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ORIGINAL PAPER

Snow gliding on a south-facing slope covered with larch trees

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Abstract
• ***Context*** Snow gliding is a downhill motion of snow on the ground; observations have shown gliding to be possible not only on open slopes but also in forest stands. Larch stands, with their low canopy density and open forest structure with clearings and gaps, are particularly prone to high glide rates. Snow gliding may have negative effects on juvenescent trees which can be damaged by extraction from the ground.
• ***Aim*** The goal of this study was to determine whether snow gliding depends on forest cover (canopy) and size of clearings.
• ***Methods*** Snow gliding was measured during eight winter periods at six measuring positions (ranging from 'dense forest' to 'open slope') in and beside a larch stand in the Stubai Valley, Tyrol, Austria.
• ***Results*** The results showed that gliding is strongly influenced by forest cover. Snow gliding increases with decreasing canopy density. The difference between the six measuring positions was highly significant ($p<0.005$).
• ***Conclusion*** The identified glide cracks on at least two measuring positions, indicating extreme glide rates and, therefore, strong negative effects on juvenescent trees. To prevent glide rates of a magnitude such as this requires a mature forest with at least 300 stems/ha.

Keywords Snow gliding · Glide avalanches · Larch forest · High-altitude afforestation · Control measures

1 Introduction

Snow gliding is a downhill motion of snow on the ground (In der Gand and Zupancic 1966) or, in other words, a translational slip of the entire snowpack over the ground (McClung and Schaerer 2006). It should be distinguished from creep, which is the result of settlement and internal shear deformation parallel to the slope (In der Gand and Zupancic 1966). A scheme of glide and creep motion is given in Fig. 1.

Glide cracks (Fig. 2) result from rapid gliding (In der Gand and Zupancic 1966). Gliding snow sluffs are small avalanches that slide on the ground and which occur when there is rapid snow gliding (In der Gand and Zupancic 1966).

Snow gliding is affected by inclination, aspect, roughness and temperature of the ground surface, as well as by the thickness and characteristics of the snowpack (Haefeli 1939). In der Gand and Zupancic (1966) note that the ground roughness and the lowermost boundary layer of the snow cover are the main influences on snow gliding with the main condition being the existence of a smooth ground surface (In der Gand and Zupancic 1966; McClung and Schaerer 2006). Haefeli (1939) notes that slow glide motion can be particularly observed on grassy slopes while Frutiger and Kuster (1967) indicate that slopes with a dense coverage by long grass and slaty rock surfaces are prone to intensive gliding, and McClung and Schaerer (2006) specify that the fastest glide rates occur on smooth and grassy slopes. However, a further requirement is the presence of a thin layer of wet snow at the base of the snowpack (In der Gand and Zupancic 1966) which is formed by melting at the snow–earth interface (In der Gand and Zupancic 1966) when the temperature at the bottom of the snowpack is 0 °C, guaranteeing the existence of free water at the interface (McClung and Schaerer 2006). According to McClung and Clarke (1987), free water promotes the separation of the snowpack from the ground. Moreover, glide velocity increases with increasing slope inclination (In der Gand and Zupancic 1966). McClung and Schaerer (2006) note that the slope angle must be at least 15° for roughness typical of alpine ground cover for snow gliding to occur. Snow gliding also depends on aspect; it is generally higher on sun-exposed slopes.

According to In der Gand and Zupancic (1966), glide velocity also increases with increasing weight of the snowpack;

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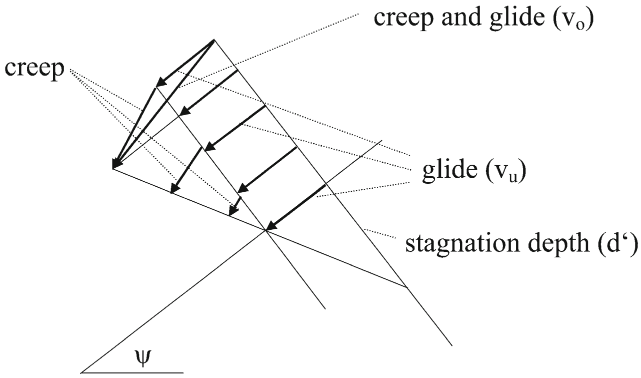

Fig. 1 Schematic diagram of snow creep and glide (In der Gand and Zupancic 1966). v_o movement due to creep and glide, v_u movement due to glide, d' stagnation depth and ψ slope inclination

the same authors also note that any temperature change causes a change in glide velocity, i.e. a decrease in snow temperature is inhibitive to glide movement and vice versa (In der Gand 1968a).

The magnitude of snow gliding extends from millimetres to centimetres per day (In der Gand and Zupancic 1966; de Quervain 1966). Frutiger and Kuster (1967) indicate that over an ordinary winter, gliding generally reaches up to several decimetres; however, it can also achieve distances of one or more metres (depending on the weather and snow conditions).

