Avalanche protection of windthrow areas: A ten year comparison of cleared and uncleared starting zones

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Abstract
In 1990 storm Vivian destroyed large montane and subalpine protection forests in potential avalanche starting zones. In the first decade after the storm, uncleared areas prevented avalanche release, whereas severe avalanche activity in cleared areas was observed. Down slope movement of lying stems during the first two years was considerable due to branches breaking under snow loads, but later in the first decade the subsequent movement towards the ground surface was relatively small. An experimental application of the calculated maximum snow load with a statistical return period of 30 years on lying stems showed that after 10 years the stems are stable, and are even quite resistant to further movement for up to 30 years. The increasing loss of wood strength after a decade decreases the protection capacity of uncleared parts. This capacity loss must be compensated for by the protective function of upcoming regeneration. If necessary, the partially weakened protection capacity in uncleared areas can be reinforced by installing moderate technical measures. This is an economically very favourable solution since complete clearing involves the inevitable installation of expensive avalanche supporting structures on the whole area.

Keywords: windthrow areas, avalanche starting zones, managing storm damage, protection function, Switzerland

1 Introduction

1.1 To clear or not to clear?

The windthrow damage caused by the storm Vivian in February 1990 made further forest management difficult, especially on steep slopes at higher altitudes where the avalanche protection forests had been destroyed. Where villages or regularly frequented roads were endangered by new potential avalanche tracks, difficult questions of almost Shakespearian dimension arose: To clear (and implement technical protection measures) or not to clear (and rely on the possible protection function of the lying stems)?

Traditionally, windthrow areas have been cleared by the forest service. Cleared slopes in avalanche starting zones used to be reforested after the erection of technical avalanche barriers. In 1990, the enormous amount of windthrow timber combined with falling timber prices promoted the exploration of alternative ideas such as not clearing. The lying stems were expected to provide the protection needed until natural regeneration was strong enough to fulfil the required avalanche protection function.

1.2 Current knowledge

Very little information on the protection capacity of lying stems and only scarce information on the development of natural decay of wood with time was available in 1990.

The following questions of silvicultural but also of socio-economic importance were asked in the 1990s:

- Are lying stems capable of reliably preventing avalanche release?
- What is the influence of snow depth and snow quality?
- Are avalanches in uncleared windthrow areas capable of eroding lying stems in the track? Are stem-carrying avalanches more dangerous than pure snow avalanches?
- How does the decay of the lying stems affect their protection function?

Observations in two test areas of more than 30° inclination showed that in the first few years after the windthrow no avalanches started in uncleared areas, whereas in comparable adjacent cleared areas some avalanches occurred (FREY *et al.* 1995). During these winters, however, there were no extreme snow or avalanche danger conditions, and the maximum snow depth was at most 1.5 m. As for avalanche protection, Vivian had thrown the stems into a generally quite favourable position, and most stems were lying more or less horizontally and intertwined. These facts may explain the good performance of uncleared areas in preventing avalanches.

The lying stems are assumed to act similarly to technical avalanche supporting structures. Therefore the stems were compared to the technical structures dimensioned according to the Swiss Guidelines (BUWAL 1990). For the test areas, the vertical height of supporting structures should be 2.5–3.0 m according to a calculated maximum snow depth with a statistical return period of 100 years. The corresponding distance between two construction lines was determined to be 20–25 m in the slope direction. The analogous height of the stems was estimated between 0.5 m and more than 2.5 m, with the distance between stems much less than 20 m. Root plates were judged as contributing an additional desired increase in the roughness of the terrain. Therefore, the windthrown stems were considered capable of preventing avalanche release.

The height of the lying stems is reduced over time due to the supporting branches breaking and the wood decaying thus reducing the stems protection capacity. In addition, the downhill movement of lying stems was measured with aerial photographs (FREY *et al.* 1995). A comparison of more than 200 objects in the test area "Schwanden" showed the mean movement distances of objects (stems, stumps, root plates) between 1990/91 and 1993 was as follows:

mean movement in horizontal direction:	5 to 10 cm
mean movement in vertical direction:	10 cm
maximum movement in vertical direction:	100 cm

These relatively small movements were not considered important enough to reduce the protection capacity of the lying stems.

Several cantonal Forest Services published reports after the storm Vivian, e.g. Kantonsforstamt Glarus (1995) found there had been no avalanche release in windthrow areas. SCHWITTER (1996) showed that cleared avalanche starting zones in endangered areas had to be provided with wooden supporting structures. In addition, tripods were needed to protect existing regeneration nuclei from snow creeping and gliding. In some parts no clearing was carried out, and the lying stems were used as protection from natural hazards. In the early years after the storm these measures seemed to be successful.

The Swiss Federal Forest Administration published in BUWAL (2000) a decision-support tool for windthrow areas drawing on the knowledge mentioned above and also some preliminary results of the current paper adapted to practical use.

1.3 Hypotheses

This report is based on the following hypotheses:
- In windthrow areas of the subalpine and montane zone, more or less horizontally lying stems in uncleared areas effectively prevent avalanche release for several years or even decades.
- In cleared areas, the frequency and size of avalanches are distinctly greater than in uncleared areas.
- Even extreme snow pressure on lying stems does not induce mixed log-snow avalanches.
- The protection function of the lying stems does not decrease before natural regeneration and/or afforestation becomes effective (cf. SCHÖNENBERGER this issue b).

To clarify these hypotheses, the following data was recorded and analysed:
- Amount and direction of snow forces on lying stems under natural conditions.
- Strength of lying stems compared to snow forces.
- Movement distance of lying stems 10 years after Vivian related to the decay of the stems.
- Information about movements caused by snow forces of stems that have been lying for more than 10 years.

