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TITLE: Snow gliding and loading under two different forest stands: a case study in the north-western Italian Alps.

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Davide Viglietti, male, was born in Cuneo on 7th of June 1980. He is PhD graduated in Forestry and Environmental Sciences at University of Turin, Faculty of Agriculture.

ABSTRACT:

26 The presence of a thick snowpack could interfere with forest stability, especially on steep
27 slopes with potential damages for young and old stands. The study of snow gliding in forests is
28 rather complex because this phenomenon could be influenced not only by forest features, but also
29 by snow/soil interface characteristics, site morphology, meteorological conditions and snow
30 physical properties. Our starting hypothesis is that different forest stands have an influence on the
31 snowpack evolution and on the temperature and moisture at the snow/soil interface, which,
32 subsequently, could affect snow gliding processes and snow forces.

33 The study site is located in a subalpine forest in Aosta Valley (NW-Italy) and includes two plots at
34 the same altitude, inclination and aspect but with different tree composition: Larch (*Larix decidua*)
35 and Spruce (*Picea abies*). The plots were equipped with moisture and temperature sensors placed at
36 the snow/soil interface (O horizon) and glide shoes for continuous monitoring of snow gliding. The
37 recorded data were related to periodically monitored snowpack and snow/soil interface properties.
38 Data were collected during two winter seasons (2009-10 and 2010-11). The snow forces on trees
39 were analytically calculated either from snowpack data and site morphology or also from measured
40 snow gliding rates.

41 Different snow accumulation were observed under the two different forest stands, with a significant
42 effect on temperature and moisture at the snow/soil interface. The highest snow gliding rates were
43 observed under Larch and were related to rapid increases of moisture at the snow/soil interface. The
44 calculated snow forces were generally lower than the threshold values reported for tree uprooting
45 due to snow gliding, as confirmed by the absence of tree damages in the study areas.

46

47 **KEY WORDS:** snow/soil interface; temperature; water content; snow forces; trees

48 **1. Introduction**

49 Snow forces are a result of glide and creep processes of the snowpack: a) snow gliding is the slow
50 downhill motion of the snow on the ground mainly influenced by the roughness of the ground
51 surface and the wetness of the lowermost boundary layer of the snow cover; b) snow creep is the
52 result of settlement and internal shear deformation parallel to the slope (In der Gand and Zupancic
53 1966).

54 The snow gliding is strictly dependent on physical snow characteristics, overall depth, density and
55 moisture, and on morphological features, overall slope angle and surface roughness (McClung and
56 Larsen 1989; Jones, 2004; Margreth 2007; Höller et al. 2009). In the first period of extensive
57 research of glide processes and glide avalanches, Bader et al. (1939) found that the most important
58 factors that have an effect on glide are slope exposure, degree of surface roughness, temperature at
59 the ground surface and the thickness and properties of the snow cover. They proposed that the
60 primary action of these factors is their effect on the frictional conditions of the slide surface. Basal
61 friction is obviously reduced by the presence of liquid water at the snow/soil interface (McClung
62 and Clarke, 1987). Also Clarke and McClung (1999) stated that gliding can occur if 1) the interface
63 is smooth (e.g. bare rock or grassy vegetation), 2) the temperature at the snow/ground interface is at
64 0° C, guaranteeing the presence of free water at the interface, and 3) the slope angle is at least 15°
65 for roughness typical of alpine ground cover. Moreover, the intensity of gliding rates is strictly
66 related to increases in snow/soil interface temperature and moisture (Lackinger 1987; McClung and
67 Larsen 1989; Clarke and McClung 1999; Newesely et al. 2000).

68 The wide-scale analysis of snow gliding intensity in alpine and subalpine areas has to take into
69 account the land-use changing: the abandonment of pastures and the natural afforestation could
70 cause a significant change on the ground roughness. In particular, Newesely et al. (2000) found that
71 the abandonment of agriculture land may foster an increase of snow gliding rates due to the
72 reduction of basal frictions.

73 Although forests can reduce the snow gliding intensity (Leitinger et al. 2008) by preventing snow
74 accumulation and homogeneous snow distribution due to interception and falling of snow from the
75 crowns (Höller 1995, 2001), it is not possible to totally exclude snow gliding in forest. Snow
76 gliding might have significant effects on forest plants; in particular, juvenescent trees might be
77 uprooted from the ground or the growth of young plants might be strongly affected by the snow
78 forces (In der Gand 1978). According to these evidences, Höller et al. (2009) evaluated, with
79 different approaches, the snow gliding rates in an Austrian subalpine stand of small trees (*Pinus*
80 *cembra*, *Larix decidua* and *Picea abies*). In the same work, snow forces measured in field, and
81 back-calculated with different equations, were compared to the forces necessary to uproot the young
82 trees: the authors measured that forces equal to 950 N and 3500 N can uproot juvenescent trees with
83 a diameter of 0.02 m and 0.045 m, respectively.

84 The study of the snow gliding phenomenon in forests is rather complex because it is influenced not
85 only by forest features (species, crown, diameter and density), but also by site (slope angle,
86 morphology, aspect), meteorological (air temperature, rain on snow events) characteristics and
87 snowpack structure. Moreover, the impact of snow forces on trees depends on the forest
88 characteristics itself, and it could lead to different consequences in term of tree stability.

