195.

Dorren L.K.A., Berger F. 2006. Panarchy and sustainable risk prevention by managing protection forests in mountain areas. In: RISK21- Coping with Risks due to Natural Hazards in the 21st Century. 2006. Amman W.J., Dannenmann S., Vulliet L. (eds.). London, Taylor and Francis Group: 203–214.

Dorren L.K.A. 2016. Rockyfor3D (v5.2) revealed - Transparent description of the complete 3D rockfall model. ecorisQ paper (www.ecorisq.org): 32 p.

Dupire S., Bourrier F., Monnet J.-M., Bigot S., Borgniet L., Berger F., Curt T. 2016. The protective effect of forests against rockfalls across the French Alps: influence of forest diversity. Forest Ecology and Management, 382: 269–279.

Dupire S., Curt T., Bigot S., Fréjaville T. 2019. Vulnerability of forest ecosystems to fire in the French Alps. European Journal of Forest Research, 138, 5: 813–830.

Evangelista P.H., Kumar S., Stohlgren T.J., Young N.E. 2011. Assessing forest vulnerability and the potential distribution of pine beetles under current and future climate scenarios in the Interior West of the US. Forest Ecology and Management, 262: 307–316.

Feistl T., Bebi P., Hanewinkel M., Bartelt P. 2013. The role of slope angle, ground roughness and stauchwall strength in the formation of glide-snow avalanches in forest gaps. In: International snow science workshop proceedings 2013. Naiim- Bouvet F., Durand Y., Lambert R. (eds.).: 760–765.

Feistl T., Margreth S., Bebi P., Bartelt P. 2014. Forest damage by wet and powder snow avalanches. In: International Snow Science Workshop, Banff: 657–664.

Feistl T., Bebi P., Christen M., Margreth S., Diefenbach L., Bartelt P. 2015. Forest damage and snow avalanche flow regime. Natural Hazards Earth System Sciences, 15: 1275–1288.

Franklin J.F., Shugart H.H., Harmon M.E. 1987. Tree death: Cause and consequence. BioScience, 37, 8: 550–556.

Franklin J.F., Lindenmayer D.B., Thornburgh D.A., Pelt R., Van Chen J., Spies T.A., Carey A.B., Shaw D.C., Berg D.R., Harmon M.E., Keeton W.S., Bible K. 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. Forest Ecology and Management, 155, 1–3: 399–423.

Frelich L.E. 2002. Forest Dynamics and Disturbance Regimes: Studies from Temperate Evergreen - Deciduous Forests. Cambridge, Cambridge University Press: 280 p.

Frey W., Thee P. 2002. Avalanche protection of windthrow areas: A ten year comparison of cleared and uncleared starting zones. Forest Snow and Landscape Research, 77, 1: 89–107.

Garbelotto M., Gonthier P. 2013. Biology, epidemiology, and control of Heterobasidion species worldwide. Annual Review of Phytopathology, 51, 1: 39–59.

Germain D., Filion L., Hétu B. 2006. Snow avalanche activity after fire and logging disturbances, northern Gaspé Peninsula, Quebec, Canada. Canadian Journal of Earth Sciences, 42, 12: 2103–2116.

Gonthier B.P., Brun F., Lione G., Nicolotti G. 2012. Modelling the incidence of *Heterobasidion annosum* butt rots and related economic losses in alpine mixed naturally regenerated forests of northern Italy. Forest Pathology, 42, 1: 57–68.

Graham R.T., McCaffrey S.M. 2003. Influence of forest structure on wildfire behaviour and the severity of its effects. (Miscellaneous Publication). Washington, DC, USDA Forest Service: 12 p.

Harrington R., Fleming R.A., Woiwod I.P. 2001. Climate change impacts on insect management and conservation in temperate regions: can they be predicted? Agricultural and Forest Entomology, 3: 233–240.