2 Material and methods

2.1 Overview

The following methods were applied:
- Field measurements and observations on snow and snow movements in various windthrow areas were made from 1991 to 2001, including during the severe winter 1998/99 (Section 2.3).
- The snow pressures were calculated based on information gained in test areas (Section 2.4).
- The degree of decay of stems with time and their static strength were estimated (Section 2.5).
- Aerial and terrestrial photographs were taken and analysed (Section 2.6).
- Experiments were performed *in situ* with impact forces on lying stems corresponding to snow pressure (Section 2.7).

2.2 General site descriptions

Many of the observations and measurements were made in selected test plots set up in the general project described by SCHÖNENBERGER (this issue a). For avalanche questions only the steeper test plots could be involved, namely Disentis and Pfäfers.

To predict long-term developments, old windthrow areas were sought for comparison, but without success because the Forest Service had cleared all such plots. In “Scatlè”, a nature reserve owned by Pro Natura Switzerland and run by ETH Zurich, avalanche thrown stems documented in 1965 and 1984 could still be found. The forest reserve site Scatlè lies between the test plots Disentis and Pfäfers. A description is found in KLÖTI (1991). The most important features of the used part of the test area are: 9°03’ E, 46°47’ N, 1550–1700 m a.s.l., exposition east, slope inclination 20–45°.

General snow climate conditions in the test fields of Disentis, Pfäfers and Scatlè are quite representative of most regions in the subalpine and montane zone of the Northern Alps.

For a more general overview of snow and avalanche conditions in areas damaged by Vivian, additional observations were made in the Canton of Glarus, the mountain part of St. Gall and in the Canton of Grisons, especially during the severe winter 1998/1999.

2.3 Documentation of snow and avalanche conditions and gliding snow measurements in test fields

Snow depth was calculated, measured and modelled:
- An initial calculation of expected maximum snow depths in the 4 test areas was made in 1991 using edition 1990 of BUWAL (1990), and considering special conditions of the areas such as general location, altitude and exposition.
- All test areas were equipped with metal stakes with markers every 50 cm. The actual snow depth was optically measured several times per winter at the beginning of the study, and later in only exceptional situations. The number and year of equipment are shown in Table 1.
- To obtain the daily snow depths in the test areas, available data from the snow measurement station net of FISAR (Federal Institute for Snow and Avalanche Research Davos; Table 1) were combined with the sporadic measurements made at the snow stakes in a regression model. The formulas for the development of the snow depth for each area were adjusted continuously. These values are important for calculating snow pressure.

Table 1. Test areas where snow depth was measured and calculated.

Test area	Number of snow stakes	Installation	Stations FISAR used for Modelling
Disentis	10	1991	Sedrun, Andermatt
Pfäfers	42	1991	St. Margrethenberg, Flumserberg
Schwanden	10	1991	Wald ZH, Flumserberg
Zweisimmen	6	1991	Saanenmöser, Gsteig
Scatlè	3	1996	Plaun Laax, Siat

For the development of young trees, a late date of disappearance of the snow cover may be limiting for survival and growth (SCHÖNENBERGER and FREY 1988). Therefore, in several spring periods of the early 1990's the remaining snow cover in the cleared and the uncleared parts of the test areas was mapped.

Gliding snow may seriously damage young trees (FREY *et al.* 1993). From 1991 to 1996, the total amount of snow gliding was measured in three test areas using the method "totalizing gliding shoes" over a whole winter period (IN DER GAND 1968). Gliding shoes were installed each winter: 30 at Pfäfers, 34 at Disentis, 12 at Schwanden.

In the test areas Disentis and Pfäfers, avalanche events between 1991 and 2001 were observed and mapped regularly from the opposite valley side. Information on potential avalanche situations was provided by the avalanche forecast service at FISAR and by local forest services.

2.4 Calculation of snow pressure on lying stems

Maximum snow depth is a very important factor affecting snow pressure. Different statistical return periods of maximum snow depth are standardized, e.g. 30 years, 100 years or 300 years (BUWAL 1990). To calculate the dimensions of permanent avalanche supporting structures, e.g. steel barriers in areas above the timberline, a return period of 100 years is used. Because windthrow areas should be reforested within 20 to 50 years, we worked with a statistical return period of 30 years.

Formulas of snow pressure on avalanche barriers are given in BUWAL (1990). Snow pressure on lying stems has to be considered in a special way, because only very few stems lie totally on the ground. The surface of most stems is 0.5 to 3 m above ground. The development of the snow cover varies around and on the stems, as shown by winter measurements and observations in the areas Pfäfers, Disentis and Scatlè:

Snow pressure on more or less horizontally lying stems was therefore calculated for 1 m-segments of the stems using formula (1) (see also Fig. 1):

$$S'N \cong (H-H')^2 * N * f_c \quad (1)$$

S'N calculated 30 year maximum snow pressure [kN /m]
H maximum vertically measured snow depth with a return period of 30 years [m]
H' vertical distance ground – upper surface of stem [m]
N glide factor (equal to 1 because the ground surface was very rough; BUWAL 1990)
f_c altitude factor (equal to 1 for an altitude of 1500 m a.s.l.; BUWAL 1990)

The direction of the snow pressure forces was calculated by formula (2) (see also Fig. 1):

$$\chi = 90° - (\varepsilon - \varphi) \text{ while } \tan \varepsilon = a / N * \tan \varphi) \quad (2)$$

χ angle between vertical direction and resultant of snow pressure [°]
φ slope inclination angle [°]
a factor considering the snow quality (value set for areas below timber line: 0.45; BUWAL 1990)

For $\varphi = 1$ formula (2) yields $\chi = 0$ (pure vertical setting of snow).