89 The aim of this work is to analyse the snowpack evolution and snow gliding movements under
90 different forest covers Larch (*Larix decidua*) and Spruce (*Picea abies*) stands, in order to determine
91 the snow forces acting on trees of different species and diameters. In particular, we aim at
92 evaluating the influence of physical properties as temperature and moisture at the snow/soil
93 interface on snow gliding processes, and consequently on snow forces.

94 **2. Methodology**

95 2.1. The study site

96 As this research was developed within the project “Forêts de protection: techniques de gestion et
97 innovation dans les Alpes occidentals” in the frame of the Operational Program ALCOTRA Italy-
98 France (2009-2012), the study site was chosen within a snow avalanche protection forest. It is
99 located in the Municipality of Brusson, in the Aosta Valley Region (North Western Italian Alps), at
100 an elevation of 1950 m a.s.l. It is characterized by a south aspect and a mean slope angle of about
101 40°. The coniferous mixed forest of the study site is mainly composed of larch (*Larix decidua*),
102 spruce (*Picea abies*) with a lower presence of pinus (*Pinus uncinata*). The lower part of the forest
103 was reforested in 1940, in order to protect the village beneath, and it was pastured.

104 The climate of the area is continental humid subarctic, with a mean annual air temperature equal to
105 + 4 °C and a mean annual precipitation equal to 718 mm. The mean annual snow depth is 175 cm
106 (Mercalli et al. 2003).

107 Two adjacent plots (40x40 m), located at the same elevation and aspect, were chosen (Fig. 1): a)
108 one within a larch stand (Larch plot) and b) another one within a spruce stand (Spruce plot). By
109 counting all trees in each plot (with stem diameter > 5 cm) the average stem density was determined
110 equal to 300 stems/ha for both plots. The crown canopy, measured as crown projection, amounted
111 to 60% for the Larch plot and 65% for the Spruce plot. The average stem diameter was 40 cm and
112 the most of the trees were included in the range 30 - 40 cm (10 cm interval). The natural
113 regeneration was generally scarce.

114 2.2 Data collection

115 At the snow/soil interface (O horizon) each plot was equipped with thermistor probes, with
116 accuracy of ± 0.1 °C, (MadgeTech®) and volumetric moisture probes, which measure the dielectric
117 constant of the media through the utilization of capacitance/frequency domain technology, with

118 accuracy of ± 3 % VWC, (EC-5MadgeTech). Temperature and moisture measured at snow/soil
119 interface were named respectively as Ti and Mi.

120 Moreover, two glide shoes connected to potentiometers (Sommer®) (Fig. 2) as developed by In
121 der Gand (1954) and successively applied by other scientists (e.g. Leitinger et al. 2008; Höller et al.
122 2009), were placed in each plot at a minimum distance of 5 m below the first upwards tree. The
123 potentiometers were calibrated in order to convert the electric signal registered by the snow shoes
124 into downward movement (mmd^{-1}), caused by snow gliding. All sensors were connected with a
125 central data logger (Datataker® DT-80) supplied by a long duration battery and set to record the
126 different parameters every 15 minutes. The electric wires were cabled underground in order to
127 minimize their effect on the surface roughness.

128 The meteorological data were acquired by an automatic snow and weather station closed to the site
129 (Gressoney-Weissmetten 2038 m a.s.l.) belonging to the Ufficio Centro Funzionale of the Aosta
130 Valley Region.

131 The snowpack physical characteristics (snow depth $-H_S-$, snow density $-\rho-$, grain types and size,
132 snow temperatures, hand hardness index) were measured monthly, following standard international
133 methods (Fierz et al., 2009): 8 snow profiles in winter 2009-10 and 3 snow profiles in winter 2010-
134 11 were done in both plots. The damages to the trees were evaluated in the field by observations of
135 eventual uprooted trees and broken branches at the end of winters.

136 Data collection was done from the middle of November 2009 until the end of April 2010 (called
137 winter 2009-10) and from the middle of November 2010 until the end of April 2011 (called winter
138 2010-11). The seasons were identified according to meteorological quarterly subdivision: fall
139 included September, October, November; winter included December, January and February; spring
140 included March, April and May.

141 2.3 Calculation of snow forces

142 The calculation of snow forces on stems was done following the approach used by Höller et al.
143 (2009). In particular, two different methods were applied by using a) empirical equations (Margreth
144 et al., 2007) - see section 2.3.1 - and b) snow gliding data recorded with glide shoes (Mc Clung and
145 Larsen, 1989) - see section 2.3.2. We calculated snow forces for different stem diameters (0.02,
146 0.05, 0.1, 0.2, 0.3, 0.4, 0.5 m) in order to consider the real diameter distribution observed in the
147 field and to compare our results with the available literature.

148

149 2.3.1 Snow pressure according to the Swiss guidelines

150 Margreth et al. (2007) applied the Swiss Guidelines with some improvements in order to calculate
151 snow pressure on cableway masts. The snow pressure was calculated with the following equation
152 (Eq.1):

153

$$154 \qquad \qquad \qquad \mathbf{Eq.1} \qquad \qquad S'_N = \rho g (H_S^2 / 2) K N$$

155 where:

156 S'_N is the snow pressure component in the line of slope per meter run of the supporting surface along
157 the contour line [kNm^{-1}];

158 ρ is the density of the snow cover [tm^{-3}];

159 g is the gravitational acceleration [ms^{-2}];

160 H_S is the vertical snow depth [m];

161 K is the creep factor dependent on the slope inclination ψ and the density ρ ;

162 N is the glide factor.

163

164 In Margreth et al. (2007) the K factor was associated to fixed snow density values. We interpolated
165 those values in order to calculate the exact K factor from the snow density that we measured in the
166 field ($y = 0.73 x + 0.547$, $r^2 = 0.991$, where y corresponds to $K/\sin 2\psi$ and x to ρ). After that, $K/\sin 2\psi$
167 was multiplied by $\sin 2\psi$ (where ψ corresponds to the inclination of the study site).