Harvey B.J., Donato D.C., Romme W.H., Turner M.G. 2013. Influence of recent bark beetle outbreak on fire severity and postfire tree regeneration in montane Douglas-fir forests. Ecology, 94: 2475–2486.

Heurich M. (ed.). 2001. Forest dynamics in mountain forests after windthrow and bark beetle attack. Wissen-schaftliche Reihe Nationalpark Bayerischer Wald 14: 182 p.

Hlasny T., Kristek S., Holusa J., Trombik J., Urbancova N. 2011. Snow disturbances in secondary Norway spruce forests in Central Europe: regression modeling and its implications for forest management. Forest Ecology and Management, 262: 2151–2161.

Holtmeier F.K. 2009. Mountain timberlines - ecology, patchiness, and dynamics. Dordrecht, Springer: 438 p.

Holtmeier F.K. 2015. Animals' influence on the landscape and ecological importance, Natives, Newcomers, Homecomers. Dordrecht, Springer: 489 p.

Holtmeier F.K., Broll G. 2018. Subalpine forest and treeline ecotone under the influence of disturbances: A review. Journal of Environmental Protection, 9: 815–845.

Horvat A., Zemljič M. 1998. Protierozijska vloga gorskega gozda (Mountain forest as a countererosion factor). In Gorski Gozd. Diaci J. (ed.). Ljubljana, Biotehniška fakulteta, Oddelek za gozdarstvo in obnovljive gozdne vire: 411–424.

Imbeck H. 1987. Schneeprofile im Wald. Winterberichte des Eidg, Instituts für Schnee - und Lawinenforschung Davos, 50: 177–183.

IPCC 2014. Climate Change 2014: Synthesis Report of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva

Irland L.C. 1998. Ice storm 1998 and the forests of the Northeast: A Preliminary assessment. Journal of Forestry, 96, 9: 32–40.

Jactel H., Petit J., Desprez-Loustau M.L., Delzon S., Piou D., Battisti A., Koricheva J., 2012. Drought effects on damage by forest insects and pathogens: A meta-analysis. Global Change Biology, 18, 267–276.

Jactel H., Bauhus J., Boberg J., Bonal D., Castagneyrol B., Gardiner B., Gonzalez-Olabarria J.R., Koricheva J., Meurisse N., Brockerhoff E.G. 2017. Tree diversity drives forest stand resistance to natural disturbances. Current Forestry Reports, 3: 223–243.

Jahn J. 1988. Entwaldung und Steinschlag. In: International Congress Interpraevent, Graz. Conference Proceedings, 1: 185–198.

Jancke O., Dorren L.K.A., Berger F., Fuhr M., Köhl M. 2009. Implications of coppice stand characteristics on the rockfall protection function. Forest Ecology and Management, 259, 1: 124–131.

Johnson E. 1987. The relative importance of snow avalanche disturbance and thinning on canopy plant populations. Ecology, 68: 43–52.

Kashian D., Turner M., Romme W., Lorimer C. 2005. Variability and convergence in stand structural development on a fire-dominated Subalpine Landscape. Ecology, 86: 643–654.

Klopčič M., Poljanec A., Gartner A., Bončina A., 2009. Factors related to natural disturbances in mountain Norway spruce (*Picea abies*) forests in the Julian Alps. Ecoscience, 16, 1: 48–57.

Köster K., Voolma K., Jõgiste K., Metslaid M., Laarmann D. 2012. Assessment of tree mortality after windthrow using photo-derived data. Annales Botanici Fennici, 46, 4: 291–298.

Kramer K., Brang P., Bachofen H., Bugmann H., Wohlgemuth T. 2014. Site factors are more important than salvage logging for tree regeneration after wind disturbance in Central European forests. Forest Ecology and Management, 331: 116–128.

Kraüchi N., Brang P., Schönenberger W. 2000. Forests of mountainous regions: gaps in knowledge and research needs. Forest Ecology and Management, 132, 1: 73–82.

Kulakowski D., Rixen C., Bebi P. 2006. Changes in forest structure and in the relative importance of climatic stress as a result of suppression of avalanche disturbances. Forest Ecology and Management, 223, 1–3: 66–74.