Snow gliding can have negative effects on forest plants; the so-called *Säbelwuchs* [sweep of the bole] is a typical indicator of trees having been affected by snow gliding in previous years. However, juvenescent trees may also be uprooted from the ground, with several authors describing this type of damage to juvenescent trees (Höller et al. 2009). According to In der Gand (1968b), plants can be uprooted as a result of snow gliding and the accompanying tensile forces. He found that growth of young plants is adversely impacted by the force

Fig. 2 Glide crack in a forest clearing. The picture was taken in Dec. 1992 in a south-facing larch stand nearby the Kaserstattalm, Stubai Valley, Tyrol. The larch trees on the right side are characterized by *Säbelwuchs* [sweep of the bole] which is a typical indicator of trees having been affected by snow gliding in previous years

released from glide cracks (Fig. 2) and gliding snow sluffs, and it is therefore necessary to prevent the extreme glide rates caused by these events in order to protect afforestations.

In der Gand (1968b) specifies appropriate measures for reducing glide motion to a tolerable extent (a tolerable extent is defined as that extent at which damage to plants and afforestations are prevented), distinguishing three categories of action: (1) measures that increase the roughness of the ground surface (e.g. *Bermen* [earth terraces]), (2) measures that contribute to anchoring the lowermost layers of the snowpack (stakes and glide control structures), and (3) measures that cause an interdigitation of the snow and vegetation (plantings).

Ammer and Mössmer (1986) added some detail to the glide control measures, proposing values for the required distances between pales and terraces. Similar specifications are found in Leuenberger (1989), who has published a construction manual for temporary control measures, and in an information sheet by Meyer-Grass (1985).

Mössmer et al. (1990) investigated the ability of various tree species to regenerate in snow gliding areas and found that *Picea abies* is less suitable while *Larix decidua* and, in areas with strong gliding, *Pinus mugo* are more favourable. Zenke (1985) has investigated avalanches in mountain forests and found glide cracks in the openings of low-density stands. Meyer-Grass (1985) has determined the protective effect of different forest types against avalanches, as well as appropriate temporary measures.

However, long-term investigations of snow gliding in forest stands are not currently available. The present study is based on 8 years of snow gliding measurements from characteristic sites in and beside a low-density larch stand near the timberline.

The objectives were to

- Determine the influence of forest cover on glide rates
- Identify glide avalanche areas in forest stands near the timberline
- Indicate management instructions for low-density forest stands (e.g. to specify the number of stems required to prevent high glide rates and consequently the release of glide avalanches)

2 Snow glide models

In der Gand and Zupancic (1966) assume an additive interaction of dry and viscous friction and found the following equation:

$$v = (\delta/\eta) d\rho g (\sin\Psi - \mu\cos\Psi) \quad (1)$$

where v is the glide velocity, μ the friction coefficient, d the snowpack thickness perpendicular to the slope, ρ the mean snow density, g the acceleration of gravity, Ψ the slope inclination, δ the thickness of the viscous boundary layer, and η the coefficient of viscosity of the boundary layer.

Equation (1) indicates that the glide velocity increases with the weight of the snow and the slope inclination and decreases with increasing friction; moreover, it depends on the relationship of the boundary layer thickness and viscosity.

McClung (1975) assumes that snow gliding is similar to glacier sliding and finds a relationship between basal shear stress and glide velocity. The generalized glide constitutive law is (McClung 1975):

$$v = d'\tau/\eta_s \qquad (2)$$

where v is the glide velocity; d' the stagnation depth which is the depth below the surface at which the averaged velocity profile meets the z-axis (Fig. 1); τ the shear stress, which is the product of snow density, acceleration due to gravity, snow thickness and the sine of the slope angle and η_s is the shear viscosity which depends on crystal shape, snow density and snow temperature. The stagnation depth (d') is an apparent thickness of a boundary layer and can be expressed as (Salm 1977):

$$d' = 1/(2\pi)^3(\lambda_o/A)^2\lambda_o \qquad (3)$$

where d' is the stagnation depth, A the amplitude of the bed topography and λ_o the wavelength of the bed topography.

McClung (1975) also considers the effect of timber on snow gliding; he made the assumption that the effect of interdigitation is to introduce a constant drag, τ_o, on the snowpack with a corresponding reduction in glide velocity. According to McClung (1975), this would be equivalent to a reduction in shear stress so that the resulting equation reads as follows:

$$v = (d'/\eta_s)(\tau - \tau_o) \qquad (4)$$

Subsequently, McClung and Clarke (1987) introduced an improved snow glide model that provided for a relationship between basal shear stress, τ, glide velocity v and liquid water by adding υ, the viscous analogue of Poisson's ratio.

3 Material and methods

3.1 Experimental site

The study area was located in Stubai Valley (approximately 35 km from Innsbruck, Austria) in and beside a larch stand near the timberline at about 1,900 m.a.s.l. (aspect SE to SW; inclination from 28° to 32°; coordinates 11° 18′ E, 47° 07′ N). Because of the very smooth ground surface (see below), the area is prone to high glide rates, which allowed the assumption to be made that the slope is a typical snow gliding area; this was confirmed by several observations (see Fig. 2).

Figure 3 gives an overview of the study site, with the numbers shown in the figure corresponding to the six measuring positions chosen for detailed investigations. Table 1 specifies the six measuring positions.

The ground surface of all measuring locations was characterized as very smooth. The amplitudes (A) and wavelengths (λ_o) of the ground surface (see Eq. (3)) were obtained by using an elastic aluminium pole (length 2 m) that was matched to the ground surface. This procedure resulted in a deformation of the pole, which was then used as a measure for the roughness of the bed topography. The measurements yield amplitudes (A) in the range 0.015 to 0.02 m and wavelengths (λ_o) between 0.9 and 1.05 m. According to the Swiss guidelines (Margreth 2007), amplitudes of this magnitude indicate a relatively smooth ground surface.