168 In Margreth et al. (2007), the N factor depends on the ground roughness and aspect: it increases
169 from WNW-N-ENE to ENE-S-WNW and it is inversely related to the ground roughness. Forest is
170 not a determining parameters in the choice of N . Therefore, in our forested plots, we used the
171 ground class 1, assuming that stems determined a high surface roughness (more than boulders). The
172 study site was included in the ENE-S-WNW aspect class, because it is located on a South slope.
173 Finally, we chose a glide factor N equal to 1.3.

174 Equation 1, which is valid only for infinitely long planes, was integrated, as suggested by Margreth
175 et al. (2007), with a coefficient (η_F), in order to consider the end-effect forces on narrow obstacles.
176 η_F was calculated with the following equation (Eq. 2):

177

178 **Eq.2** $\eta_F = 1 + c(D/W)$

179 where:

180 D is the snow thickness (calculated as $H_S \cdot \cos \psi$, where H_S is the vertical snow depth measured in the
181 field and ψ is the slope angle);

182 W is the width of the structure (that corresponded to the stem diameter);

183 c is a non-dimensional coefficient and depends on the snow gliding intensity. It is usually deduced
184 from the Swiss Guidelines. We used the smallest coefficient ($c = 0.6$) because the snow gliding is
185 typically low in dense forest areas (Höller 2001).

186 Subsequently, equations 1 and 2 were joined in equation 3:

187

$$\text{Eq.3} \quad S'_{N,M} = \rho g (H_s^2/2) K N \eta_F (W/D)$$

189

190 Finally, the snow pressure $S'_{N,M}$ was multiplied by the different stem diameter classes in order to
 191 compare our results, in term of forces, with those presented by Höller et al. (2009).

192

193 2.3.2 Snow pressure according to Mc Clung and Larsen (1989)

194 This method considered the snow gliding rates directly measured in the field to determine principal
 195 stress on structures in dependence of the stagnation depth:

196

$$\text{Eq.4} \quad \sigma = \{ [2/(1-\nu)] [(d'/D) + (L/H_s)] \} 0.5 \rho g D \sin \psi + 0.5 [\nu/(1-\nu)] \rho g D \cos \psi$$

198

199 where:

200 σ is the maximal principal stress of the snow on a structure [Nm^{-2}];

201 ν is the Poisson coefficient deduced from Salm et al.(1971). We used $\nu = 0.1$ that corresponds to a
 202 mean snow density of 250 kgm^{-3} , equal to the density we measured in our plots;

203 L/H_s is a dimensionless creep parameter calculated by McClung and Larsen (1989) equal to $0.27 +$
 204 $(\nu/12)$;

205 D is the snow thickness;

206 ρ is the snow density measured in the field [kgm^{-3}];

207 g is the gravitational acceleration [ms^{-2}];

208 ψ is the slope angle;

209 d' is the stagnation depth.

210

211 The stagnation depth is a fundamental parameter to formulate the boundary condition at the
212 snow/soil interface. We calculated the stagnation depth d' from the measured snow gliding rates
213 using Equation 5 (McClung, 1974):

214

215 **Eq.5** $d' = [\mu V_g] / [2(1 - \nu) \rho g D \sin \psi]$

216 where:

217 μ is the viscosity, equal to 10^{11} Pa for snow;

218 V_g is the snow gliding velocity [mmd^{-1}]. According to Hoeller (2009) we used the maximum daily
219 snow gliding rate recorded during winters 2009-10 and 2010-11;

220 ν is the Poisson coefficient.

221

222 2.4 Statistical analysis

223 Descriptive statistics were used to analyzed meteorological pattern, snow physical characteristics,
224 and snow gliding data. Correlation analysis between temperature and moisture at snow/soil
225 interface and between air temperature and temperature and moisture at snow/soil interface were
226 carried out using the SPSS 12.0 for Windows (SPSS, 2003).

227

228 **3. Results and discussion**

229 3.1 Winter 2009-10

230 3.1.1 Meteorological pattern

231 The mean air temperatures was -5.2 °C with a minimum value of -14.3 °C registered on 19th of
232 December 2009 (Fig. 3a). This season was characterized by one short mild period, from December
233 6th to 10th, when the air temperature reached positive values with a maximum of +3.9 °C. The mean
234 daily air temperature became constantly positive after 20th of April 2010. Concerning precipitations,
235 the automatic weather station recorded a cumulative precipitation equal to 330 mm of snow water
236 equivalent (SWE). The maximum snow depth (135 cm) was reached on 2nd of April 2010.
237 The cumulative snowfall was lower than the 75 years historical data (488 mm of SWE) reported by
238 Mercalli et al. (2003): in particular, the difference was remarkable especially during January,
239 February and April.

240 3.1.2 Snow physical characteristics

241 In the *Larch plot*, the measured snow depth reached a maximum of 60 cm on January 13th. The snow
242 density ranged between 184 kgm⁻³ (on January 13th) and 362 kgm⁻³ (on March 3rd). The first snow
243 profile (December 9th) shown an isothermal snowpack with a basal layer characterized by slush
244 crystals (MFsl). From the middle of December to the middle of February the thermal gradient
245 increased and determined the formation of faceted crystals (MCso) and depth hoar (DHcp). In
246 March the snowpack was again mostly at isothermal conditions with a predominance of melt-freeze
247 crusts (MFcr).