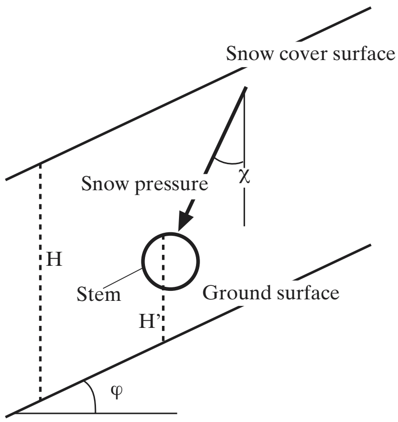

Fig. 1. Symbols used for calculation of snow pressure.

Formula (1) is an approximate adaptation of the formula for a rigid wall of height H with H' = 0, which has been verified in numerous measurements and theoretical calculations since 1939, and checked several times using computer codes (see e.g. BADER *et al.* 1989). The adaptation is valid for H' when not too close to H. Formula (2) was developed together with formula. (1).

Another approach to calculate the total snow pressure on a horizontally lying stem is to think of the single stem as a technical avalanche barrier (BUWAL 1990). Then the calculation includes the whole snow pressure from the upslope snow cover of 15 to 25 m corresponding to the distance between two structure lines. This would lead to three to five times higher values for the snow pressure on one single stem than in formula (1), and does not take into account that several stems can receive the snow pressure. To compare the two ways of calculating the pressure, the total amount of snow pressure in the test area Pfäfers was calculated (5.8 kN/m^2). On a test plot of 150 m^2 surface, six stems fully receive and another four stems partially share the load of this total snow pressure and – following formula (1) – are able to hold about 40% of this load. This seems reasonable, and the rest of the snow pressure will be dealt with by the roughness of the ground. For horizontally lying stems calculations were therefore made using formula (1).

At the test field Scatlè the stems had been broken and transported by the avalanches of 1965 and 1984. Therefore they were deposited in different directions, with some also lying parallel to the slope direction. Snow pressure for such stems had to be adjusted from the values determined from formula (1). For 1 m-segments, formula (3) gives for this situation:

$$C \cong S'N * D * E_{korr} * K * J \tag{3}$$

C calculated 30 year maximum snow pressure on stems in the slope direction [kN]
S'N calculated 30 year maximum snow pressure [kN / m]; see formula (1)
D diameter of the lying stem [m]
E_{korr} factor to obtain the effective snow pressure to be received by the stem (values set between 2.1 and 5.0 depending on the stem position, diameter and height above ground; adapted from BUWAL 1990)
K reduction factor introduced to take into account the effect of the extreme roughness of the terrain (big boulders) and the influence of the regularly abundant younger trees 3–6 m in height; set to 0.6.
J an additional reduction factor (set 0.6 to 0.8) was applied for stems at Scatlè which are totally covered by the crowns of adult trees with important snow interception; J is set = 1 for stems not covered.

2.5 Wood decay, breaking and movement of lying stems

Wood decay and the breaking of supporting branches is decisive for the stability of lying stems. If stems gradually settle closer to the ground, they provide less effective protection against avalanche release. Down-slope translation of stems could also alter their protection efficacy. To examine the movement and possible breaking of lying stems, a series of stems in the test areas of Pfäfers and Scatlè were mapped in three dimensions in 1996 and 1997. For future observation, 64 exactly measured points in the test area Disentis were marked in autumn 2001 (see Section 2.6).

A trial approach to estimate the solidity of some stems at the test area Pfäfers was carried out using Resistograph®, an apparatus which continuously records drilling resistance (Rinn *et al.* 1996).

Older trees like those in the test area Scatlè are supposed to break under heavy snow loads. Given the heavy snow pressure in the winter 1998/99 in this region, the bending moment of the mapped stems was calculated using formula (4) for fixed-end beams and formula (5) for freely supported beams:

$$M_{\text{fixed-end beam}} = (R + G_w) * r^2 / 2 \tag{4}$$

$$M_{\text{freely supported beam}} = (R + G_w) * r^2 / 8 \tag{5}$$

M bending moment
R 30 year maximum snow pressure as calculated in either formula (1) or, if more appropriate, (3)
r length of beam
G_W = $G_{W'}$ (specific weight of wood; 650 kg per m^3) * A (cross-section)

Section modules (W) of a circular log with radius (a) is shown in formula (6)

$$W = a^3 * \pi / 4 \quad (6)$$

σ_W bending strength; admitted resistance to bending for wood (value for dry healthy wood ≅ 75 N/mm^2; reduced to 50 N/mm^2 due to presence of decay)

The term σ_B (bending stress) compares M (formula (4) and (5)) with the bending strength of wood (formula (7))

$$\sigma_B = M / W \quad (7)$$

If the ratio of bending stress to bending strength is >1, breaking can be expected. (8)

2.6 Aerial and terrestrial photographs

Comparisons of the positions of lying stems and changes over time can be made by using aerial photographs of test sites taken several times between 1990 and 2001. For further investigations of the translation of lying stems, Disentis was chosen because:

- the slope inclination is steep enough to allow the release of avalanches;
- most of the observed avalanches occurred at Disentis;
- an annual uninterrupted series of terrestrial photos is available.

As the vegetation expanded (cf. WOHLGEMUTH *et al.* this issue) it partially covered the stems, making it difficult to measure them exactly, especially in the aerial photographs. A special flight was made in spring 2001 to get photographs comparable to those made in 1991 when there was no ground vegetation covering the stems.

Analytical photogrammetry methods were used to validate these aerial photographs by the Swiss Federal Survey Direction, with a scale of ~1:4000, colour, taken on 21 August 1991 and 10 May 2001. Instrumentation was provided by WSL, using the analytical stereorestitution system LEICA BC2000S with a double image plate carrier, superimposition system by Aviosoft, PC-Unix computer on Solaris platform, photogrammetric software by Aviosoft, Berneck, and a flatbed plotter LEICA TA10. Natural ground points (stones, trees, stumps, root plates and footpath intersections) were used as pass points to set up the 2 stereo models.