The climate of Stubai Valley is characterized by a rather continental influence. At the observation site in Telfes (which is at the valley mouth, elevation 1,070 m), the average temperature in January is −3.1 °C and −4.8 °C at the observation site in Mutterbergalm (which is at the valley head, elevation 1,720 m); the corresponding values in February are −1.5 and −5.0 °C, respectively. In March the average temperature ranges from 2.1 °C in Telfes to −2.0 °C at Mutterbergalm. The temperature and snow conditions in the study area (1,900 m) are shown in Table 2.

3.2 Methods of measurements

Snow gliding was measured at all six measuring locations. Measurements were undertaken using glide shoes developed by In der Gand (1954); glide shoes are small sleds (10 cm× 15 cm) which are placed on the ground before the winter snow cover starts. A steel wire (4 m long) was fixed to the upper side of each shoe and then inserted on the other side into the

Fig. 3 Overview of the experimental site in Kaserstattalm (latitude 47° 07′ N; longitude 11° 18′ E); the *numbers* indicate the various measuring positions

Table 1 Description of the six measuring positions

Location	Altitude	Aspect	Inclination	Characterization
1. Open slope	1,880 m	SSE	30°	
2. Open stand	1,875 m	SSW	30°	Nearest trees located 3 m to the west (a single larch with a height of 12.5 m and stem diameter of 31 cm) and 3 m to the east (a single larch with a height of 7.5 m and stem diameter of 10 cm); the extrapolated number of stems was estimated to be about 200 to 250 stems/ha.
3. Dense forest	1,870 m	S	30°	Nearest trees located 3 m in a westerly direction (two large larches with heights of 17 m and stem diameters of 35 and 41 cm, respectively) and 4 m to the north (a single larch with a height of 16.5 m and stem diameter of 35 cm); further trees were located to the east (two small larches, each with a height of 7.5 m and stem diameter of 11 cm) and to the south; the extrapolated number of stems was estimated to be approximately 300 to 350 stems/ha.
4. Small clearing with dimensions of 8 m×8 m	1,875 m	SSE	30°	Two major larches on the western edge (height 16 m; stem diameter 39 cm), and several smaller larches on the north and north-eastern edge; on the south-eastern edge, a few major larches (the tallest tree having a height of 20 m and stem diameter of 53 cm) delimitate the clearing; the extrapolated number of stems was estimated to be about 100 stems/ha.
5. Boundary of a large clearing with dimensions of 20 m×30 m	1,875 m	SSE	30°	Larches with heights of 16 m (30 cm in diameter) on the western edge and some smaller larches (between 3.5 and 6 m tall) on the northern edge, four larches with heights of 14 m (23 cm diameter) on the north-eastern edge; the larches on the southern edge of the clearing reach heights of about 14 m; the extrapolated number of stems was estimated to be approximately 50 to 60 stems/ha.
6. Centre of a large clearing with dimensions of 20×30 m	1,870 m	SSE	30°	The larches on the north-western edge reach heights of 14 m (23 cm diameter); on the eastern and south-eastern edge of the clearing larches with a height of 16 to 20 m (up to 6 cm diameter); the larches on the south-western edge reach heights of 11 to 20 m; the extrapolated number of stems was estimated to be about 35 to 40 stems/ha.

measuring box, where it was wound round the axle. A small disc with a couple of pins was mounted on one end of the axle, which actuated a microswitch. Every time a glide shoe moved more than 2 mm, one full pulse was transmitted from the microswitch to a datalogger. The principle of the glide measurements is illustrated in Fig. 4. All experiments were carried out in the winter periods 1992/1993 to 1999/2000 (except the winter of 1993/1994, due to breakdown of the batteries).

3.3 Methods of data analysis

Cross-tabulation tables were used to identify whether snow gliding was significantly different between the six measuring zones. This method is recommended when data are not normally distributed and an analysis of variance (ANOVA) is therefore not possible. Glide rates were grouped into classes using cross-tabulation tables, and the frequency on each site was tested within several classes (0 mm h^{-1}, 1 mm h^{-1}, 2 mm h^{-1}, and higher); a χ^2 test was used to establish whether a uniform distribution existed. The frequency tables were calculated using the software STATISTICA.

An extreme value distribution (Gumbel 1958) was used to estimate the maxima of the mean glide rates per day. The Gumbel distribution was calculated for every measuring zone using the respective glide rates of each of the 7 years. Even though the snow gliding data set contained 7 years of measurements (and more comprehensive time series might not be available from other study areas), it should be noted that a statistical analysis of extreme values usually requires a longer time series [according to Dyck and Peschke (1983), the observation period has to be one half to at least one third of the designated return period]; however, it was assumed that the values determined can be used as indicators of expected glide rates. All calculations were undertaken for return periods of 20, 50, and, for the purpose of hazard zoning, 150 years; the equations were calculated using the software STATISTICA.