Kulakowski D., Veblen T.T. 2007. Effect of prior disturbances on the extent and severity of wildfire in Colorado subalpine forests. Ecology, 88, 3: 759–769.

Kulakowski D., Bebi P., Rixen C. 2011. The interacting effects of land use change, climate change and suppression of natural disturbances on landscape forest structure in the Swiss Alps. Oikos, 120, 2: 216–225.

Kulakowski D., Jarvis D., Veblen T.T., Smith J. 2012. Stand-replacing fires reduce susceptibility to mountain pine beetle outbreaks in Colorado. Journal of Biogeography, 39: 2052–2060.

Kupferschmid Albisetti A.D., Brang P., Schönenberger W., Bugmann H. 2003. Decay of *Picea abies* snag stands on steep mountain slopes. Forestry Chronicle, 79, 3–4: 247–252.

Lange H., Økland B., Krokene P. 2006. Thresholds in the life cycle of the spruce bark beetle under climate change. Interjournal for Complex Systems, 1648: 1–10.

Lausch A., Fahse L., Heurich M. 2011. Factors affecting the spatio-temporal dispersion of *Ips typographus* (L.) in Bavarian Forest National Park: a long-term quantitative landscape-level analysis. Forest Ecology and Management, 261, 2: 233–245.

Lexer M.J., Hönninger K., Scheifinger H., Matulla C., Groll N., Kromp-Kolb H., Schadauer K., Starlinger F., Englisch M. 2002. The sensitivity of Austrian forests to scenarios of climatic change: a large-scale risk assessment based on a modified gap model and forest inventory data. Forest Ecology and Management, 162, 1: 53–72.

Lindner M., Fitzgerald J.B., Zimmermann N.E., Reyer C., Delzon S., van der Maaten E., Schelhaas M.J., Lasch P., Eggers J., van der Maatern-Theunissen M., Suckow F., Psomas A., Poulter B., Hanewinkel M. 2014. Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? Journal of Environmental Management, 146: 69–83.

Lindner M., Maroschek M., Netherer S., Kremer A., Barbati A., Garcia-Gonzalo J., Seidl R., Delzon S., Corona P., Kolström M., Lexer M. J., Marchetti M. 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and Management, 259, 4: 698–709.

Maringer J., Ascoli D., Dorren L., Bebi P., Conedera M. 2016a. Temporal trends in the protective capacity of burnt beech forests (*Fagus sylvatica* L.) against rockfall. European Journal of Forest Research, 135, 4: 657–673.

Maringer J., Ascoli D., Küffer N., Schmidtlein S., Conedera M., 2016b. What drives European beech (*Fagus sylvatica* L.) mortality after forest fires of varying severity? Forest Ecology and Management, 368: 81–93.

Maringer J., Conedera M., Ascoli D., Schmatz D.R., Wohlgemuth T. 2016c. Resilience of European beech forests (*Fagus sylvatica* L.) after fire in a global change context. International Journal of Wildland Fire, 25, 6: 699–710.

Maroschek M., Rammer W., Lexer M.J. 2015. Using a novel assessment framework to evaluate protective functions and timber production in Austrian mountain forests under climate change. Regional Environmental Change, 15, 8: 1543–1555.

Mayer A.C., Stöckli V. 2006. Long-term impact of cattle grazing on subalpine forest development and efficiency of snow avalanche protection. Arctic, Antarctic, and Alpine Research, 37, 4: 521–526.

McClung D.M. 2001. Characteristics of terrain, snow supply and forest cover for avalanche initiation caused by logging. Annals of Glaciology, 32, 1: 223–229.

McClung D.M., Schaerer P.A. 2002. The Avalanche Handbook. Seattle, WA, The Mountaineers Books: 326 p.

Meunier S., Ruel J.C., Laflamme G., Achim A. 2002. Résistance comparée de l'épinette blanche et du sapin baumier au renversement. Canadian Journal of Forest Research, 32: 642–652.