248

249

250 The maximum snow depth measured in the *Spruce plot* (66 cm) was reached on February 2nd. The
251 snow density ranged between 163 kgm⁻³ (on December 22nd) and 296 kgm⁻³ (on March 3rd). From
252 the middle of December till the middle of February the thermal gradient increased and determined
253 the formation of faceted crystals (MCso) and depth hoar (DHcp). In March the snowpack reached
254 isothermal conditions with a predominance of cluster rounded crystals (MFcl).

255 3.1.3 Temperature and moisture at the snow/soil interface

256 In the *Larch plot*, the temperature at the snow/soil interface T_i (Fig. 3b) was positive until
257 December 10th, except on November 29th, when a first freezing event occurred (daily average $T_i = -$
258 1.3 °C). Later T_i remained below 0 °C from the middle of December until the end of March. A
259 sharp increase of T_i (which reached 0 °C) was observed on December 26th, January 1st, February
260 19th, March 3rd and March 18th. The moisture at the snow/soil interface M_i (Fig. 3c) was correlated
261 with the soil ($r = +0.498$; $p < 0.01$) and air temperatures ($r = +0.418$; $p < 0.01$). The maximum
262 values were recorded several times during this winter season and in particular on December 8th
263 (21%), with a wetting rate of 2%/day for 11 days, on December 25th (20%), with a wetting rate of
264 15% in one day and on February 26th (22%) with a wetting rate of 5%/day for 2 days. The period
265 between the beginning of January and the middle of February was characterized by a constant value
266 of M_i close to 10%.

267

268 In the *Spruce plot* the temperature at the snow/soil interface T_i (Fig. 3b) was positive until
269 November 29th ($T_i = -0.8$ °C). Later T_i remained constantly below 0 °C from the middle of
270 December until the end of March. The moisture at the snow/soil interface M_i (Fig. 3c) showed
271 remarkable oscillations until the beginning of January, with 3 maximum values recorded on
272 November 16th (14%), with a wetting rate equal to 2.5%/day for 4 days, on December 11th (15%),
273 with a wetting rate of 1%/day for 14 days and on December 25th (13%), with a wetting rate of

274 6.5%/day for 2 days. Later, M_i remained constant (around 5%) until March 19th. From March 19th to
275 24th a remarkable increase was observed (+3.2%/day), reaching a moisture value of 21.3% on
276 March 24th. M_i was correlated with T_i ($r = +0.641$; $p < 0.01$) and air temperature ($r = +0.631$, $p <$
277 0.01).

278 3.1.4 Snow gliding

279 While not any snow gliding event was observed in the *Spruce plot*, in the *Larch* one, only a single
280 event of snow gliding occurred (Fig. 3d) between December 1st and 14th after the first seasonal
281 snowfall of 30 cm. In this period, M_i rose by 20% and the dominant grain type in the basal layer
282 observed on December 9th was slush (MFsl), indicating a consistent presence of liquid water. The
283 cumulative movement of the glide shoes was equal to 19 mm, with an average daily snow gliding
284 rate of 1.9 mm/day for 10 days and a maximum daily snow gliding rate of 3.9 mm/day. The
285 volumetric moisture at the snow/soil interface increased with a wetting rate +3.8%/day for 5 days.
286 From the middle of December until the end of the monitoring period, no snow gliding was
287 observed, although a significant increase of snow/soil interface temperature and moisture was
288 recorded at the end of March (wetting rate of +1.5 % day for 12 days).

289

290 3.1.5 Snow forces

291 In the *Larch plot*, the snow forces on stems with different diameters, calculated by Equation 3, as
292 in Margreth et al. (2007), ranged from 3 to 290 N (Fig. 4a). Two maximum values were calculated:
293 the first at the middle of January ($H_S = 60$ cm and $\rho_{\text{snow}} = 184 \text{ kgm}^{-3}$) and the second at the
294 beginning of March ($H_S = 47$ cm and $\rho_{\text{snow}} = 362 \text{ kgm}^{-3}$).

295 We also calculated the snow forces as in Mc Clung and Larsen (1989), in correspondence of the
296 single snow gliding episodes (beginning of December), when a movement of 3.9 mmday^{-1} was

297 registered by the snow shoes. The necessary input values for the snow depth and density were taken
298 from the snow pit dug on 9th of December: $H_S = 25$ cm and $\rho_{\text{snow}} = 250 \text{ kgm}^{-3}$. The resulting
299 forces ranged from 11 to 284 N on the different stem diameters (Tab. 2).

300

301 In the *Spruce plot* the snow forces on stems with different diameters, calculated by Equation 3, as
302 in Margreth et al. (2007), ranged from 2 to 361 N (Fig. 4b). A maximum was observed at the
303 middle of February, when H_S was equal to 66 cm and $\rho_{\text{snow}} 231 \text{ kgm}^{-3}$.

304 During winter 2009-2010, it was not possible to calculate the snow forces as in Mc Clung and
305 Larsen (1989), as no snow gliding event occurred under Spruce.