The accuracy of photogrammetrically measured points in their position X+Y is proportional to the image scale or constant referring to the image (KRAUS 1996). The height accuracy σZ depends on the flying height Z above ground.

For marked ground points the following standard values (mean error) apply:

position σXY	= ±6μ on the image
height σZ	= ±0.8‰ of flying height Z above ground
grid measurements	= 0.08–0.11‰ of Z.

In our series of measurements non-marked trunks were measured photogrammetrically. This meant the measurements did not obtain quite the standard values described above, but they are satisfactory, having the following values:

position σXY	= ±8–10μ, theoretically, corresponding to 3–4 cm on the image at the scale of 1:4000. Given the potential for human error, accuracy in the order of 10–15 cm has to be assumed.
height σZ	= ±0.15–0.20‰ of flying height above ground (~1400 m) corresponding to ±21–28 cm on ground.

The absolute orientation of the two stereo models in 1991 and 2001 on the analytical stereo plotter was based on natural ground control points obtained in field surveys with the instrument LEICA TC1000k. Root mean standard error of the absolute orientation was calculated to XY = 15 cm and Z = 20 cm.

Terrestrial photographs by Documenta Natura could be evaluated in an annual time series from 1992 to 2001 (Fig. 2). A total of 126 stems were considered. For 25 test stems measured using aerial photographs, the yearly translation in the Z axis could be visually estimated and compared with GIS measurements. These two methods showed a mean difference between the situations 1992 to 2000 smaller than 10% for the Z axis. For the same stems, absolute height above ground surface was measured in the field in 2001 and checked with terrestrial photographs.

Using the terrestrial photographs, the 25 test stems were identified on the 1991 stereo model and two to four points per stem were photogrammetrically measured: initial point, fracture point(s) if existing, and end point. 64 points on the 25 stems were measured and marked in the field for future investigations, as described in Section 2.5.

The same stems were located on the 2001 stereo model and their new positions photogrammetrically measured. The double image plate carrier of the analytical stereo plotter permits a model change in the georeferenced XYZ space, i.e. the stereo model of 1991 could be compared with the stereo model of 2001. Changing from the master model to the slave model, the 3D cursor moves to exactly the same XYZ position it had in the master model. This is possible only if the two stereo models are oriented in the same coordinate system.

Fig. 2. Terrestrial view of the test area Disentis, detail of uncleared area, in 1992 (left) and in 2001 (right). Photographs taken from exactly the same place, identical in clipping and scale, deskewed using GIS. Photo Documenta Natura.

2.7 Experiments to test the maximal snow pressure on stems

During the observed time period of 11 years, no winter with the natural snow depth of a statistical 30 year return period could be expected. Therefore experiments with technically applied loads on lying stems were prepared in the test fields Pfäfers and Scatlè. In autumn 1998 these experiments were conducted in Pfäfers. The stems were exposed to continuously increased loads until a sudden movement of the stem hindered the application of the load in the correct direction of strength corresponding to formula (2).

Figure 3 shows the situation of a stem (No. 4A) at the beginning and at the end of the loading. To distribute the load uniformly over the whole stem, an aluminium reinforced squared timber was fixed to the stem, and marker sticks were positioned. The load was applied by a steel rope. The test arrangement as a whole is shown in Figure 4. The applied load was measured by a pull-strength apparatus connected to a computer. This system has been used successfully in testing avalanche barrier anchorage.

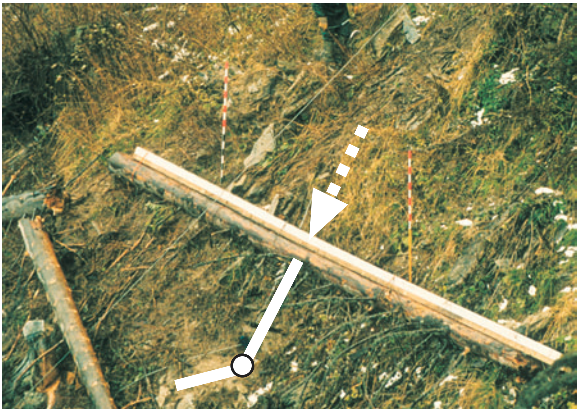

Fig. 3. Test area Pfäfers, load experiment on stem 4A with marker sticks. Beginning of load application (above; fixation at the stem, pulley and rope marked) and at the end of the experiment (below).

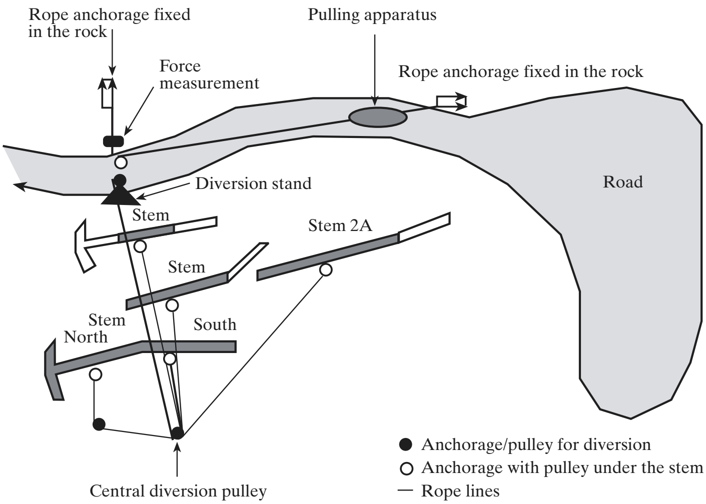

Fig. 4. Experiment design used at Pfäfers (described in 2.7). The grey parts of the stems were tested.

