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ORIGINAL PAPER

Post-windthrow management in protection forests of the Swiss Alps

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Abstract The two storms Vivian (1990) and Lothar (1999) left an area of roughly 9000 ha of fully damaged protection forests in Swiss mountain regions. Given this huge dimension, questions arose on how to manage these areas to keep the protection gap, i.e. the time period with reduced overall protection against natural hazards, short. Quantifications are presented for the stability of lying logs left in place, the frequency of post-disturbance mass movements, and the tree regeneration in windthrow areas. The average height above ground of unsalvaged lying logs decreased from 2.1 m shortly after disturbance to 0.8 m 20 years later. In the period 1990–2014, the number of avalanches in windthrow areas was markedly small, and annual rates of shallow landslides and debris flows in windthrow areas did not differ from rates in comparable undamaged forested areas. Regeneration density rarely exceeded 4000 stems ha^{-1} 20 years post-windthrow at elevations above 1200–1500 m a.s.l. Mean height of tallest trees reached 5.6 m in areas that were cleared and 6.5 m in those left unsalvaged. Trees planted post-windthrow were 1.0–2.4 m taller than naturally regenerated ones. Practitioners rated the protective effect to be acceptable 24 years post-disturbance in only 5 out from 16 observed windthrow areas (31%), with planting trees as the main cause of success. We conclude that in protection forests the regeneration speed after disturbance rarely meets practitioner's expectations in terms of both stem density and stand structure. However, leaving woody debris from wind disturbance in place proved to replace protective effects for an astonishingly long time. An intensive management with salvage logging, planting and even technical constructions seems therefore only inevitable on windthrown areas where risks seem too high based on hazard, damage potential and possible spread of bark beetles to nearby protection forests. A management alternative applicable to many other cases of windthrown protection forests is to plant trees between lying stems.

Keywords Extreme events · Natural regeneration · Planting · Protection gap · Woody debris

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Nomenclature: Lauber et al. (2012)

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Introduction

Winter storms are by far the most severe disturbance agents in forests of whole Europe (Schelhaas et al. 2003; Seidl et al. 2014). They hit western European countries most dramatically, but also episodically produce huge damage in Central and increasingly also in Eastern Europe (Fink et al. 2009). Consequently, mountain forests along the Alpine Arc are also affected. The winter storms Lothar (1999) and Vivian/Wiebke (1990) have been, to-date, not only the most disastrous storm events since 1950 in whole Europe (Gardiner et al. 2013), but also the most disastrous disturbances to Swiss forests during the last 150 years (Usbeck et al. 2010). Both storms hit protection forests in the Alps, i.e. forests that protect people and assets against the impact of natural hazards such as rockfall and snow avalanches (Brang et al. 2001). On slopes above important traffic infrastructures or settlements, post-windthrow management often consisted in salvage harvesting followed by the establishment of costly technical constructions.

After the Vivian/Wiebke event that affected mountain forests more severely than lowland forests, a controversial debate started in Switzerland on how to manage large windthrown forest patches (Schönenberger 2002a). Having been absent for several decades (Pfister 2009), such extensive forest damage with a magnitude of 5 mio m^3 and translating to 4928 ha of windthrown stands (excluding small gap damage; Schüepp et al. 1994) was unknown to practitioners (example of damage patterns: Fig. 1). Of these roughly 50-km^2 windthrown forests, 58.6% or 2888 ha are currently assigned as protection forests (data source: Federal Office of the Environment, December 2015). Nine years later, Lothar completely damaged another 24,148 ha, with 25.6% or 6182 ha of forests with protective function. In summary, adequate management was required for 9070 ha of protection forests with full damage. Due to the ban of clear-cutting in Switzerland since 1902 (Mather and Fairbairn 2000), little was known regarding the natural reforestation potential in large windthrow areas (Schönenberger 2002a) and advice on how to appropriately manage windthrown areas, especially at elevations above 1200–1500 m a.s.l. where shorter growing seasons limit the speed of natural regeneration (Schönenberger 2002a; Wohlgemuth et al. 2002), was not based on clear evidence.

Uncertainties about potential risks after windthrow were particularly high where Vivian and Lothar hit forests with a protective role against natural hazards (Frey et al. 1995; Frey and Thee 2002). While the protective role of intact forests was well known already before 1990 (Zeller 1982) and generally undisputed (Dorren et al. 2005; Wehrli et al. 2007; Vacchiano et al. 2016), experience about short- and long-term post-disturbance effects of lying stems and about succession processes was virtually absent (Schwitter et al. 2015). In order to reduce high risks of natural hazards in wind disturbed protection forests, windthrow areas were usually cleared and re-planted. Additionally, artificial barriers against avalanches and rockfall were constructed at