Table 2 Temperature and snow conditions in the study area (1,900 m) during the period of investigations (1992/1993 to 1999/2000)

	Mean air temperature (°C)			Max snow depth (m)
	Jan.	Feb.	March	
1992–1993	−0.7	−2.4	−2.6	0.7
1994–1995	−5.7	−0.7	−3.5	0.7
1995–1996	−0.5	−5.9	−3.6	0.2
1996–1997	−0.1	−0.7	0.8	0.5
1997–1998	−2.0	1.4	−2.2	0.5
1998–1999	−1.8	−6.4	−0.6	1.4
1999–2000	−4.2	−2.5	−1.0	1.2

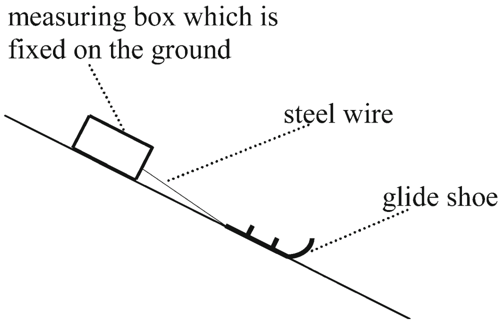

Fig. 4 Principle of glide measurements

4 Results

The mean glide rates per day are shown in Table 3. While mean glide rates did not even reach 0.5 mm day^{-1} (Table 3) in the dense forest (measuring zone 3, with a canopy density of 90–95 %), higher rates were determined for those sites where canopy density is less than 90 %; in measuring zone 2, for example, glide rates exceeded 1.0 mm day^{-1} in 1994/1995, 1998/1999 and 1999/2000 (Table 3).

As canopy density decreased to a clear state, snow gliding increased rapidly. As shown in Table 3, glide rates in the large clearing (measuring zones 5 and 6), as well as in the small clearing (measuring zone 4), were considerably higher than in the forest (measuring zones 2 and 3). For example, mean glide rates in 1994/1995 were about 9 mm day^{-1} in the small clearing, more than 10 mm day^{-1} at the boundary of the large clearing, and 7.3 mm day^{-1} in the centre of the opening. High glide rates were also found in 1999/2000, especially for measuring zones 4 and 5.

The statistical analysis is illustrated in Fig. 5, which shows glide rate frequencies for all measuring zones in the two classes, 1 and 2 mm h^{-1}. The difference between the various measuring zones was highly significant (p<<0.005) in all winter periods.

As shown in Fig. 5, high glide rate frequencies in classes 1 (1 mm h^{-1}) and 2 (2 mm h^{-1} and higher) were found on measuring zones 1 (open slope), 4 (small clearing), 5 (boundary of large clearing), and 6 (centre of the large clearing), although a decrease at zone 1 was noticed in the later years, which can be explained by growth of young trees. On the other hand, snow gliding at measuring zone 3 (dense forest) was characterized by lower frequencies in both classes 1 and 2. A similar trend was also expected for measuring zone 2; however, glide rates at 2 differed from those at zone 3, because even though the frequencies in class 2 (2 mm h^{-1} and higher) were fairly similar to those at measuring zone 3, higher frequencies were observed in class 1 (1 mm h^{-1}). However, in all years (except 1997/1998), the glide frequencies in class 2 were higher in the clearings (measuring zones 4, 5 and 6) than in the forest (measuring zones 2 and 3). The contrasting trend in 1997/1998 would appear to be a result of the dry winter; data from 1997/1998 should therefore not be used for an overall interpretation.

From 1992/1993 to 1997/1998, the glide rate frequencies from all measuring zones were considerably higher in class 1 than in class 2 (except for zone 1 in the winter of 1995/1996); this trend might be related to the slightly lower snow depth in these winter periods (so that higher glide rates [2 mm h^{-1} and higher] were less frequent).

Snow gliding in 1998/1999 and 1999/2000 was characterized by a differing trend. While on measuring zone 2 (open forest) and 3 (dense forest) the frequencies in class 1 were higher than in class 2, the frequencies on the remaining measuring zones do not indicate a clear difference between class 1 and class 2 (in 1999/2000 the glide rate frequencies on measuring zone 4 and 6 were even higher in class 2 than in class 1). It was assumed that the deeper snowpack in 1998/1999 and 1999/2000 caused higher frequencies in class 2 (except on measuring zones 2 [open forest] and 3 [dense forest] where, because of the lower snowpack in the forest, a contrary trend was identified).

In general two main trends can be determined from Fig. 5: (1) moderate gliding in the winter periods 1995/1996, 1996/1997 and 1997/1998 (which is a result of the very low snow depth in these three winter periods; see Table 2) and (2) consistently lower glide rates on measuring zones 2 and 3

Table 3 Mean glide rates per day (millimetres per day) on six different measuring locations of the experimental site in the Stubaital (1992/1993 to 1999/2000)

	1992/1993	1994/1995	1995/1996	1996/1997	1997/1998	1998/1099	1999/2000
Open slope (1)	9.7	19.7	3.3	1.0	0.4	0.3	0.5
Open forest (2)	0.6	1.1	0.2	0.0	0.5	1.1	1.0
Dense forest (3)	0.2	0.5	0.0	0.1	0.1	0.1	0.2
Small clearing (4)	3.2	9.2	0.2	0.6	0.0	1.0	3.3
Boundary of large clearing (5)	2.9	10.7	0.2	0.9	0.1	1.4	4.2
Centre of large clearing (6)	4.9	7.3	0.6	0.4	0.0	0.7	0.7