Moos C., Dorren L., Stoffel M., 2017. Quantifying the effect of forests on frequency and intensity of rockfalls. Natural Hazards and Earth System Sciences, 17: 291–304.

Moos C., Bebi P., Schwarz M., Stoffel M., Sudmeier-Rieux K., Dorren L. 2018. Ecosystem-based disaster risk reduction in mountains. Earth-Science Reviews, 177: 497–513.

Moris J., Vacchiano G., Ravetto E.S., Lonati M., Motta R., Ascoli D. 2017. Resilience of European larch (*Larix decidua* Mill.) forests to wildfires in the western Alps. New Forests, 48: 663–683.

Motta R., Haudemand J.C. 2000. Protective forests and silvicultural stability. An example of planning in the Aosta valley. Mountain Research and Development, 20, 2: 74–81.

Nagel T.A., Diaci J., 2006. Intermediate wind disturbance in an old-growth beech-fir forest in southeastern Slovenia. Canadian Journal of Forest Research 36: 629–638.

Netherer S., Schopf A. 2010. Potential effects of climate change on insect herbivores in European forests - General aspects and the pine processionary moth as specific example. Forest Ecology and Management, 259: 831–838.

Newesely C., Tasser E., Spadinger P., Cernusca A. 2000. Effects of land-use changes on snow gliding processes in alpine ecosystems. Basic and Applied Ecology, 1: 61–67.

Nykänen M.L., Peltola H., Quine C., Kellomäki S., Broadgate M. 1997. Factors affecting snow damage of trees with particular reference to European conditions. Silva Fennica, 31, 2: 193–213.

Papaik M.J., Canham C.D, Woods K.D., Latty E. 2005. Effects of an introduced pathogen on resistance to natural disturbance: Beech bark disease and windthrow effects of an introduced pathogen on resistance to. Canadian Journal of Forest Research, 35, 8: 1832–1843.

Patten R.S., Knight D.H. 1994. Snow avalanches and vegetation pattern in Cascade Canyon, Grand Teton National Park, Wyoming, U.S.A. Arctic and Alpine Research, 26, 1: 35–41.

Peltola H., Kilpeläinen A., Gregow H., Strandman H., Kellomäki S., Venäläinen A. 2010. Impacts of climate change on the risk of snow-induced forest damage in Finland. Climate Change, 99: 193–209Perret S., Dol F., Kienholz H. 2004. Rockfalls into forests: Analysis and simulation of rockfall trajectories - considerations with respect to mountainous forests in Switzerland. Landslides, 1: 123–130.

Peterson D.L., Prichard S.J., McKenzie D. 2000. Disturbance in mountain forests. In: Forests in sustainable mountain development: A state of knowledge report for 2000. Task force on forests in sustainable mountain development. Price M.F., Butt N. (eds.). CABI Publishing: 51–58.

Pintar J. 1968. Snežni plazovi: 1. del. Ljubljana, Podjetje za urejanje hudournikov: 49 p.

Pugh E.T., Small E.E. 2012. The impact of pine beetle infes- tation on snow accumulation and melt in the headwaters of the Colorado River. Ecohydrology, 5, 4: 467–477.

Pukkala T., Laiho O., Lähde E. 2016. Continuous cover management reduces wind damage. Forest Ecology Management, 372: 120–127.

Putallaz J.M. 2010. Protection a` long terme contre les avalanches sur les surface de chablis. Etude sur l’efficacite´ me´canique des arbres au sol: M.Sc. thesis. Zurich, ETH, Department of Environmental Sciences: 116 p.

Quine C., Gardiner B. 2007. Understanding how the interaction of wind and trees result in windthrow, steam breakage, and canopy gap formation. In: Plant disturbance ecology - The Process and the Response. Johnston E.A., Miyanishi K. (eds.).: 103–115.