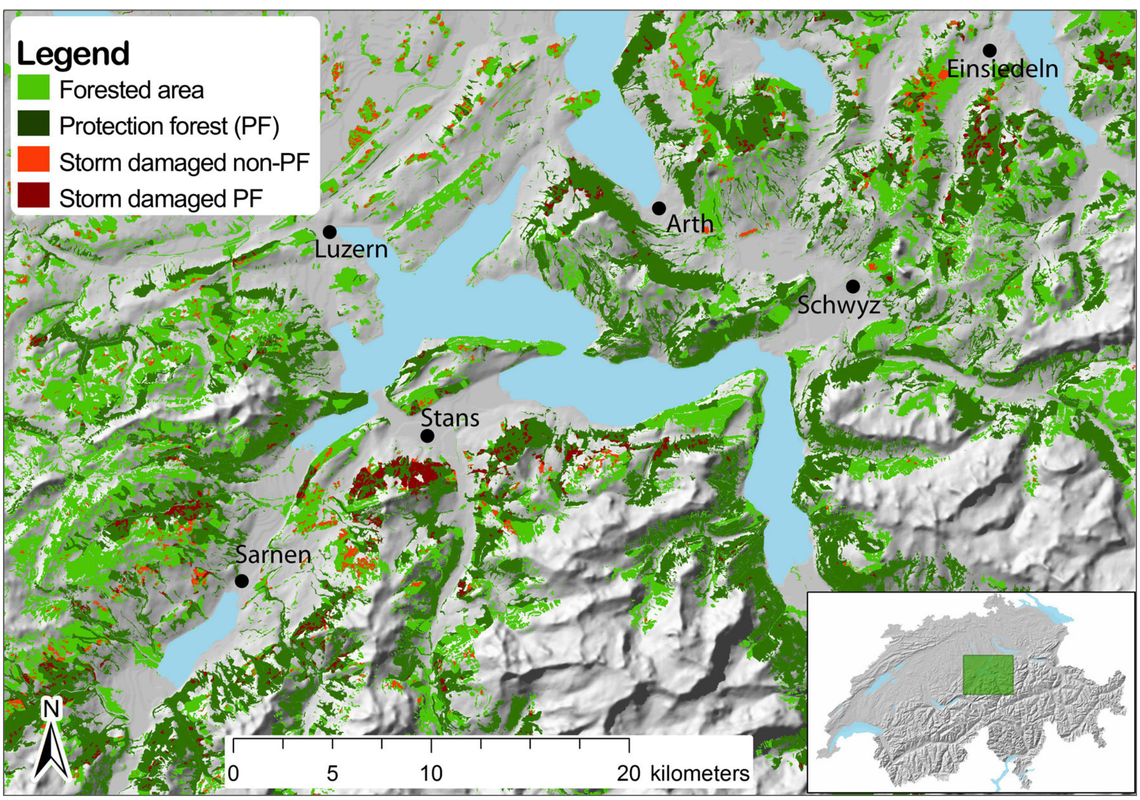

Fig. 1 Storm damage in forests with and without protection function caused by the winter storms Vivian (1990) and Lothar (1999): cut-out of the nationwide map showing the North-Eastern Swiss Alps. Source of protection forest area: SilvaProtect-CH (Losey and Wehrli 2013)

many places (Schüepp et al. 1994), resulting in total costs of more than 200 million Swiss Francs (Holenstein 1994; WSL 2001; Bründl and Rickli 2002). This raised questions about alternative management strategies, which would rely more on natural forest succession (Schönenberger et al. 1995).

A first research initiative started directly after the storm Vivian (Schönenberger et al. 1995; Schönenberger 2002b) and aimed at investigating and comparing the re-colonisation by plant and animal species, and in particular forest regeneration, in cleared, cleared and planted and uncleared windthrow areas of >1 ha size. To our knowledge, this approach was unique and we are not aware of similar research in protection forests using treatment comparisons worldwide.

New research was started shortly after Lothar (1999), which left 2.5 times more damaged wood than Vivian, and two times more protection forests windthrown (data source: Federal Office of the Environment, December 2015).

Under the impression of the big damage, results of the first studies were published (Schönenberger et al. 2002), and awareness grew that the first research approach was not suited to derive general conclusions. The new activities now also addressed the protective effects of unharvested logs acting as a mechanical resistance, the speed of tree regeneration, and the use of new knowledge to better adapt the management to the local conditions prevailing before and after wind damage (Rammig et al. 2007). In particular, some investigations revolved around the question of how much time will pass until a windthrown stand with protective function may regain its function (Fig. 2), a question that is especially relevant at elevations above 1200 m a.s.l. with high shares of coniferous trees (Ott et al. 1997) where the interaction of steep terrain and ample precipitation may result in mass movements—snow avalanches in winter and debris flow or shallow landslides in warmer seasons (Dorren et al. 2004; Humphreys et al. 2015; Olmedo et al. 2015). If all timber is harvested, protective effects need to be re-established by constructions against snow avalanches and rockfall. Conversely, the lying logs themselves, if left in place, offer an alternative option to ensure continuous protection. While this effect decreases over time, it may still be sufficient to bridge the time needed for regrowth of natural or planted regeneration. However, it may take a certain period of time until the full protective effect of the former stand is regained (Brang and Lässig 2000; Bebi et al. 2015). Such a "protection gap" must be taken into account when taking management decisions in protection forests after severe disturbance (BAFU 2008). Obviously, the protection gap is expected to be more pronounced and to last longer at higher elevations with steep slopes, higher precipitation and slower regrowth.

In this paper, we compile results of own published and unpublished studies (Table 1) on regeneration rates and quality after windthrow, and on the protective effect of fallen trees left on site. These results are put into perspective with practitioner's field observations 24 years after the storm Vivian and discussed in the light of the protection gap principle. The following questions are addressed:

- How long do windthrown trees left in place protect against avalanches and rockfall in mountain forests at higher elevations?
- How does the tree regeneration develop in windthrow areas in mountain forests, in terms of density, tree height, and spatial distribution? Which factors limit tree regeneration?
- Which measures can be taken to minimise the temporary loss of protective effects in windthrown mountain forests?