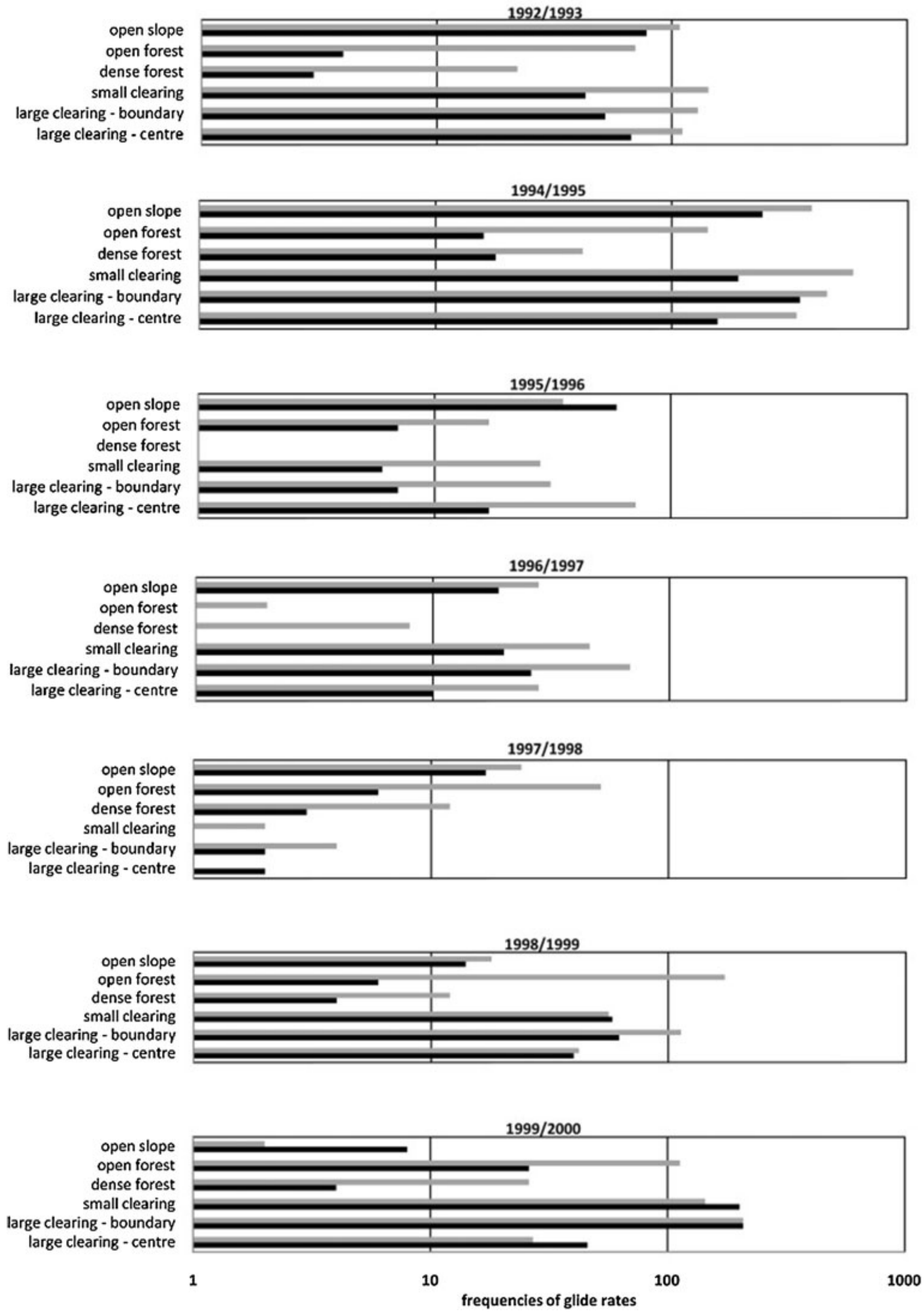

Fig. 5 Frequencies of glide rates on six different measuring locations (1992/1993–1999/2000); *grey* frequencies in class 1 (glide rates with 1 mm h^{-1}), *black* frequencies in class 2 (glide rates with 2 mm $h^{-1}$and higher); frequencies in class 0 (glide rates with 0 mm h^{-1}) are not shown in this figure; note that the *x*-axis is on a logarithmic scale

(compared with the adjacent clearings). Even small clearings (e.g. measuring zone 4—clearing with dimensions of 8×8 m) do not cause much decrease of glide rates. In order to reduce snow gliding to an uncritical value (at least to a moderate intensity [7.5–1.5 mm day^{-1}]; see paragraph after next) clearings should be less than the dimensions of measuring zone 4; it is suggested that the size is no more than 40 m^2.