Radtke A., Toe D., Berger F., Zerbe S., Bourrier F. 2014. Managing coppice forests for rockfall protection: Lessons from modeling. Annals of Forest Science, 71, 4: 485–494.

Rammig A., Fahse L., Bugmann H., Bebi P. 2006. Forest regeneration after disturbance: A modelling study for the Swiss Alps. Forest Ecology Management, 222, 1–3: 123–136.

Ravanel L., Magnin F., Deline P. 2017. Impacts of the 2003 and 2015 summer heatwaves on permafrost-affected rock-walls in the Mont Blanc massif. Science of the Total Environment, 609: 132–143.

Robinet C., Roques A. 2010. Direct impacts of recent climate warming on insect populations. Integrative Zoology, 5: 132–142.

Rouault G., Candau J., Lieutier F., Nageleisen L., Martin J., Warzee N. 2006. Effects of drought and heat on forest insect populations in relation to the 2003 drought in Western Europe. Annals of Forest Science, 63: 613–624.

Rudolf-Miklau F., Sauermoser S., Mears A.I. (eds.). 2015. The technical avalanche protection handbook. Berlin, Ernst & Sohn: 430 p.

Sakals M.E., Innes J.L., Wilford D.J., Sidle R.C., Grant G.E. 2006. The role of forests in reducing hydrogeomorphic hazards. Forest Snow and Landscape Research, 80, 1: 11–22.

Schmidt M., Hanewinkel M., Kändler G., Kublin E., Kohnle U. 2010. An inventory-based approach for modeling single-tree storm damage - experiences with the winter storm of 1999 in southwestern Germany. Canadian Journal of Forest Research, 40: 1636–1652.

Schneebeli M., Bebi P., 2004. Snow and Avalanche Control. In: Encyclopedia of Forest Science. Burley J., Evans J., Youngquist J.A. (eds.). Elsevier: 397–402.

Schönenberger W., Wasem U. 1997. Wiederbewaldung einer Waldbrandfläche in der sub- alpinen Stufe bei Müstair. Schweizerische Zeitschrift für Forstwesen, 148, 6: 405–424.

Schönenberger W. 2000. Silvicultural problems in subalpine forests in the Alps. In: Forests in sustainable mountain development: A state of knowledge report for 2000. Task force on forests in sustainable mountain development. Price M.F., Butt N. (eds.). CABI Publishing: 197–203.

Schönenberger W. 2002: Post windthrow stand regeneration in Swiss mountain forests: the first ten years after the 1990 storm Vivian. Forest Snow and Landscape Research, 77, 1–2: 61–80.

Schönenberger W., Noack A., Thee P. 2005: Timber structures against natural hazards in windthrow sites in mountain protection forests. Forest Ecology and Management, 213: 197–208.

Schweizer J., Jamieson B., Schneebeli M. 2003. Snow avalanche formation. Reviews of Geophysics, 41, 4: 1–25.

Schumacher S., Bugmann H. 2006. The relative importance of climatic effects, wildfires and management for future forest landscape dynamics in the Swiss Alps. Global Change Biology, 12, 8: 1435–1450.

Seidl R., Schelhaas M.J., Lindner M., Lexer M.J. 2009. Modelling bark beetle disturbances in a large scale forest scenario model to assess climate change impacts and evaluate adaptive management strategies. Regional Environmental Change, 9, 2: 101–119.

Seidl R., Rammer W., Lexer M.J. 2011a. Climate change vulnerability of sustainable forest management in the Eastern Alps. Climatic Change, 106, 2: 225–254.

Seidl R., Fernandes P.M., Fonseca T.F., Gillet F., Jönsson A.M., Merganičová K., Netherer S., Arpaci A., Bontemps J.D., Bugmann H., González-Olabarria J.R., Lasch P., Meredieu C., Moreira F., Schelhaas M.J., Mohren F. 2011b. Modelling natural disturbances in forest ecosystems: A review. Ecological Modelling, 222, 4: 903–924.