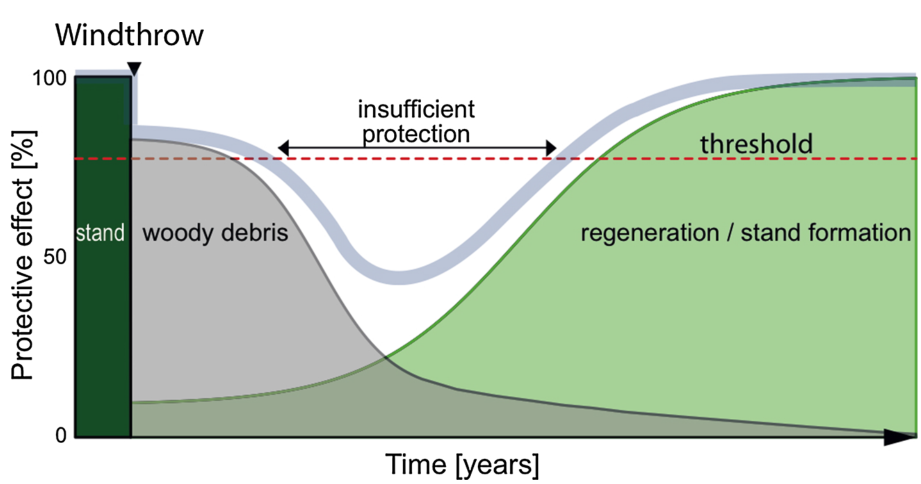

Fig. 2 Development of the protective effect (*blue*; curves are not strictly additive) of the pre-windthrow stand (*green*), woody debris (*grey*), and regenerating trees (*light green*) as a function of time after windthrow in wind damaged mountain forests (adapted from BAFU 2008). A hypothetical threshold indicates the minimum protective effect against avalanches in times of considerable snow accumulation. (Color figure online)

Table 1 Data sources and analyses used to evaluate post-windthrow management in Switzerland

Study subject, storm event	Time and sample description	Source
Windthrow damage		
Vivian (1990, February)	1990, aerial photographs, nationwide	Scherrer (1993)
Lothar (1999, December)	2000, aerial photographs, nationwide	Scherrer Ingenieurbüro (2001)
Terrain stability		
Vivian; height of logs in place	1992, 2001, 2010; case study	Bebi et al. (2015)
Vivian; dislocation of logs in place	1992, 2001, 2009; case study	Bebi et al. (2015)
Vivian; pulling logs in place	1998, 2010; case study	Frey and Thee (2002)
Protective effect		
Vivian; evaluation using 5 criteria	2010, $n = 26$	Bebi et al. (2015)
Vivian; expert evaluation	2014, $n = 16$	Schwitter et al. (2015)
Mass movement events		
Vivian, Lothar; StorMe database	1990–2012; cantons Grisons, Berne	Bebi et al. (2015)
Post-windthrow regeneration		
Vivian, regeneration of trees	1991–2010, time series; $n = 10$	Brang et al. (2015)
Vivian, regeneration of trees	2010, nationwide sample; $n = 24$	Kramer et al. (2014)
Lothar, regeneration of trees	2001–2010, time series; $n = 13$	Brang et al. (2015)
Lothar, regeneration of trees	2010, nationwide sample; $n = 66$	Kramer et al. (2014)

Methods

The stability and protective effects of windthrown trees were evaluated by repeated pulling experiments and a long-term analysis of stem movements in the uncleared windthrow area Cavorgia/Disentis at 1500–1600 m a.s.l. (Frey and Thee 2002; Schönenberger et al. 2005; Bebi et al. 2015). The dislocation of lying stems between 1992 and 2010 was analysed on the basis of high-resolution aerial ortho-photographs (1:4000) from the years 1992, 2001 and 2009 and complementary field measurements in 1992, 2001 and 2010 (Bebi et al. 2015). Pulling experiments on lying stems were conducted in 2010 and outcomes compared to an earlier similar experiment in uncleared windthrow areas in 1998 (Frey and Thee 2002). The forces necessary to move and to finally break the stems were measured and related to forces of snow packs based on long-term snow data from the study area. To evaluate the current state of avalanche protection on windthrow areas, 26 (partly salvage logged) windthrow areas in potential avalanche release areas were selected according to their location in potential risk areas and their representative distribution in the Swiss Alps at elevations ranging from 1170 to 1770 m a.s.l., 20 years after the storm Vivian (Bebi et al. 2015). The protection efficacy was evaluated based on four criteria (Bebi et al. 2015): (1) Crown coverage (DG) according to Meyer-Grass and Schneebeli (1992) and Frehner et al. (2005); (2) number of stems per hectare according to Meyer-Grass and Schneebeli (1992) and Ishikawa et al. (1968) for various stem diameter (dbh) and slope classes; (3) BSH factor: i.e. the ratio of the current tree top height in a stand (height of the 100 thickest trees per ha) and the locally expected maximum snow depth within a 30-year period (with corrections for aspect and for maximum snow depths of a 100-year period (Stoffel et al. 2006); (4) slope-dependent gap length and width according to protection forest management guidelines (Frehner et al. 2005).

In order to relate these investigations on windthrow areas to real natural hazard events, we used cadastre data of such events (snow avalanches, rockfall, shallow landslides, and debris flows) with damaging effect ("StorMe", cadastre database of the cantons Bern and Grison, Federal Office of the Environment BAFU, © 2015.) for the period 1990–2012 (Bebi et al. 2015). We overlaid digitised polygons of these events with digitised windthrow patches of the two storms Vivian and Lothar, counted windthrow areas where such events took place, and grouped the occurrences for each year and each process. For rockfall events, landslides and debris flows, we determined also the rate of the area affected in relation to the whole windthrow area and compared it with the rate of affected area in undamaged forest terrain.

Tree regeneration of seedlings/saplings ≥20 cm was assessed in a network of inventories on permanent plots in 5 mountain and 6 lowland windthrow areas exposed to no intervention, salvage logging or salvage logging and planting (Brang et al. 2015), in regeneration samples in windthrown protection forests (Bebi et al. 2015), and in a nationwide sample of 90 windthrow areas larger than 3 ha and originating from either Vivian ($n = 24$) or Lothar

($n = 66$) (Kramer et al. 2014). The latter sample serves as a nationwide reference of tree regeneration 10 years post-Vivian and 20 years post-Lothar. The three Vivian study sites (Disentis, Pfäfers and Schwanden) served to compare effects of the three treatments mentioned above (Brang et al. 2015). Finally, in 2014, i.e. 24 years after the storm Vivian, practitioners rated the protective effect in 16 windthrow areas with different post-disturbance management and located at elevations from 1450 to 1730 m a.s.l. (Schwitter et al. 2015). The evaluation was based on a decision support handbook (BAFU 2008).