The trend that snow gliding is affected by the forest cover is also reflected by the maximal glide rates (Table 4). Exceptional values were measured in late winter and spring 1993 due to an increase of temperature; as shown in Table 4, glide rates ranged from a few millimetres per hour (open forest, dense forest) via 81 mm h^{-1} (centre of the large clearing) to 122 mm h^{-1} (open slope). High rates were also found in the winter 1995/1996 (Table 4); these were related to glide

Table 4 Maximal glide rates (millimetres per hour) on six different measuring locations of the experimental site in the Stubaital (1992/1993 to 1999/2000)

	1992/1993	1994/1995	1995/1996	1996/1997	1997/1998	1998/1999	1999/2000
Open slope (1)	122	–[a]	44	–[a]	2	2	30
Open forest (2)	2	–[a]	2	2	5	2	2
Dense forest (3)	3	–[a]	2	1	2	2	2
Small clearing (4)	39	–[a]	4	2	2	3	4
Boundary of large clearing (5)	39	–[a]	4	3	2	4	28
Centre of large clearing (6)	81	–[a]	21	2	2	2	5

[a] Maximum values could not be verified

avalanches in November 1995. Between 7 and 9 November, glide rates indicated a strong increase for measuring zone 1 (open field); the daily values ranged from 68 mm day^{-1} (9 November) to 328 mm day^{-1} (8 November), with a maximum rate of 44 mm h^{-1} occurring on 9 November (Fig. 6). A value of 21 mm h^{-1} (Fig. 6) was measured at zone 6 (large clearing). Insignificant glide rates were observed for zone 2 (larch stand) and zone 3 (dense forest).

The results of the extreme value distribution (Table 5) are specified for a 20–50- and 150-year return period (the 150-year period was chosen, because it is used in many countries for the purpose of avalanche hazard zoning). Table 5 illustrates that glide rates in the clearings (measuring zones 4, 5 and 6) already exceed 7.5 mm day^{-1} for a 20-year return period. According to Höller (2012), glide rates can be divided into four levels: (1) very high (>30 mm day^{-1}), (2) high (30–7.5 mm day^{-1}), (3) moderate (7.5–1.5 mm day^{-1}) and (4) low (<1.5 mm day^{-1}). A rate of more than 7.5 mm day^{-1} is a critical value for juvenescent trees (Höller 2012). Glide rates in the forest (measuring zone 3) are shown to have been almost negligible (even under the assumption of a high return period; Table 5); according to this classification, all values in the clearings thus belong to class 2, whereas glide rates in the forest only belong to classes 3 and 4. These results can also be used to derive the necessary stem density. In order to achieve glide rates not exceeding the indicated values of class 4, the stem density should be in the range of the corresponding values of measuring zone 3 (about 300 to 350 stems/ha).

5 Discussion and conclusions

Essentially, the determined glide rates found in this study fit well with the results of other investigations. In der Gand (1968b) has measured snow gliding near to Davos, finding mean glide rates of between 1.7 mm day^{-1} (1960/1961) and 29.5 mm day^{-1} (1965/1966). Clark and McClung (1999) investigated snow gliding on a plane rock slope near to the Coquihalla Passes (Canada); their measurements, made in 1992/1993 and 1993/1994, show averaged glide rates of between 4.2 mm day^{-1} (March 1993) and 21.6 mm day^{-1} (November 1993). According to Clarke and McClung (1999), full-depth avalanches are generally triggered when glide rates exceed 10 to 15 mm day^{-1}. Considering a 50-year return period, values of this magnitude are possible for at least four of the measuring zones (open slope, small clearing and large clearing; see Table 5). It can therefore be concluded that the release of avalanches is possible on open slopes but may also be possible within forest sites similar to measuring zones 6, 7 and 8 (provided that the return period is at least 50 years).

The degree of glide rates changed from year to year (Table 3). This variability can be explained by the different

Table 5 Calculated maxima of mean glide rates per day (millimetres per day) for a 20-, 50- and 150-year return period; $x=-\ln(\ln(T/T-1))$, T=return period. Equations are based on values of Table 2

	Equation	20-year return period	50-year return period	150-year return period
Open slope (1)	$y=1.875+6.001x$	19.70	25.28	31.92
Open forest (2)	$y=0.441+0.414x$	1.67	2.06	2.51
Dense forest (3)	$y=0.098+0.144x$	0.53	0.66	0.82
Small clearing (4)	$y=1.094+2.713x$	9.15	11.67	14.68
Boundary of large clearing (5)	$y=1.291+3.132x$	10.59	13.51	16.97
Centre of large clearing (6)	$y=0.880+2.340x$	7.83	10.01	12.60

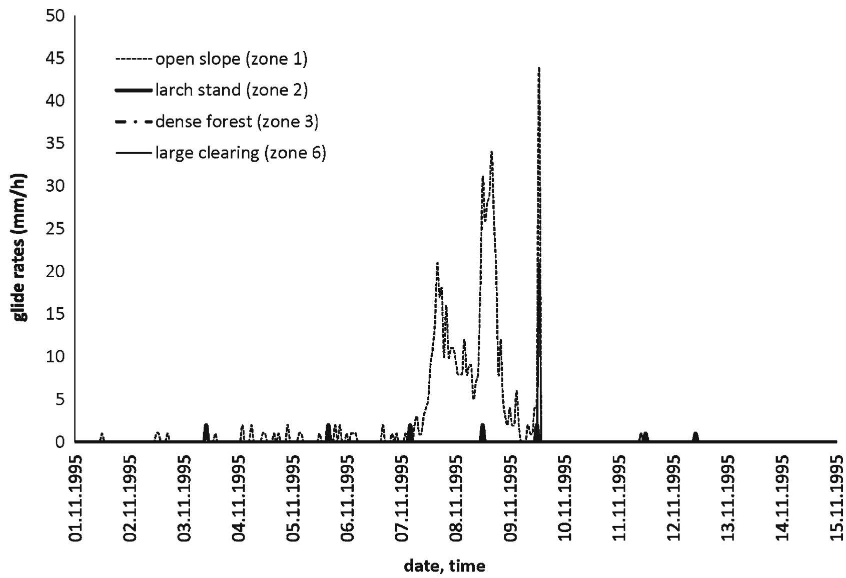

Fig. 6 Glide rates (millimetres per hour) on four different measuring locations of the experimental site in the Stubaital in the first 2 weeks of November 1995