Analogous experiments planned for 1999 on the older stems at the test site Scatlè were carried out because the natural snow load in the winter 1998/99 turned out to be in the order of the statistical 30-year return period (see Section 3.1). The appropriate stems had been mapped in previous years. The movements and breaking of these stems caused by the natural snow load were determined and compared with the resistance of the wood using the calculations in formulas (4) to (8).

3 Results

3.1 Snow depth, winter characteristics

Vertical snow depth was measured with the help of snow sticks and daily values calculated. The results over 11 winter periods are shown in Table 2, and the calculated daily values of the extremely snow-rich winter 1998/1999 for all areas are shown in Figure 5.

Comparing the 1998/99 return periods of measured maximum snow depth (SLF 2000) with the calculated statistical return periods, the different test areas show considerable differences:

– a return period of 30 years was reached in the test area Scatlè;
– a return period of ≈ 20 years was reached at Pfäfers and Schwanden;
– a return period of ≈ 10 years was reached at Schwanden and Zweisimmen.

Table 2. Mean maximum snow depth of 11 winters (1990/91–2000/01), with measured and calculated maximum snow depths (BUWAL 1990); all test areas

Area	Mean maximum snow depth [cm]	Calculated 30 year maximum snow depth [cm]	Maximum measured snow depth [cm]
Pfäfers	114	240	201
Disentis	110	250	165
Schwanden	84	200	168
Zweisimmen	75	240	149
Scatlè	158	320	316

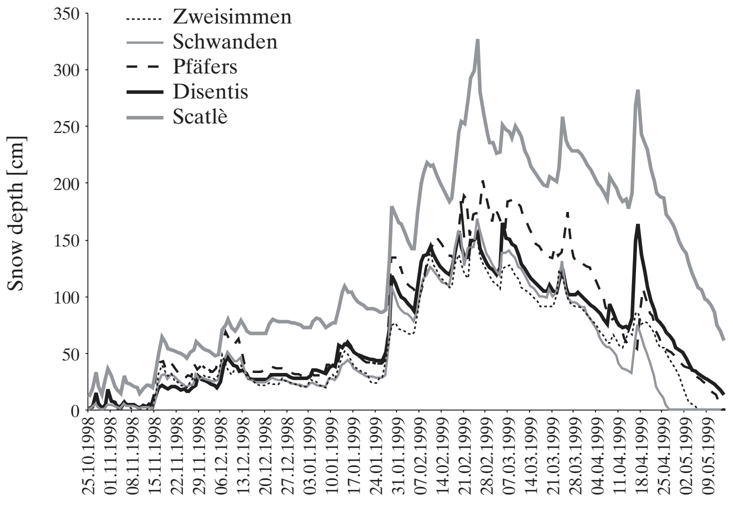

Fig. 5. Calculated daily values of snow depth [cm] in the severe winter 1998/1999; all areas.

The snow cover in the spring periods of the early 1990s generally disappeared completely in April and therefore was not a limiting factor for young trees. The cleared parts of comparable test areas stayed snow-covered some days longer than uncleared parts where the stems had been heated by radiation.

Snow gliding was measured at Schwanden, Pfäfers and Disentis in four winter periods only. Annual total gliding distances reached mean values of 2 to 10 cm, with maximum values of 40 cm. No significant differences could be found between cleared and uncleared areas. The winter 1994/95 showed the strongest gliding snow phenomena in the series of winters 1990/91 to 2000/01 (SLF 2001 until 1998/99, and supplemented with further measurements in other permanent plots).

Most dangerous avalanches start as slab avalanches (SLF 2000). This type of avalanche occurs only if the layering of the snow cover is continuous over large distances. In uncleared areas, the lying stems influence the snow cover by preventing the development of continuous even layering and also by producing holes in the snow around the covered stems. Disturbed continuous layering in the snow cover above completely covered stems or cracks in the snow cover reaching to the ground were regularly observed (Fig. 6). Therefore, lying stems can reduce the probability of dangerous slab avalanche release in snow layers that are higher than the stems.

Fig. 6. Snow cover around a stem lying directly on the ground showing cracks in the snow cover reaching the ground. Mean snow depth 80 cm (test area Scatlè, 26 March 1998).

3.2 Observed avalanches

The result of regular mapping of avalanches (1991/92 to 2000/01) in the test area Disentis is illustrated in Figure 7 for avalanches with a damaging potential. A photograph of the uncleared part of Disentis in February 1999 is shown in Figure 8. No avalanches occurred in the uncleared part.

In the test area Pfäfers, avalanches of considerable size were observed only in winter 1991/92 (4/5 March, 1992). Because a heavy slab avalanche with more than 80 cm fracture depth and three smaller slabs occurred in the cleared test area, the construction of wooden snow rakes in the following years became necessary since the valley road was endangered. Two slab avalanches of medium size occurred in another cleared area, whereas in the uncleared area only one small slab of 25 m length occurred. This was stopped by the lying stems.