Results

In the case study of Disentis, the average height of fallen Norway spruce (*Picea abies*) trees above ground dropped from 2.1 m 1 year after disturbance to 1.3 m 10 years later and further to 0.8 m 20 years after disturbance (Fig. 3). Despite a high degree of wood decay, stems broke on average only at a force of 16.2 kN after 19 years, corresponding to the pressure of a snow pack of ca. 1.8 m height (Bebi et al. 2015). At that location, such snow packs are expected once or twice in a century (Bebi et al. 2015). Twenty years after Vivian, the average cover of recruitment in 26 windthrow areas at higher elevations was 24% and did not exceed 50% in any of the investigated plots (Bebi et al. 2015). According to the guidelines for protection forests in Switzerland (Frehner et al. 2005; Appendix 1), 50% canopy cover provided by adult trees serves as a threshold requirement for avalanche protection, altogether with small gaps not exceeding 25–60 m of vertical length along slopes. Likewise, other criteria of a protection forest such as minimum tree top height or stem density were also not met in these 26 areas 20 years after the storm Vivian (Bebi et al. 2015). Nevertheless, only five avalanches and 19 rockfall

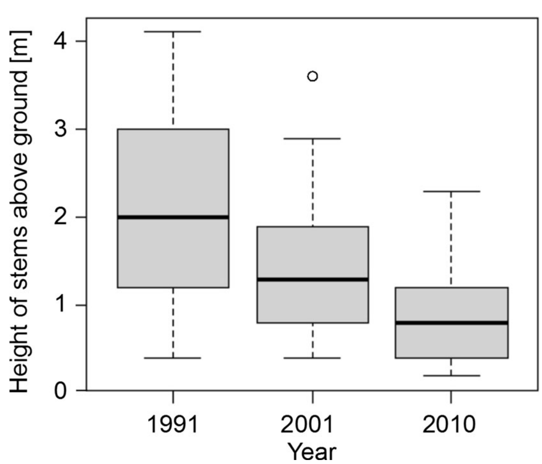

Fig. 3 Height above ground of lying logs after the storm Vivian (1990) in Disentis, Switzerland (data from Bebi et al. 2015)

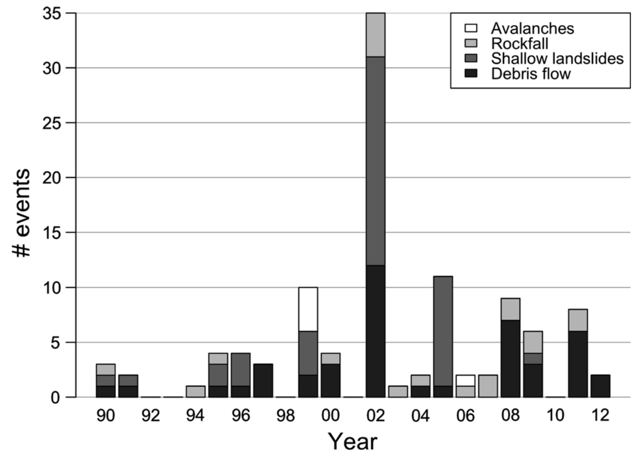

Fig. 4 Number of mass movement events in the period 1990–2012 in windthrow areas after Vivian (1990) and Lothar (1999) of the cantons Bern and Grisons. *Data source*: StorMe cadastral database for extreme events, Federal Office of the Environment BAFU, © 2015

events were observed on the generally very steep Vivian areas between 1990 and 2012 in the cantons Bern and Grisons (Fig. 4). In contrast, shallow landslides (41 events) and debris flows (44 events) originating from windthrow areas were more than two times more frequent than rockfall events. In particular, most shallow landslides occurred in 2002 (12 years after Vivian) and in 2005 (5 years after Lothar). The overlay analysis of landslides, debris flows and rockfall events in and outside of windthrow areas revealed, however, no significant difference between the rates of affected windthrow area compared with the rate of affected area in other forested terrain.

Stem density of regenerating trees varied considerably in large windthrow areas along a wide ecological gradient in Switzerland (Fig. 5), with on average 6000–8000 stems ha^{-1} below 1200 m a.s.l. 10 years post-storm (Lothar; empty circles) and densities falling to <4000 stems ha^{-1} 20 years post-storm (Vivian; filled circles) at elevations above 1500 m a.s.l (Wohlgemuth and Kramer 2015). The percentage of advance regeneration (dotted line) decreased from broadleaved forests of mainly European beech (*Fagus sylvatica*) at lower elevations (mostly Lothar areas) to coniferous forests mainly dominated by Norway spruce at higher elevations (mostly Vivian areas). Expert knowledge suggests 2500–4000 stems ha^{-1} (10–130 cm) as a minimum seedling/sapling density to fulfil the protection function in a future forest (Bühler 2005). However, 50% of the areas across all elevation levels did not reach the number of 4000, and 25% even not 2500 stems ha^{-1}. At higher elevations and 20 years after the storm Vivian, the 10 largest trees per windthrow area reached a height of 6.5 ± 0.9 m (mean ± SE) in areas with no intervention and 5.6 ± 0.5 m in cleared areas, with an average of 2.2 ± 0.5 and 2.0 ± 0.2 m, respectively, if all stems are