weather and snow conditions (Höller 2001a, b). For example, snow depth in the periods 1995/1996 and 1996/1997 was below average, which led to relatively low glide rates. However, changes in plant cover with time must also be taken into account. In particular at measuring zone 1 (open slope), where young trees are becoming established (e.g. spruce), snow gliding at the beginning of the observation period (1992/1993) was clearly higher than in the later years (Table 3).

The statistical analysis indicated that glide rates in the clearings were clearly greater than in the forest. There was found to be a strong increase of snow gliding in the clearings and gaps of south-facing larch stands. High glide rates were measured not only at measuring zones 5 and 6 (large clearing) but also in the small clearing with dimensions of only 8×8 m (measuring zone 4). Snow gliding is, however, relatively low in the forest; the frequencies in class 2 indicated moderate glide velocities in the forest (measuring zones 2 and 3). In contrast, these measurements yield glide rates in the large clearing (20×30 m) of 81 mm h^{-1} (1992/1993).

Previous investigations have found that glide rates of this kind of magnitude mainly occur when the glide movement develops to a so-called glide crack. Glide cracks are half-moon crevices which open in the snow cover as a result of tensile failure during rapid gliding (In der Gand and Zupancic 1966).

Lackinger (1988) measured snow gliding on a south-west-facing slope of 36–42° near Innsbruck, Austria. He found glide rates of 60 mm h^{-1} in April 1987, after the snow cover had ruptured. In November 1952, In der Gand (1954) observed glide rates of 168 mm h^{-1} on a south–south-east-facing slope (inclination approximately 38°) in the Parsenn area of Switzerland. In December 1954, he observed rates of over 200 mm h^{-1} on a south-facing slope near Davos, Switzerland (In der Gand 1956). In both cases, the gliding was released by glide cracks. Using the results of this study and the findings from In der Gand (1954) and Lackinger (1988), it can be assumed that glide cracks should be expected not only on open slopes but also at forest sites that are similar to measuring zones 4, 5 and 6 (forest clearings). This assumption was confirmed by observations from the author (see Fig. 2).

As described by In der Gand (1968b), major glide rates are those that are combined with glide cracks and gliding snow sluffs. Major glide rates are able to cause forces that may affect afforestation. According to the four levels of glide rates devised by Höller (2012; see above), gliding snow sluffs occur almost exclusively on slopes with very high glide rates (1), while glide cracks can be expected on slopes with a high level of snow gliding (2). This implies that only glide rates with a high (2) or very high (1) intensity can be considered as critical for juvenescent trees. The necessary force to uproot young trees (stem diameter 0.025 m, height 0.5 m) is about 1,000 N (Höller et al. 2009); according to Höller et al. (2009), values of this magnitude can be regularly caused by gliding on a smooth ground surface (where glide rates correspond to a high (2) and very high (1) intensity). To ensure tree growth under these conditions, it may not be sufficient to plant a high number of tress. Although 3,000 to 5,000 plants/ha were afforested in the surroundings of the experimental site (unpublished map of the Austrian Service for Torrent and Avalanche Control), many trees were damaged by intensive gliding (Höller et al. 2009). In order to reduce gliding (and to avoid snow glide damages), appropriate measures (see below) must be considered.

The lower glide rates in the forest mainly result from the anchoring effect of the stems, which stabilize the lowermost layers of the snowpack. The influence of the forest on gliding, with respect to air temperature, is negligible (according to Höller (1998, 2001), the forest has a significant influence on the snow surface temperature [warmer snow surface in the forest] but less influence on air temperature).

The results indicate that, under the given conditions (south-facing slope with 30° inclination, very smooth surface and 0.7 m snow depth), 300 to 350 stems/ha are sufficient to achieve low-intensity glide rates (class 4). Slightly lower stem numbers (200–250 stems/ha—comparable to measuring zone 2) cause higher glide rates, although these rates do not exceed the values in class 3. As snow gliding increases with inclination and snow depth (Haefeli 1939; In der Gand and Zupancic 1966), it has to be assumed that on slopes inclined by greater than 40° and at snow depths of 2 m, a forest with about 200 to 250 stems/ha (comparable to measuring zone 2) will be insufficient to keep glide rates within the range of class 3.