306

307 3.2 Winter 2010-11

308 3.2.1 Meteorological pattern

309 In winter 2010-11 the mean air temperatures was -3.0 °C with a minimum value of -14.3 °C
310 recorded on 18th of December (Fig. 3). Winter 2010-11 was characterized by frequent and longer
311 mild periods than winter 2009-2010. The mean daily air temperature became constantly positive
312 from 22nd March. Concerning precipitations, the automatic weather station recorded a cumulative
313 precipitation equal to 298 mm of snow water equivalent (SWE). The maximum snow depth (156
314 cm) was reached on 17th March 2011.

315 The cumulative snowfalls was lower than the 75 years historical data (488 mm of SWE) reported by
316 Mercalli et al. (2003): in particular, the difference was remarkable especially during January,
317 February and April.

318 3.2.2 Snow physical characteristics

319 In the *Larch plot*, a maximum snow depth equal to 28 cm was observed on December 2nd. The
320 snow density ranged between 146 kgm^{-3} (on December 2nd) and 340 kgm^{-3} (January 18th). The first

321 snow profile shown a kinetic metamorphism with the presence of faceted crystals (FCso), which
322 we found also on January 18th. Moreover the dominant grain type in the basal layer was rounded
323 polycrystals (MFpc) suggesting a previous presence of liquid water. On March 23rd a prevalence of
324 cluster rounded crystals (MFcl) was observed.

325 In the *Spruce plot*, the maximum snow depth was observed in the last snow profile (28 cm) on
326 March 23rd. The snow density ranged between 230 kgm⁻³ (on December 2nd) and 320 kgm⁻³ (January
327 18th). The first snow profile revealed the beginning of kinetic metamorphism, with faceted crystals
328 (FCso) as prevalent crystals; moreover a thin ice layer (IFil) was observed at the bottom of the
329 snowpack. On March 23rd a prevalence of rounded crystals (RGlr) was observed.

330

331 3.2.3 Temperature and moisture at the snow/soil interface

332 The temperature sensors in the *Larch plot* were repeatedly damaged by rodents, therefore the
333 measurements were interrupted. The recorded T_i values ranged only from November to December
334 and from the end of January until the middle of February (Fig. 3b).

335 The moisture at the snow/soil interface M_i (Fig. 3c) was characterized by 4 sharp increases: the first
336 (34%) occurred from November 14th to 16th (wetting rate: +12%/day); the second (34%), occurred
337 from December 5th to 9th (wetting rate: +9%/day); the third (37%) occurred from January 13th to
338 16th (wetting rate: +5%/day); the fourth (32%), occurred from March 13th to 20th (wetting rate:
339 +4%/day). On the contrary, M_i strongly decreased (-25%) from November 21th until December 4th,
340 with a drying rate equal to -1.8%/day. M_i was positively correlated with the air temperature ($r =$
341 +0.256; $p < 0.01$).

342 In the *Spruce plot* the temperature at the snow/soil interface T_i (Fig. 3b) was constantly negative
343 from November 24th until March 3rd, except three periods when it reached 0 °C (December 8th,
344 January 14th to 18th and February 6th to 11th). Two minimum values were reached, on December 18th

345 (-4.6 °C) and January 21th (-4 °C). When the snow/soil interface temperature increased, also the
346 moisture M_i did ($r = +0.650$ $p < 0.01$), and the maximum values, 42%, 49% and 33%, were reached
347 on November 16th, January 15th and February 9th, respectively (Fig. 3c). Instead, the minimum
348 water content measured in the Spruce plot (0%) was reached at the beginning of December when
349 the snow/soil interface was frozen.

350 3.2.4 Snow gliding

351 In the *Larch plot*, several snow gliding events were measured with a cumulative movement of 77
352 mm (Fig. 3d).

353 The first snow gliding event was recorded after the first snowfall (25 cm) at the end of November.
354 From November 13th to November 23rd a cumulative movement of 43 mm was recorded. In this
355 period, T_i was positive (daily average $T_i = 1.4$ °C) and a remarkable snow/soil moisture increase (+
356 7.4%/day for 3 days) occurred. The highest snow gliding rate (1.4 mm/day) was measured on
357 November 17th. In the snow profile dug closer in time to this snow gliding event (December 2nd) the
358 dominant grain type in the basal layer was rounded polycrystals (MFpc), indicating that melt-freeze
359 metamorphism occurred, with the presence of some liquid water.

360 Until the middle of January, the snow gliding rates decreased, with a cumulative value equal to 5.8
361 mm. From January 19th till April 4th other snow gliding events were observed (for a cumulative
362 movement of 29 mm): the highest daily movement was recorded on January 20th (0.4 mm/day) and
363 on March 3rd (0.1 mm/day), after a significant increase of M_i (respectively +2.4/day for 7 days and
364 +8.7 in one day). Especially on January 18th an increase in snow moisture across the snow pack was
365 observed: the basal layer contained a significant amount of liquid water. No snow gliding was
366 observed from February 6th until 16th because the study plot became snow free.

367

368 In the *Spruce plot*, only a single snow gliding event was observed, after the first snowfall, with a
369 cumulative displacement of 16 mm, from the 13th to the 25th November. In the snow profile dug
370 closer in time to this snow gliding event (December 2nd) a thin ice layer (IFil) was observed at the
371 bottom of snowpack indicating a previous presence of some liquid water at the snow/soil interface.
372 The highest snow gliding rate (0.4 mm/day), was measured on November 19th, after a significant
373 increase of the volumetric moisture (+4.75/day for 3 days). From the end of November until the end
374 of the monitoring period, no snow gliding was observed, despite several increments at the snow/soil
375 interface moisture were recorded.