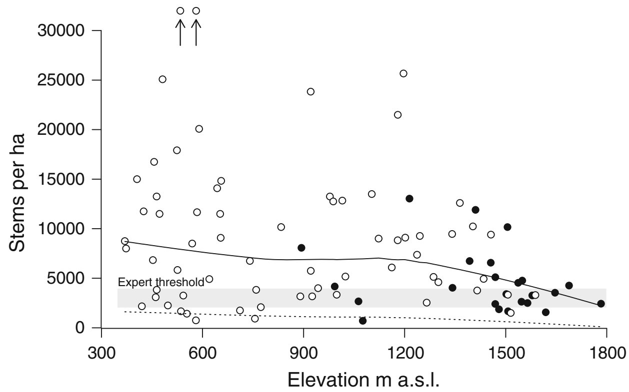

Fig. 5 Elevation versus regeneration densities in windthrow areas in Swiss forests, 10 years after the storm Lothar (*empty circles*, $n = 66$) and 20 years after the storm Vivian (*filled circles*, $n = 24$). Lowess functions indicate the relation between elevation and total regeneration (*solid line*) and advance regeneration (*dotted line*) for all windthrow areas ($n = 90$; data from Kramer et al. 2014). The *grey horizontal bar* marks a minimum density of young trees (10–130 cm tall) to maintain, on the long run, the protective effect (see text)

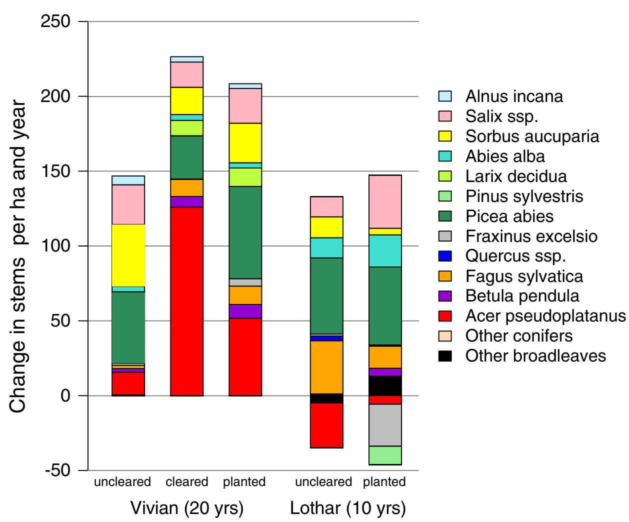

Fig. 6 Average annual change in stem numbers of natural regeneration in 19 windthrow areas, per species, grouped by storm events (Vivian, Lothar) and treatments (uncleared, cleared, cleared & planted; adapted from Brang et al. 2015)

considered. Trees that had germinated prior to windthrow were three times taller than those that germinated afterwards.

Net sapling establishment rates during the first 8 years (Vivian areas) or 10 years (Lothar areas) after the storm represent the change in stem density, resulting from ingrowth and mortality. In Vivian areas, these rates varied from 147 (no intervention) over 208 (cleared and planted) to 226 stems ha^{-1} $year^{-1}$ (cleared), while in Lothar areas rates were around 100 stems ha^{-1} $year^{-1}$ (Fig. 6). The largest increase was observed in Norway spruce, European beech and willow (*Salix* spec.), in Vivian gaps also in sycamore (*Acer pseudoplatanus*) and rowan (*Sorbus aucuparia*).

In the permanent plots of Vivian study sites Disentis, Pfäfers and Schwanden, trees of stand-forming Norway spruce and beech planted shortly after the windthrow were 1.0–2.4 m taller than naturally regenerated trees (Fig. 7). By planting, structural gaps, i.e. places where trees did not establish, could be omitted.

From a practitioner's judgement, the protective effect 24 years after disturbance was acceptable only in five out of 16 windthrow areas (31%). In particular, in four of the five positive cases, planting of trees was used (Fig. 8). In contrast, cleared and no intervention areas with natural regeneration only remained mostly deficient regarding the protective effect.

Discussion

Protective effect of lying stems

Twenty-five years of experiments, measurements and observations in windthrow areas in mountain forests provide a more solid basis for decision support after disturbance events in protection forests compared to the situation right after the storm Vivian in 1990. Our studies in uncleared, cleared and cleared/planted windthrow areas suggest that lying stems (resulting from either breakage or uprooting) provide a considerable protective effect during the first years after a blowdown, with decreasing effect size over time towards a presumed critical stage. Ideally, tree regeneration increasingly replaces the protective effect of the woody debris, but the regeneration process is often too slow. Already early after windthrow research had started, several authors suggested the appearance of such a critical "protection gap period" with reduced overall protection against natural hazards (Brang and Lässig 2000; Frey and Thee 2002), especially if an area is not planted and/or secured with technical constructions. The importance of this protection gap period is also indicated by the failure of most investigated windthrow areas to meet the minimum thresholds of silvicultural guidelines established for the management in protection forests (Frehner et al. 2005) and was also confirmed by the evaluation of practitioners 24 years after the storm Vivian (Fig. 8).

Observations of natural hazard events in windthrow areas since 1990 ideally complement the measurements of stand attributes and regeneration progress at these sites. Our results suggest that a valuation of protection gaps depends on the type of natural hazards. From the small number of avalanche observations in windthrow areas since 1990 (of which none was released in an uncleared site), we infer that lying stems, root plates and stumps after a windthrow create considerable terrain and surface roughness (e.g. Hollaus et al. 2011). This phenomenon has not