When stem numbers decreased even further (<100 stems/ha; comparable to measuring zones 4, 5 and 6), snow gliding clearly increased; the glide rates are already within class 2, and juvenescent trees can be expected to be damaged by extraction from the ground. This means that at locations such as these, it is necessary to reduce snow gliding by the use of appropriate measures (see below). The suggestions with reference to stem numbers are based on conditions of a very smooth ground surface, and it is clear that a rougher ground surface will have lower glide rates; however, this should not be taken as a basis for having lower stem numbers. In any case, we have assumed that 300 to 350 stems/ha are required in order to keep glide rates within class 4. If it is not possible to achieve this number of stems (and thus to keep the glide rates in the range of class 4 or at least class 3), then it is necessary to reduce glide rates by the use of appropriate measures.

According to Höller (2012), technical systems (e.g. small wooden supporting structures) are needed to facilitate a considerable reduction in snow gliding where there are very high glide rates (class 1); glide rates of a high intensity (class 2) can also be reduced by measures which increase the roughness of the ground surface (earth peaks and small terraces).

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References

Ammer U, Mössmer EM (1986) Technische Maßnahmen gegen Schneebewegungen zum Schutz von Aufforstungen und Naturverjüngungen in Gebirgslagen. Mitt. Staatsforstverwaltung Bayern 43:7–78

Clarke J, McClung D (1999) Full-depth avalanche occurrences caused by snow gliding, Coquihalla, British Columbia, Canada. J Glaciol 45: 539–546

de Quervain M (1966) Problems of avalanche research. IAHS-Publ 69: 15–22

Dyck S, Peschke G (1983) Grundlagen der Hydraulik. VEB Verlag fur Bauwesen, Berlin, 388 pp

Frutiger H, Kuster J (1967) Über das Gleiten und Kriechen der Schneedecke in Lawinenverbauungen. Schweiz Z Forstwesen 10: 633–643

Gumbel EJ (1958) Statistics of extremes. Columbia Univ. Press, New York, 375 pp

Haefeli R (1939) Schneemechanik mit Hinweisen auf die Erdbaumechanik. In: Der Schnee und seine Metamorphose. Beiträge zur Geologie der Schweiz – Geotechnische Serie – Hydrologie, Lieferung 3,Kümmerly und Frey, Bern, 65-241

Höller P (1998) Tentative investigations on surface hoar in mountain forests. Ann Glaciol 26:31–34

Höller P (2001a) The influence of the forest on night-time snow surface temperature. Ann Glaciol 32:217–222

Höller P (2001b) Snow gliding and avalanches in a south-facing larch stand. In: soil-vegetation-atmosphere transfer schemes and large scale hydrological models (Proc. Maastricht Symp., July 2001), IAHS Publ. 270: 355–358

Höller P (2012) Zur Bestimmung schneegleitgefährdeter Standorte und Planung von Gleitschutzmaßnahmen bei Hochlagenaufforstungen. Allg Forst und Jagdzeitschrift 183:94–100

Höller P, Fromm R, Leitinger G (2009) Snow forces on forest plants due to creep and glide. Forest Ecol Manag 257:546–552

In der Gand H (1954) Beitrag zum Problem des Gleitens der Schneedecke auf dem Untergrund. Winterbericht Eidg. Inst. f. Schnee-und Lawinenforschung 17:103–117

In der Gand H (1956) Spezielle Lawinen- und Lawinenuntersuchungen im Parsenngebiet. Lawinen und Gleitschnee Winterbericht Eidg. Inst. f. Schnee-und Lawinenforschung 19:93–101

In der Gand H (1968a) Neue Erkenntnisse über das Schneegleiten. Schweiz Bauzeitung 86:557–661

In der Gand H (1968b) Aufforstungsversuche an einem Gleitschneehang Mitteilungen der Schweizerischen Anstalt für d. Forstl. Versuchswesen 44:233–326

In der Gand H, Zupancic M (1966) Snow gliding and avalanches. In: Scientific aspects of snow and ice avalanches (Proc. Davos Symp., April 1965), IAHS Publ. 69: 230–242

Lackinger B (1988) Zum Problem der Gleitschneelawine. Proc Interpraevent 1988, Graz 3:205–226

Leuenberger F (1989) Temporärer Stützverbau und Gleitschneeschutz. Handbuch/Bauanleitungen des EISLF, 1. Auflage

Margreth S (2007) Defense structures in avalanche starting zones. Technical guideline as an aid to enforcement. Environment in Practice no. 0704. Federal Office for the Environment, Bern; WSL Swiss Federal Institute for Snow and Avalanche Research SLF, Davos, 134 pp

McClung D (1975) Creep and the snow–earth interface condition. In: Snow Mechanics (Proc. Grindelwald Symp., April 1974), IAHS Publ. 114: 236–248

McClung D, Clarke GKC (1987) The effects of free water on snow gliding. JGeophys Res 92:6301–6309

McClung D, Schaerer P (2006) The avalanche handbook. The Mountaineers Books, Seattle, 342 pp

Meyer-Grass M (1985) Waldlawinen: Gefährdete Bestände, Maßnahmen. Merkblatt No. 1 Eidg. Institut für Schnee- und Lawinenforschung, 6pp

Mössmer EM, Ammer U, König A (1990) Eignung von Baumarten zur Verjüngung gleitschneegefährdeter Schutzwaldflächen im bayerischen Hochgebirge. Allg Forstzeitschrift 9–10

Salm B (1977) Snow forces. J Glaciol 19:67–100

Zenke B (1985) Lawinenstriche im Bergwald. Jahrbuch des Vereins zum Schutz der Bergwelt 49–63