376

377 3.2.5 Snow forces

378 In the *Larch plot*, the snow forces on stems with different diameters calculated by Equation 3 (as in
379 Margreth et al., 2007) ranged from 0.5 to 29 N (Fig. 5a). The snow forces decreased from the
380 beginning of December ($H_S = 28$ cm; $\rho_{\text{snow}} = 146 \text{ kgm}^{-3}$) to the beginning of January ($H_S = 10$ cm;
381 $\rho_{\text{snow}} = 340 \text{ kgm}^{-3}$) and then remained almost constant until the end of the season. Also according
382 to Mc Clung and Larsen (1989), the snow forces decreased across the season since the maximum
383 snow gliding rate, 1.4 mmday^{-1} , was observed on November 17th and the minimum one, 0.1 mmday^{-1} ,
384 was measured on March 03rd. The resulting forces ranged from 2 to 184 N (Tab.2).

385 In the *Spruce plot*, the snow forces on stems with different diameters calculated by Equation 3 (as in
386 Margreth et al., 2007) ranged from 0.6 to 21 N (Fig. 5b). The snow forces were almost constant
387 until the beginning of January ($H_S = 11$ cm; $\rho_{\text{snow}} = 320 \text{ kgm}^{-3}$) and then started to increase until
388 the end of March ($H_S = 28$ cm; $\rho_{\text{snow}} = 260 \text{ kgm}^{-3}$). We also calculated the snow forces as in Mc
389 Clung and Larsen (1989), in correspondence of the single snow gliding episode (second half of
390 November), when a movement of 0.4 mm was registered by the snow shoes. The necessary input
391 values for the snow depth and density were taken from the snow pit dug on December 2nd: $H_S = 20$

392 cm and $\rho_{\text{snow}} = 232 \text{ kgm}^{-3}$. The resulting forces ranged from 3 to 66 N on the different stem
393 diameters (Tab. 2).

394

395 3.3 Comparison between Larch and Spruce plots

396 3.3.1 Snow physical characteristics

397 From our results, it seems that the tree species affect only some physical characteristics of the
398 snowpack. In fact, the crystal type and dimension were similar both under Larch and Spruce stands.
399 Instead, the snow depth evolution had a different pattern within the two sites: in full winter,
400 snowfalls generated a deeper snowpack in the Larch plot, because of the reduction of snow
401 interception due to the absence of leaves in the winter period; on the contrary, in spring, the shadow
402 effect due to the evergreen cover maintained a deeper snowpack and increased the snow duration
403 under the Spruce plot. The same effect of crown interception was found by Gubler and Rychetnik
404 (1991) and Motta (1995).

405 A higher average snow density was observed under Spruce, especially after snowfalls with mild air
406 temperature, maybe due to the liquid water input from the melted snow intercepted by the tree
407 crowns. The snow density under Larch gradually increased and exceeded the values recorded under
408 Spruce, when the direct solar radiation during spring time became relevant.

409 3.3.2 Temperature and moisture at the snow/soil interface

410 The mean snow/soil interface temperature was higher within the Larch than within the Spruce plots,
411 especially during fall and spring. An explanation could be that the greater snow accumulation under
412 Larch during early winter, when the soil was unfrozen, could have reduced the soil cooling rate,
413 while the higher snow depth in the Spruce plot in late winter and spring could have determined a
414 delay in the soil warming. Several authors (e.g. Brooks and Williams 1999; Freppaz et al. 2008)

415 found that approximately a snow depth equal to 30-40 cm accumulating early in the winter season
416 prevents soil from freezing.

417 Concerning the moisture at the snow/soil interface, we registered larger fluctuations in the Larch
418 than in the Spruce plot. The reason might be that a lower crown cover permitted the irradiation to
419 reach the snowpack surface. This energy input increased the snow water content at the surface,
420 which, due to a thin snowpack, was able to percolated until the ground. On the contrary, in the
421 Spruce plot, the larger crown cover made the influence of the irradiation negligible.

422

423 3.3.3 Snow gliding

424 In both years the total snow gliding was higher under Larch than under Spruce. This fact was
425 probably due to a lower snowpack basal friction under Larch than under Spruce, caused by great
426 fluctuations of moisture at the snow/soil interface. The cumulative snow gliding did not exceed 100
427 mm, as found also by Höller (2001) for a dense forest. This result confirmed that snow gliding is
428 generally low when the canopy density is relatively high.

429

430 3.3.4 Snow forces

431 Generally, lower forces were calculated below Spruce than below Larch, due to the larger snow
432 accumulation recorded in the latter site. We did not find any damages to young trees in both plots.

433

434 **4 General discussion**

435 From our results, the snow/soil interface moisture significantly influenced the snow gliding
436 processes. In particular the water content at the snow/soil interface was related to the snow/soil
437 interface temperature; moreover, it resulted strongly positively correlated with air temperature. It
438 seemed that the velocity of the wetting front in the snowpack was strongly influenced by air
439 temperature and snow depth, with a contrasting effect: higher air temperature and lower snow depth

440 let the wetting front to move faster within the snowpack. Jones et al. (2001) also suggested that
441 peak discharges from a snowpack with flow instabilities could be much higher and faster if the pack
442 was homogeneous. In fact, we found that during early winter, when the snow cover was thin and
443 homogeneous (mainly characterized by fresh snow) the volumetric moisture at the bottom increased
444 in less than 24 hours under both plots after the increase of air temperature. Instead, during full
445 winter, when the snowpack was thicker, after an increase of air temperature, the snow/soil interface
446 moisture increased due to the wetting front from the surface (which reached the bottom of the snow
447 cover within a maximum of 4 days) but also due to the increase of the snow/soil interface
448 temperature (which reached 0 °C).