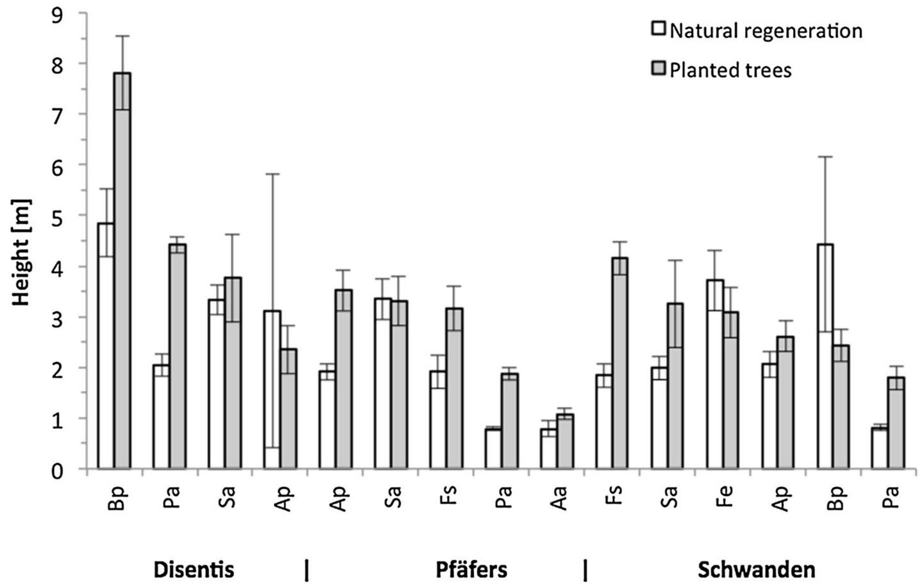

Fig. 7 Average heights of most abundant tree species in 20-year-old windthrow areas (Vivian: $n = 24$): natural regeneration versus planted trees (data from Brang et al. 2015). Aa, *Abies alba*; Ap, *Acer pseudoplatanus*; Bp, *Betula pendula*; Fe, *Fraxinus excelsior*; Fs, *Fagus sylvatica*, Pa, *Picea abies*; Sa, *Sorbus aucuparia*

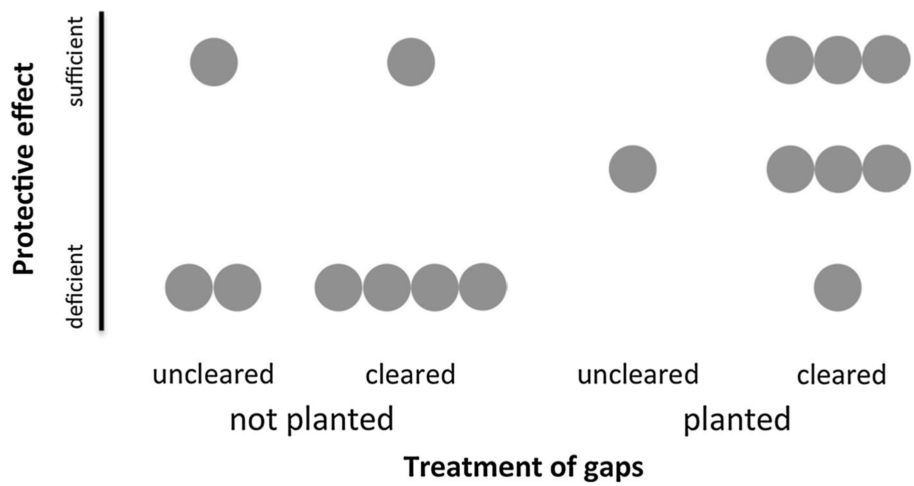

Fig. 8 Protective effect in 16 windthrow areas (*circles*) with different treatments, as subjectively judged 24 years post-storm by mountain forest experts, at elevations ranging from 1450 to 1670 m a.s.l. (data from Schwitter et al. 2015)

yet been sufficiently recognised by practitioners and has not been incorporated in practical guidelines. However, the protective effects of felled trees against rockfall are currently tested in France (Olmedo et al. 2015). The important role of terrain roughness is in line with studies on avalanche release in forests, which show that both terrain roughness and regenerating trees not only contribute to the prevention of avalanche release, but may also reduce the run-out distance of avalanches (Feistl et al. 2014; Teich et al. 2014). The small number of avalanche observations in windthrow areas in the period 1990–2012 could also partly be explained by the singularity and timing of typical “avalanche winters”: There was only one such event since 1990, which occurred only 9 years after Vivian, i.e. when the average effect of the lying stems was still much larger than 20 years post-windthrow (Fig. 4; Bebi et al. 2015). Few observations of rockfall events on windthrow areas (Fig. 4) suggest a similar strong effect of remaining dead wood in combination with post-windthrow regeneration (Schönenberger et al. 2005). This corresponds with other studies, which show that large lying logs may, by increasing the surface roughness, considerably contribute to the protection against rockfall (Gauquelin and Courbaud 2006; Dorren et al. 2015; Fuhr et al. 2015). However, stones that accumulate behind woody debris may be released again in the future once the retaining wood has sufficiently decayed. This process may be indicated by an increasing number of rockfall events observed in older windthrow areas (Fig. 4; Bebi et al. 2015).

Our data provide more evidence for a protection gap related to shallow landslides and debris flows, with clear peaks in the years 2002 mainly on sites affected by Vivian (1990) and 2005 mainly on sites affected by Lothar (1999). This is in line with research on roots, which shows that the root reinforcement of disturbed mountain forests is strongly reduced 2–3 years after the trees have died, and that the original protection will only be restored by the establishment of new roots (Vergani et al. 2014). Again, the occurrence of strong rain events in relation to the age of the windthrow areas needs to be considered in the valuation of protection gap periods. In particular, 2005 was the most catastrophic year regarding flooding for the last 40 years, and strong rain events in 2002 produced the highest economic damage due to debris flow and landslides for the last 40 years (Andres et al. 2015). The length of a post-windthrow protection gap thus not only depends on site conditions and the question of clearing or not, but also on the type and the severity of natural hazard events. In comparison, periods of protection gaps after bark beetle outbreaks—a subject that is not studied in this paper—are likely to appear later due to a delay in both tree mortality and snag decay (Kupferschmid and Bugmann 2005, Bebi et al. 2015).