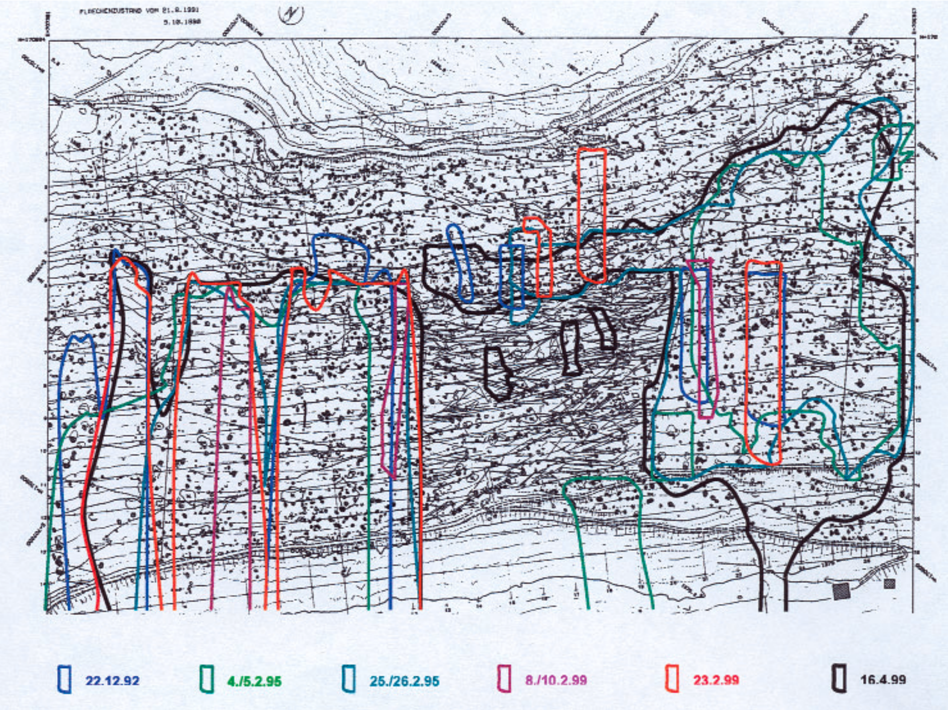

Fig. 7. Disentis, period 1991– 2001: Map of main avalanches on cleared and uncleared areas (in the centre, lower part); events of major size only (fracture width >15 m, fracture depth >50 cm, length of avalanche track >25 m).

Fig. 8. Test area Disentis, 25.2.99, snow depth 150 cm. Most of the stems are still quite visible and influencing the snow cover in a significant way. In the uncleared part (cf. Fig. 7) no avalanches occurred.

A general overview of snow and avalanche conditions in areas damaged by Vivian in the cantons of Glarus, the mountainous part of St. Gall and in the Grisons was produced in February 1999 (SLF 2000). The development of the snow cover in these large cleared areas was still strongly influenced by the roughness arising from small tree sections, root plates, branches, stumps and stones. This resulted in the snow cover conditions being more stable than they would be over smoother ground. No avalanches were observed in these rough areas, and smaller avalanches occurred only in some carefully cleared steep slopes.

In none of the observed areas could indications of mixed log-snow avalanches or of erosion of the stems by avalanches be found.

3.3 Experiments on snow pressure

An example of a load-time diagram of the experiments at Pfäfers described in Section 2.7 is shown in Figure 9. Since the load application was continuous, even very small downhill movements of the stem diminished the actual load by up to 3 kN. The total downhill distance of the stem before the final movement was 5 cm and 35 cm at the two ends of the stem. The final movement of 75 cm on one side twisted the stem too much to allow further load application in the correct angle χ. A summary report of the results of the five treated stems is given in Table 3. Mean maximum calculated snow load with a 30-year return period is 25 kN and the mean of possible maximum load applications is 23 kN.

For the older stems at Scatlè a summary of the observed fracture occurrence is given in Table 4 (16 stems observed, partial stem sections). Only marginal down-slope movements (maximum 30 cm) occurred, and most of the stems were not pressed further onto the ground surface. Only fractured stems still placed high above the surface before winter 98/99 were partially pressed down to or near to the ground surface.

The comparison of observed fractures with expected fractures applying formula (8) showed values of 0.2–0.9 for "no breakage expected" and 2.3–3.8 for "breakage expected". The calculated values showed an almost complete correspondence to the field observations. This indicates that the factors selected for the calculations of snow load and wood resistance seem to be reliable. There was no significant difference in breaking between freely supported stems and fixed-end stems.

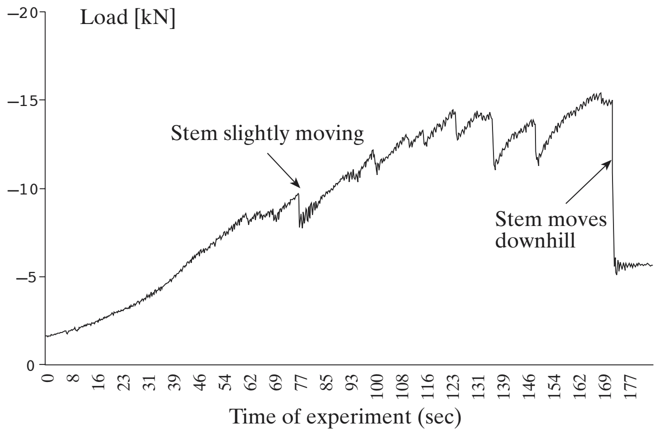

Fig. 9. Load-time diagram for stem 3A (compare Fig. 5). The total movement down slope was 5 cm at one end and 75 cm at the other end of the stem.

Table 3. Summarized test results of the load experiments on stems at Pfäfers (cf. Fig. 4, 5, 9 and 10).

Stem No.	Length [m]	Characteristics of the stem's position	$S_{N'}$ Max. calculated 30y return period [kN]	S_N maximum measured in the experiment [kN]	χ [°]
2A	17	Supported by branches	20	19	22
3A	8	± at soil surface	19	16	22
3B North	8	At soil surface	33	38	23
3B South	11	Partially broken; above surface	19	19	22
4A	10	Partially at soil surface	37	23	23
Mean [Variance]			25 [9]	23 [9]	22

$S_{N'}$ = Maximum snow pressure (return period of 30 years)
χ° = Deviation of the direction of SN' from the vertical direction

Table 4. Test area Scatlè: Percentage of stems broken by the heavy snow load in winter 1998/99.