Seidl R., Rammer W., Spies T.A. 2014a. Disturbance legacies increase the resilience of forest ecosystem structure, composition, and functioning. Ecological Applications, 24, 8: 2063–2077.

Seidl R., Schelhaas M., Rammer W., Verkerk P.J. 2014b. Increasing forest disturbances in Europe and their impact on carbon storage. Nature Climate Change, 4: 806–810.

Seidl R., Thom D., Kautz M., Martin-Benito D., Peltoniemi M., Vacchiano G., Wild J., Ascoli D., Petr M., Honkaniemi J., Lexer M.J., Trotsiuk V., Mairota P., Svoboda M., Fabrika M., Nagel T.A., Reyer C.P.O. 2017. Forest disturbances under climate change. Nature Climate Change, 7: 395–402.

Simard M., Romme W.H., Griffin J.M., Turner M.G. 2011. Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? Ecological Monographs, 81: 3–24.

Stoffel M., Schneuwly D., Bollschweiler M., Lievre I., Delaloye R., Myint M., Monbaron M. 2005. Analyzing rockfall activity (1600–2002) in a protection forest - a case study using dendrogeomorphology. Geomorphology, 68: 224–241.

Stoffel M., Huggel C. 2012. Effects of climate change on mass movements in mountain environments. Progress in Physical Geography, 36, 3: 421–439.

Stokes A. 2002. Second year report of the E.U. project Eco-slopes: Eco-engineering and con- servation of slopes for long-term protection against erosion, landslides and storms (QLK5- 2001-00289).

Stokes A., Salin F., Kokutse A.D., Berthier S., Jeannin H., Mochan S., Kokutse N., Dorren L., Abdghani M., Fourcaud T. 2005. Mechanical resistance of different tree species to rockfall in the French Alps. Plant Soil, 278: 107–117.

Stokes A. 2006. Selecting tree species for use in rockfall-protection forests. Forest Snow and Landscape Research, 80, 1: 77–86.

Stokes A., Abdghani M., Salin F., Danjon F., Jeannin H., Berthier S., Kokutse A.D., Frochot H. 2006. Root morphology and strain distribution during overturning failure of trees on mountain slopes. In: Eco- and Ground Bio-engineering: The Use of Vegetation to Improve Slope Stability. Stokes A., Spanos I., Norris J.E., Cammeraat L.H. (eds.). (Developments in Plant and Soil Sciences). Dordrecht, Kluwer Academic Publishers: 420 p.

Storck P., Kern T., Bolton S. 1999. Measurement of differences in snow accumulation, melt and micrometeorology due to forest harvesting. Northwest Science, 73: 87–101.

Sturrock R.N., Frankel S.J., Brown A.V., Hennon P.E., Kliejunas J.T., Lewis K.J., Worrall J.J., Woods A.J. 2011. Climate change and forest diseases. Plant Pathology, 60: 133–149.

Takeuchi Y., Torita H., Nishimura K., Hirashima H. 2011. Study of a large-scale dry slab avalanche and the extent of damage to a cedar forest in the Makunosawa valley, Myoko, Japan. Annals of Glaciology, 52, 58: 119–128.

Teich M., Barlet P., Grêt-Regamey A., Bebi P. 2012. Snow avalanches in forested terrain: Influence of forest parameters, topography, and avalanche characteristics on runout distances. Artic, Antarctic, and Alpine Research, 44, 4: 509–519.

Teich M., Giunta A.D., Hagenmuller P., Bebi P., Schneebeli M., Jenkins M.J. 2019. Effects of bark beetle attacks on forest snowpack and avalanche formation - Implications for protection forest management. Forest Ecology and Management, 438: 186–203.

Temperli C., Bugmann H., Elkin C. 2013. Cross-scale interactions among bark beetles, climate change, and wind disturbances: a landscape modeling approach. Ecological Monographs, 83, 3: 383–402.

Thom D., Seidl R. 2016. Natural disturbance impact on ecosystem services and biodiversity in temperate and boreal forests. Biological Reviews, 91, 3: 760–781.