Regeneration in windthrow areas

Based on the analysis of 90 Swiss windthrow areas, regeneration densities in forests disturbed by wind vary considerably, which can be mainly explained by elevation, substrate and competing vegetation (Kramer et al. 2014). Tree density at higher elevations where protection against natural hazards is the predominant ecosystem service amounts to 5000 stems per ha or less, with a surprisingly low portion of pre-storm regeneration (“advance regeneration”; e.g. Messier et al. 1999) of only about 10% in 20-year-old Vivian areas (Wohlgemuth and Kramer 2015). Such a low number of pre-disturbance regeneration was also found in gaps produced by bark beetle attacks in German mountain forests (Winter et al. 2015), and has likely been caused by the scarcity of regeneration in the pre-disturbance stands, which were often even-aged and dense. On the other hand, the density of advance regeneration strongly depends on microsite conditions (Wohlgemuth et al. 2002) or can be markedly reduced by post-disturbance logging activities (Fischer et al. 2002). Studies in unmanaged forests highlight that tree individuals that germinated before the disturbance have a large impact on forest succession (Svoboda et al. 2010; Nováková and Edwards-Jonášová 2015).

In the Swiss sample, which covered various site conditions, regeneration densities on salvage-logged areas were on average 35% (Lothar gaps) or 92% (Vivian gaps) higher than in windthrow areas where no salvage-logging took place, but due to the large variation the difference was not significant (Kramer et al. 2014). Low average rates of net post-disturbance recruitment of 100–200 stems ha^{-1} $year^{-1}$ (Fig. 8) suggest that fast succession in large windthrow areas is rather an exception and not a process on which management can fully rely.

In analogy to sapling densities, average tree heights in cleared and uncleared windthrow areas did not differ significantly. However, trees that germinated before wind disturbance were on average 3 m taller after 10 years (Lothar areas) and still 1–3 m taller after 20 years (Vivian areas). This lead of about 1–3 m in comparison with post-disturbance regeneration also equals the lead of planted trees in salvaged windthrow areas (Brang et al. 2015). A study in the Šumava National Park, Czech Republic, showed that trees grew fastest after bark beetle outbreak in areas that were clear-cut afterwards. The findings were explained by beneficial open conditions if compared to sites left without intervention (Nováková and Edwards-Jonášová 2015).

We conclude that regeneration densities in windthrow areas with no intervention tend to be smaller than in clear-cut or salvage-logged sites and that the tallest trees are either those germinated before the disturbance event or those planted afterwards. In windthrown forests with important protection function, managers will consider the site-specific regeneration conditions and complete low densities or lacking advance regeneration by planting.

In cleared windthrow areas or in areas with no intervention, pioneer vegetation as well as tall herb communities frequently hampers seedling growth (Wohlgemuth et al. 2002). The effect of competitive exclusion is natural, though unwanted in forests with protective function. This is why mountain forest management opts to avoid rapid vegetation spread by creating only small openings in which reasonable seedling growth is possible while low light levels limit competing herbs and grasses (Brang 1998). While at low elevations, raspberry (*Rubus fruticosus*), bracken (*Pteridium aquilinum*) and other fast-growing species spread in windthrow areas and may competitively exclude other tree individuals for decades (Dodet et al. 2011; Van Couwenberghe et al. 2011; Brang et al. 2015), tall herbs and grasses (e.g. *Calamagrostis* ssp.) can successfully outcompete early tree regeneration at higher elevations (Wohlgemuth et al. 2002) and may retard regeneration up to 50 years (Rammig et al. 2006). If a protective effect needs to be ensured in due time, measures may be taken early after disturbance to facilitate tree regeneration, e.g. tending measures. Otherwise, deadwood regeneration on lying stems will start only 15–20 years after a windthrow (Priewasser et al. 2013) or even later, i.e. after 30–60 years (Zielonka 2006). In forests with much dead wood in advanced decay stages (e.g. old growth or frequently disturbed forests; Jonášová et al. 2010), trees can germinate on this substrate shortly after disturbance, if they are not already present. By contrast, in most managed forests of Central Europe, dead wood is too recent or its volume too small for allowing abundant regeneration on this substrate. For instance, in 2013, dead wood amounted to an average value of 24 m^3 ha^{-1} in Swiss forests (Lachat et al. 2015), and respective values for mountain forests at higher elevations are currently 38 m^3 ha^{-1} (Swiss National Forest Inventory 2014; www.lfi.ch; 23.11.2016).

Many of the studied windthrow areas were, before the disturbance, mono-specific and even-aged stands. The broad diversity of tree species found in natural regeneration (Figs. 6, 7), as well as the mixture of late-successional and pioneer species (Fig. 6), suggests that many options for more diverse future stands exist. This is particularly important in protection forests where management should aim at mixed stands to increase both stand resistance and resilience in the face of disturbances and climatic change (Brang et al. 2008, 2016).

Measures to shorten the protection gap period

The management options in windthrown protection forests have diversified during the last two decades (Fig. 9) as a consequence of a lively debate between practitioners and scientists, e.g. in Switzerland (Angst and Volz 2002; BAFU 2008; Priewasser et al. 2013; Schwitter et al. 2015) and in France (Berger and Rey 2004). When our long-term plots in windthrow areas were established in 1991, salvage logging followed by natural regeneration (Fig. 9a) was only a theoretical management option, since historically, most windthrow areas were salvaged and subsequently planted (Fig. 9d). These measures serve to re-establish the protective effect against natural hazards as fast as possible, while salvage logging alone is intended to prevent follow-up insect calamities (Brang et al. 2006; Schwitter et al. 2015). However, as long as roots have not yet fully decayed, e.g. up to 3 years post-disturbance, shallow landslides may still be prevented by root reinforcement on