Year of breaking (Age)	% of stems with fracture (number of stems)	% of stems without fracture (number of stems)
1965 (35 years)	29% (n=2)	71% (n=5)
1983 (16 years)	33% (n=3)	67% (n=6)

3.4 Wood decay

Some stems at the Pfäfers site were tested by Resistograph to get information on the hardness of the wood. The results showed in 1998 that the sapwood part was in general softer than the heart wood when the annual rings are still visible (Fig. 10). Decay intensity was observed to decrease with height above the ground. Thus such stems are expected to withstand snow loads effectively for at least 10 to 20 years. Stems situated higher above ground are still quite effective up to 30 years after windthrow.

While fixing nails to mark stems in the area of Disentis in 2001, the sap wood was seen to be severely decayed, while the heart wood was still quite hard.

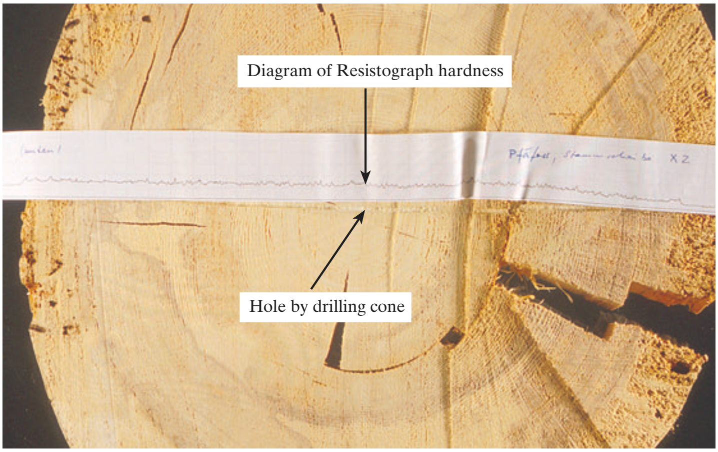

Fig. 10. Stem drilled by a Resistograph instrument to get information on the hardness of the wood; related diagram of hardness added. Test area Pfäfers, autumn 1998.

3.5 Movement of lying stems

The two different methods mentioned in Section 2.6 to evaluate the vertical movement of stems at the test area Disentis cannot be compared directly because the two series do not cover the same period. The aerial photographs of 1991 are the only ones that may be used because in 1992 the stems were no longer very visible. The terrestrial photographs have been available only since 1992, and were repeated every year until 2001 (see Fig. 2).

The mean difference in the 64 photogrammetrically measured points (Section 2.6) between 1991 and 2001 was 1.73 m in the vertical direction, and 1.31 m horizontally downhill due to slow gliding and/or rolling of the stems. The position of the measured points approached the ground surface therefore by a mean of 0.74 m (slope inclination 37°), i.e. ≈43% of the vertical movement.

On terrestrial photographs only the vertical difference could be estimated. For the same 25 stems that were measured by photogrammetry, the mean vertical difference between 1992 and 2001 was 0.76 m. The mean of all 128 stems analysed using this method was 0.70 m. The 25 selected stems seem therefore to be quite representative. Including the downhill movement as above, these stems approached the ground surface by a mean value of 0.30 m in the period 1992–2001.

The difference in total vertical movements between 1991–2001 measured by photogrammetry (1.73 m) and 1992–2001 estimated from terrestrial photographs (0.76 m) seems high (0.97 m). Assuming that the two methods do not differ extremely, the winter period of 1991/92 must have been very effective in pressing and/or rolling down the stems. Two factors seem to have acted very intensively:

1. After windthrow in 1990, the stems were supported by branches and therefore were kept quite high above the ground surface.
2. The stems were not exposed to heavy snow loads in the winter 90/91, but the heavy snow load in winter 91/92, comparable to that of winter 1998/99, turned out to be effective.

To prevent avalanche release, the height of the stems above the ground surface is considered most important, and measurements in 2001 showed this mean distance still to be 1.1 m. Figure 11 shows the development of the mean distance of the stem surface above ground between 1991 and 2001, combining all results, and compared with maximum snow depth in the previous winter. After such snow rich winters as 1992, 1995 and 1999, increased movements of the stems were observed. The continuing decrease in 2000 and 2001 could be explained by the faster decay of the wood.

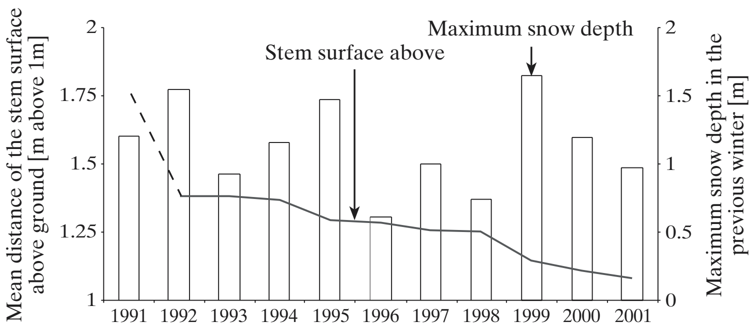

Fig. 11. Disentis, development of the mean distance of stem surfaces above ground between 1991 and 2001 (line), and maximum snow depth in the previous winter (bars).

4 Discussion

4.1 Snow and avalanche protection in cleared and uncleared areas, including time aspects

Snow depth is an important factor affecting the pressing of stems downhill. This was quite high during the winters 1991/92 to 2000/01. The 1998/99 winter, which had a maximum snow depth with a statistical return period of 30 years, was the most effective at snow loading stems. General avalanche activity was intensive (SLF 2000). Therefore the measured and observed data are considered representative of at least average winter conditions.

The quite small values of total snow gliding distance with maximum values of 40 cm are due to the very rough ground surface. They do not limit the growth of young trees (FREY and LEUENBERGER 1993). Vegetation growth (WOHLGEMUTH *et al.* this issue) adds to the roughness of the surface.