Ulanova N.G. 2000. The effects of windthrow on forests at different spatial scales: a review. Forest Ecology and Management, 135: 155–167.

Usbeck T., Wohlegmuth T., Pfister C., Volz R., Beniston M., Dobbertin M. 2010. Wind speed measurements and forest damage in Canton Zurich (Central Europe) from 1891 to winter 2007. International Journal of Climatology, 30: 347–358.

Vacchiano G., Berretti R., Mondino E.B., Meloni F., Motta R. 2016. Assessing the effect of disturbances on the functionality of direct protection forests. Mountain Research and Development, 36, 1: 41–55.

Veblen T.T., Hadley K.S., Nel E.M., Kitzberger T., Reid M., Villalba R. 1994. Disturbance regime and disturbance interactions in a Rocky Mountain subalpine forest. The Bark Beetles, Fuels, and Fire Bibliography, 82, 1: 125–135.

Veitinger, J. 2015. Release Aaeas of snow avalanches: New methods and parameters: Doctoral dissertation. University of Zurich: 161 p.

Veitinger J., Sovilla B. 2016. Linking snow depth to avalanche release area size: measurements from the Vallée de la Sionne field site. Natural Hazards and Earth System Sciences, 16, 8: 1953–1965.

Viglietti D., Letey S., Motta R., Maggioni M., Freppaz M. 2010. Snow avalanche release in forest ecosystems: A case study in the Aosta Valley Region (NW-Italy). Cold Regions Science and Technology, 64, 2: 167–173.

Volney W.J.A., Fleming R.A. 2000. Climate change and impacts of boreal forest insects. Agriculture, Ecosystems and Environment, 82, 1–3: 283–294.

Wang I.T., Lee C.Y. 2010. Influence of slope shape and surface roughness on the moving paths of a single rockfall. World Academy of Science, Engineering and Technology, International Journal of Civil and Environmental Engineering, 4, 5: 122–128.

Wasser B., Frehner M. 1996. Wegleitung Minimale Pflegemassnahmen für Wälder mit Schutzfunktion (Guidelines for minimal tending of protection forest). Bern, Bundesamt für Umwelt, Wald und Landschaft (BUWAL).

Weed A.S., Ayres M.P., Hicke J.A. 2013. Consequences of climate change for biotic disturbances in North American forests. Ecological Monographs, 83: 441–470.

Wehrli A., Weisberg P.J., Schönenberger W., Brang P., Bugmann H. 2006. Improving the establishment submodel of a forest patch model to assess the long-term protective effect of mountain forests. European Journal of Forest Research, 126, 1: 131–145.

Wermelinger B. 2004. Ecology and management of spruce bark beetle *Ips typographus* – a review of recent research. Forest Ecolology and Management, 202: 67–82.

White P.S., Pickett S.T.A. 1985. Natural disturbance and patch dynamics: an introduction. In: The Ecology of Natural Disturbance and Patch Dynamics. Picket S.T.A., White P.S. (eds.). New Work, Academic Press: 3–13.

Williams A.P., Abatzoglou J.T. 2016. Recent advances and remaining uncertainties in resolving past and future climate effects on global fire activity. Current Climate Change Reports, 2: 1–14 .

Winkler R., Boon S., Zimonick B., Spittlehouse D. 2014. Snow accumulation and ablation response to changes in forest structure and snow surface albedo after attack by mountain pine beetle. Hydrological Processes, 28, 197–209.

Wohlgemuth T., Schwitter R., Bebi P., Sutter F., Brang P. 2017. Post-windthrow management in protection forests of the Swiss Alps. European Journal of Forest Research, 136: 1029–1040.

Zeibig A., Diaci J., Wagner S. 2005. Gap disturbance patterns of a *Fagus sylvatica* virgin forest remnant in the mountain vegetation belt of Slovenia. Forest Snow and Landscape Research, 79: 69–80.