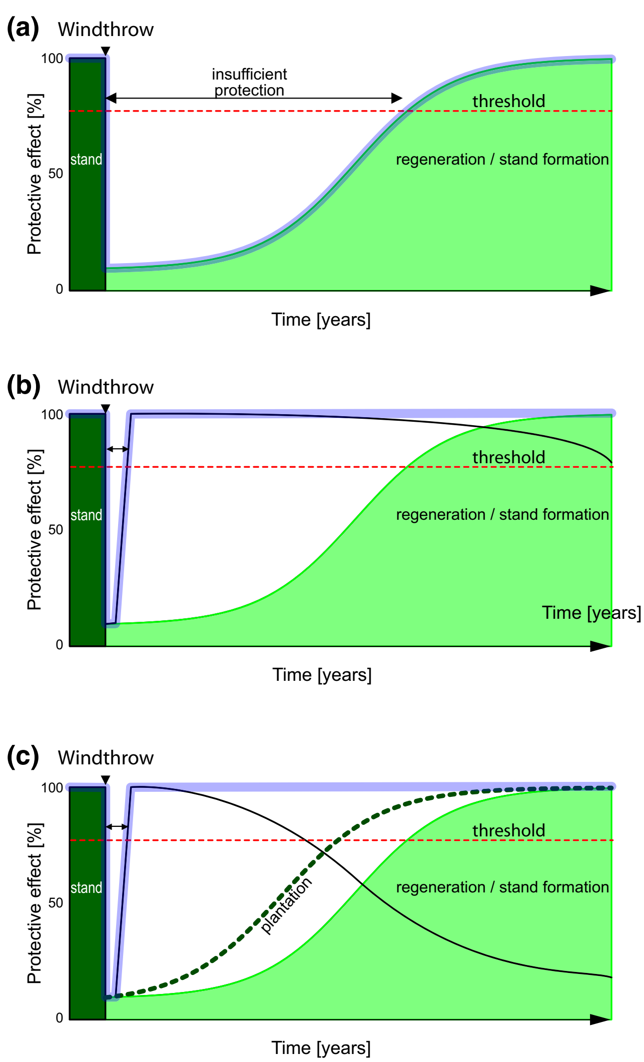

Fig. 9 Schematic development of the protective effect (in *blue*; curves are not strictly additive) in windthrow areas of mountain forests after different treatments: **a** salvage logging, natural regeneration, **b** salvage logging, permanent steel construction, **c** salvage logging, temporary wood construction and plantation, **d** salvage logging, plantation, **e** no salvage logging, **f** no salvage logging, plantation. A pre-disturbance forest stand is presumed to guarantee 100% of protective effect, and the threshold equals a hypothetic required minimum protection. (Color figure online)

cleared slopes. In contrast, the risk of avalanches will immediately be high after harvest. In densely populated regions where the damage potential below windthrown forests is high and the duration of the protection gap period is considered as too long, salvage logging is usually combined with the construction of permanent steel avalanche barriers (Fig. 9b) or temporary wooden avalanche barriers (Fig. 9c). In comparison with wooden constructions, which start to decay after ca. 20–40 years (Schönenberger et al. 2005; BAFU 2008) and are relatively cheap, steel constructions last longer but are extremely costly in establishment and maintenance. In addition, they may be disadvantageous regarding landscape aesthetics (Olschewski et al. 2012).

A management without harvesting and reforestation and/or constructions against natural hazards (Fig. 9e), as tested in our case studies, was uncommon in protection forests of the Alps before 1990. Twenty-five years of building up experience and continued research demonstrate that this management option has the potential to be applied more often in the future, in particular if (1) the damage potential below a windthrow area is low, (2) risks of subsequent bark beetle outbreaks starting from lying stems are acceptable, and (3) advance regeneration and site conditions favour a relatively fast post-windthrow succession.

Where missing advance regeneration and unfavourable site conditions indicate a long-lasting protection gap, and if bark beetles are no matter of concern, we suggest an alternative with no salvaging in combination with planting trees in groups (Fig. 9f) in order to avoid or clearly shorten the period of insufficient protection. Planting trees between lying stems was successful in two of the windthrow areas evaluated by the experts (Fig. 8). This management strategy, which has rarely been applied so far, is technically challenging due to limited accessibility in areas with no intervention and requires considering also the texture of lying logs. The long-term observation of lying logs showed substantial dislocations in steep terrain (Olschewski et al. 2012) that may cause partial destruction of already established regeneration. Also, much experience is needed to optimise the planting in the small scaled microtopography of windthrown areas (Schwitter 1996; Bebi et al. 2015).

Clearing, planting and technical constructions (Fig. 9b–d) are valid management options if the damage potential below a windthrow area is high and additional bark beetle infestations of adjacent stands are expected. Importantly, a decision for the final management measure also needs to consider site-specific conditions that vary widely in mountain forests depending on, e.g. substrate, slope and aspect. More experience and baseline data are needed regarding how lying logs moving downhill affect the density of regenerating trees.

Conclusions

The protective function of mountain forests in the Alps is at risk due to wind disturbance. Hence, the management of wind damaged protection forests should target fast recovery of protective effects to a minimum level. The regeneration speed after disturbance is rarely sufficient to meet practitioner's expectations in terms of both stem density and stand structure. However, if stems are not removed, protective effects of lying logs, though decaying, last for an astonishingly long time. Moreover, the long-lasting effect of terrain roughness seems to be underestimated, given the very low number of follow-up disturbance events like rockfalls and avalanches that have occurred in forests damaged by the storm Vivian in 1990. To conclude, windthrow areas may be managed at low intensity if risks from natural hazards and from bark beetle infestations are acceptable. In this case, logs can be left in place and trees planted between lying stems in order to accelerate forest succession. Conversely, we conclude from low regeneration numbers found at elevations above 1200–1500 m a.s.l. that intensive management with salvage logging, planting and even technical constructions is indicated if hazard risks after windthrow and the damage potential are high.

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