Immediately after windthrow, the stems are quite high above the ground surface, and they are often supported by their branches and linked to each other. Stems, branches and evergreen needles influence the development of the snow cover and effectively hinder snow movement.

During the first decade, cleared windthrow areas provide more protection against avalanche release than open fields due to the ground still being rough. However, this protective function is quite limited compared to uncleared windthrow areas, which provide much more protection.

A generalized conclusion from the first 10 years after the storm event Vivian is shown in Table 5. The results from the test areas have been supported by observations in other parts of the Swiss Alps during the avalanche winter 1998/99.

Table 5. Summary of avalanche features (starting zone, avalanche track and deposition zone) in cleared and uncleared windthrow areas in montane and subalpine zones based on all available information 1991–2001. Findings apply for at least 10 years after a windthrow event.

	Cleared	Uncleared
Starting zone	Release at 35–45° (70–100%)	Rare release at 45° (100%)
Avalanche track	Flow at 30–45° (60–100%)	Stopped at 30–40° (60–85%)
Deposition zone	Deposition at 20–30° (35–60%)	(stopped in the track)

4.2 Wood decay and translation of lying stems

Progressive wood decay plays an important role in decreasing the protective capacity of uncleared areas. Wood decay in the first decade after windthrow does not weaken stems much, and they can still withstand a maximum snow load of a statistical return period of 30 years. Lying stems can support similar snow loads for up to 30 years with 30% fractures. After 30 years, most of the stems pressed to the ground are partially or completely rotten and therefore of very limited protective value. Further information on the longevity of logs is available for the Rocky Mountains (BROWN *et al.* 1998), although in another type of climate.

Considerable translation of lying stems due to wood decay and snow pressure occurs during the early years after windthrow with further increases after winters with heavy snow loads. The movement is a combination of vertical motion and motion down slope parallel to the ground surface. During the first decade, the distance between stem surfaces and ground surface therefore is reduced only by a relatively moderate amount, which is favourable for providing good protection from avalanche release.

Measuring the movement of lying stems by comparing aerial photographs has shown the difficulties of working with stereo models of unmarked items. The problem of identifying items on aerial photographs may lead to misinterpretations. For a future comparison of aerial photographs, the markers placed on the stems in the test plot of Disentis will enable them to be clearly identified.

4.3 Are the hypotheses listed in Section 1.3 supported by the results obtained?

"In windthrow areas of the subalpine and montane zone, lying stems in uncleared areas effectively prevent avalanche release for several years or even decades."

- This was correct, at least for the first decade after the storm event. For a period of 10 to 30 years after the event, the protection capacity of an uncleared area is expected to decrease, but is still considerably higher than in cleared areas and much higher than in open fields.

"In cleared areas, the frequency and size of avalanches are distinctly greater than in uncleared areas."

- All observations and measurements confirmed this hypothesis. This is expected to be correct also for the period of 10 to 30 years after the event. Not clearing is an effective measure for protection and shows a favourable cost-protection relation.

"Even extreme snow pressure on lying stems does not induce mixed log-snow avalanches."

- Static snow pressure with a statistical return period of 30 years can provoke marginal movements of lying stems only, at least during the first decade after the storm event. Some small avalanches starting above or in uncleared areas were stopped by the lying stems without destabilizing movements of the stems.

"The protection function of the lying stems does not decrease before natural regeneration and/or afforestation becomes effective."

- A critical time period in the effectiveness of uncleared areas is probably 20 to 50 years after the storm event. The protection capacity of upcoming regeneration should therefore be accelerated as much as possible (SCHÖNENBERGER this issue b). In critical zones of a slope, specific technical protection measures such as tripods and/or wooden supporting structures can be set up if there is a decrease in the protective function of the lying stems greater than the increasing protective function of the regeneration.
- Considering avalanche protection, there is no need for clearing immediately after a storm event. The lying stems provide very good protection for at least one decade. Continuous observation in the area itself is needed. This means establishing footpaths so as to make inspection possible. Observations, especially in winter, are helpful in identifying potentially dangerous zones. With the decreasing protective potential of the lying stems, local technical measures can be installed, even after decades, to improve the protection to the necessary level.
- Where the destroyed forest had a very intensive protective function for permanently inhabited villages or frequently used roads, a combination of strong technical measures with locally uncleared parts may be appropriate.

4.4 Remaining questions

We still know relatively little about the development of uncleared and even of cleared areas several decades after the storm event. Some test areas should be re-evaluated at later dates and similar questions addressed, e.g. the decay and translation of lying stems in established areas such as Disentis. The protective capacity of the upcoming regeneration must be assessed over time, and critical avalanche situations must be mapped for further use. Modelling of regeneration and vegetation development supported by field data would be very helpful.

For most of the windthrow areas, the protection function of uncleared areas was judged to be sufficient in general, at least for the first decade after the storm. Nevertheless, special situations need to be considered separately, e.g. leeward sites near ridges with additional heavy snow depth and possible fracture heights of 2 to 3 m, or extremely steep slopes. Additional technical measures such as adapted supporting structures (BUWAL 1990) may be necessary in such sites, and even clearing may be required in some special situations.

Acknowledgements
Field observations were supported essentially by regional Forest Services, especially by R. Schwitter (Pfäfers) and A. Sialm (Disentis). The photogrammetric part was carried out by P. Thee, WSL Birmensdorf. Experimental work was only possible with assistance from FISAR technical collaborators, namely F. Leuenberger, C. Simeon, S. Frutiger and M. Hiller. B. Salm supported both the design and implementation of the experimental part. U. Heiniger contributed information on wood decay, M. Schwarz supported the field survey, and S. Margreth checked the calculation part. B. Salm and P. Bebi revised the manuscript.

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Accepted 25.7.02