449 The volumetric moisture increase of a relatively dry snow/soil interface (10-20%), seemed to be the
450 most important factors influencing the snow gliding rates: in particular snow gliding was observed
451 with wetting rates higher than 1.2%/day. The increase of volumetric moisture at the snow/soil
452 interface might reduce the snowpack basal friction as suggested by several authors (In der Gand
453 1966; Clarke and Mc Clung 1999; Höller 2001; Margreth et al. 2007). The snow gliding events
454 were mostly recorded, under both plots, during early winter and after the first snowfalls, when the
455 soil was unfrozen, as observed also in long term studies, though done in open field (In der Gand and
456 Zupancic 1966; Hoeller 2001). The first snow at ground melted on mild soil ($T_i > 0.5$ °C), thus
457 determining an increase of moisture at the snow/soil interface, where the dominant crystal type was
458 slush. During winter 2010-11, snow gliding events were observed also during spring time. These
459 phenomena were related to a sudden sharp air temperature increase, which consequently increased
460 the snowpack moisture, followed by a strong air temperature decrease, as observed by McClung
461 (1999). We could hypothesize that the snowpack became stiff and glided, as a block, on the liquid
462 water film previously formed at the soil surface.

463 The calculated snow forces were lower than the values reported in other studies in the Alps (Höller
464 et al. 2009). The differences could be attributed to the lower coefficients we used, because our study

465 site was located under a mature forest stand, while the study site considered for example by Höller
466 et al. (2009) was characterized by young trees. Moreover, our study site was characterized by lower
467 slope angle and lower snow density and thickness than the site studied by Höller et al. (2009).
468 With our data, the application of the method by Margreth et al. (2007), originally elaborated for the
469 dimensioning of the cableway masts, gave lower values than the method by Mc Clung and Larsen
470 (1989), and the differences between the two methods became more significant with larger stem
471 diameters. This difference suggests to directly measure the snow forces by using load cells on the
472 tree trunks, in order to validate the results obtainable with the two different methods.

473 The fact that we did not survey any damages to young trees, such as seasonal uproots and branch
474 breakages, is in agreements with the low snow forces obtained with the two different methods. Our
475 calculated snow forces were lower than the value of 950 N, found by Höller (2009), through pulling
476 test, as the minimum force necessary to cause uprooting of young coniferous trees (*Larix decidua*,
477 *Picea abies* e *Pinus cembra*), with stem diameters ranging from 2.5 to 5 cm.

478 However, the snow characteristics (e.g. density) and meteorological conditions (e.g. sharp increase
479 of air temperature) recorded during the two winters considered in this study, caused significant
480 snow gliding events, mainly during early winter, which contributed to determine not transcurable
481 snow forces on trees, though not producing damages.

482 Since the Climate change is expected to determine milder winter and more unstable snow cover in
483 temperate mountain regions (Cooley 1990; IPCC 2007), it is possible to speculate a change also in
484 the snow gliding processes. In particular, these areas could face a decline in snow cover (late
485 snowpack accumulation and advance of snowmelt timing), an increase of snow density and more
486 frequent episodes of rain on snow (Leung et al. 2004; Ye et al. 2008; Casson et al. 2010). Hence,
487 the basal friction of the snowpack could be reduced by the liquid water on the basal portion of the
488 snowpack and consequently amplify the rate of snow gliding. This fact might generate in future
489 higher pressure on stems diminishing trees stability and therefore the forest protective function.

490

491

492 **5 Conclusion**

493 In this work we evaluated the snowpack physical characteristics, we measured the properties at the
494 snow/soil interface, the snow gliding and we calculated the snow forces on trees of different species
495 and diameters. In particular we observed that:

- 496 a) The snowpack physical evolution (e.g. snow density, snow depth) during the whole winter
497 season was influenced by the tree species, due to the different crown interception of
498 snowfall, and the different degree of exposure of the snowpack to the incoming solar
499 radiation;
- 500 b) The wetting rate at the snow/soil interface, related with the air temperature, seemed to be the
501 most important factor influencing the snow gliding rates. The snow gliding rates seemed to
502 be higher in early winter, when the first snowfall covers an unfrozen soil. In this period,
503 snow gliding was observed after the wetting of a relatively dry snow/soil interface (moisture
504 10-20%) when the increase of moisture exceeded +1.2%/day and the interface temperature
505 was $>0.5^{\circ}\text{C}$;
- 506 c) The highest snow gliding was measured under the Larch stand;
- 507 d) The calculated snow forces were very low under both forest stands, if compared to other
508 studies, mainly because the snow depth and the snow density were scanty during the study
509 period;
- 510 e) According to the Climate change scenarios, it was possible to hypothesize an increase of the
511 snow gliding rates due to a higher moisture at the snow/soil interface.

512

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650 **Figure captions**

651

652 **Fig. 1** Localization of the study site and of the two selected plots

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654 **Fig. 2** Moisture (a) and temperature (b) sensors, and a glide shoe (c), connected to the
655 potentiometer, used in the study site

656

657 **Fig. 3** Snow depth and air temperature measured by the automatic snow and weather station (a); T_i
658 (b) M_i (c) and snow gliding (d) in each plot recorded in both the seasons (2009-10 and 2010-11)
659 when the study site was covered by snow

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661 **Fig. 4** Snow forces calculated according to Margreth et al. (2007) at different stem diameters during
662 winter 2009-10 in the Larch (a) and Spruce plots (b)

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664 **Fig. 5** Snow forces calculated according to Margreth et al. (2007) at different stem diameters during
665 winter 2010-11 Larch (a) and Spruce (b) plots

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674 m. Figures captions

675 Fig. 1: Localization of the study site and of the two selected plots.

676

677 Fig. 2: Moisture (a) and temperature (b) sensors, and a glide shoe (c), connected to the
678 potentiometer, used in the study site.

679

680 Fig. 3: Snow gliding and snow/soil interface volumetric moisture (M_i) recorded under Larch during
681 winter 2009-10.

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683 Fig. 4: Snow gliding and snow/soil interface volumetric moisture (M_i) recorded in all plots in winter
684 2010-11.

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686 Fig.5: Snow forces calculated according to Margreth et al. (2007) at different stem diameters during
687 winter 2009-10 in the Larch (a) and Spruce plots (b).

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689 Fig.6: Snow forces calculated according to Margreth et al. (2007) at different stem diameters during
690 winter 2010-11 Larch (a) and Spruce (b) plots.

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692 Fig.7: Snow forces under the Larch plot on December 4th, 2009, calculated with the two different
693 methods (Margreth et al., 2007 and Mc Clung and Larsen, 1989).

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708 n. Figures

709 Fig.1

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Fig. 2

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Fig. 4

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866 1. Tables

867 Tab.1: Mean values of the physical snow properties (according to Fierz et al., 2009) measured in the
 868 field during winter 2009-10 (8 snow profiles) and 2010-11 (3 snow profiles), under Larch (L) and
 869 Spruce (S) plots. Modal values are shown for categorical variables marked with an asterisk (*).

870

	2009-10		2010-11	
Parameter	L	S	L	S
Maximum value of snow depth (cm)	60	66	28	22
*Grain type in basal layer	FC _{so} , DH _{cp}	DH _{cp}	FC _{so}	FC _{so}
*Dominant grain	FC _{so} , MF _{pc}	FC _{so} , DH _{cp}	RG _{sr}	RG _{sr}
Maximum grain size (mm)	2.5	4	1.5	1.5
Hand hardness Index	3	4	3	2
Snow/soil interface temperature (°C)	-3.8	-2.1	-1.1	-1.8
Date of isothermal condition	March 11 rd	March 19 rd	March 14 rd	March 20 rd
Snow density (kg/m ³)	277	229	220	270

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873 Tab.2: Values of T_i and M_i (standard deviations) averaged over the respective meteorological
874 seasons in 2009-10 and 2010-11. Also the mean air temperature is shown.

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2009-10						
	Fall		Winter		Spring	
	T_i (°C)	M_i (%)	T_i (°C)	M_i (%)	T_i (°C)	M_i (%)
L	2.1 (2.4)	8.5 (8.6)	-2.2 (1.8)	11.8 (4.1)	-0.4 (1.2)	23.0 (6,0)
S	1.4 (1.7)	6.8 (4.5)	-2.7 (1.8)	4.7 (2.9)	-1.3 (1.4)	13.1 (8,2)
Air	2.0 (3.1)		-5.1 (3.6)		-1.9 (4.2)	
2010-11						
	Fall		Winter		Spring	
	T_i (°C)	M_i (%)	T_i (°C)	M_i (%)	T_i (°C)	M_i (%)
L	0.5 (1.7)	25.5 (9.9)	--	16.4 (6.8)	--	16.7 (8.2)
S	0.3 (1.8)	34.8 (5.0)	-1.5 (1.3)	16.5 (10.7)	-0.4 (0,3)	24.1 (5.2)
Air	-3.9 (5.0)		-3.1 (4.2)		0.3 (4)	

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881 Tab.3: Snow forces values calculated according to Mc Clung and Larsen (1989) for the winter
882 2009-10 for the different stem diameter classes under Larch.

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		Forces at different diameter classes (N)						
Date and snowgliding rates		0.02 m	0.05 m	0.1 m	0.2 m	0.3 m	0.4 m	0.5 m
887	December 4 th , 3.9mm/day	11.37	28.43	56.86	113.72	170.58	227.47	284.30

888 Tab.4: Snow forces values calculated according to Mc Clung and Larsen (1989) for the winter
889 2009-10 for the different stem diameter classes under Larch (L) and Spruce (S).

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L							
Date and snowgliding rates	Forces at different diameter classes (N)						
	0.02 m	0.05 m	0.1 m	0.2 m	0.3 m	0.4 m	0.5 m
November 17 th , 1.4 mm/day	7.38	18.46	36.92	73.83	110.75	147.66	184.54
January 20 th , 0.4 mm/day	2.55	6.39	12.77	25.55	38.32	51.10	63.87
March 03 rd , 0.1 mm/day	1.82	4.54	9.08	18.17	27.25	36.34	45.42
S							
Date and snowgliding rates	Forces at different diameter classes (N)						
	0.02 m	0.05 m	0.1 m	0.2 m	0.3 m	0.4 m	0.5 m
November 19 th , 0.4 mm/day	2.62	6.56	13.11	26.22	39.33	52.45	65.56

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