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1 **Hummocks affect soil properties and soil-vegetation**
2 **relationships in a subalpine grassland (North-Western Italian**
3 **Alps)**

4
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13

14

15 **Abstract**

16 Earth hummocks are small cryogenic mounds, covered by grass, closely spaced in grassland or wetlands.
17 Hummock microtopography establishes specific microclimatic conditions, with small-scale variations in soil
18 thermal properties and water regimes, which influence biogeochemical cycles. These properties, coupled
19 with different litter decomposability, may cause variations on soil physical and chemical properties and
20 pedogenesis, as well as a selective distribution of plant species.

21 The work has been carried out at the LTER site of Tellinod (Torgnon, Aosta Valley, NW Italy). The site is
22 characterized by a *Nardus stricta* subalpine hummocky grassland located at 2100 m a.s.l., which shows the
23 dominance of *Nardus* on hummocks and a prevalence of dicotyledons in interhummocks (i.e. the
24 depressions between consecutive hummocks). Such distribution indicates that earth hummock pattern was
25 reflected in soil properties. In order to confirm this hypothesis, we analyzed and compared soil pedogenesis
26 and topsoil characteristics between hummocks and interhummocks. In addition, litter bags were incubated in
27 hummock and interhummock positions to investigate litter decomposition rate as related to microtopography
28 and plant species and its effects on topsoil edaphic properties.

29 The results confirm that hummocky topography significantly influences topsoil properties, pedogenesis and
30 vegetation distribution, with large differences between hummocks and interhummocks. The hummocky soil
31 can be fully classified as Podzol, based on both the morphological and chemical diagnostic properties;
32 however, morphological and chemical evidences indicate that the degree of podzolization differs significantly
33 under hummocks and interhummocks. In addition, the results verify a faster decomposition of dicotyledons in
34 the nutrient-richer interhummock topsoils compared to the podzolized hummocks positions, and an overall
35 slower decomposition rate of *Nardus* litter. All these factors contribute to the creation and conservation of a
36 unique pedo-environment in this subalpine grassland.

37

38 1. Introduction

39 Earth hummocks are small cryogenic mounds generally less than 1.5 m high (Grab, 2005), dome-shaped
40 (Sharp, 1942), covered by grass, usually closely spaced in grassland or wetlands on flat or gentle slopes.
41 They are strictly related to cryoturbation processes, induced by seasonal frost activity and moisture
42 availability, with or without permafrost (Van Vliet-Lanoë, 2014).

43 Earth hummocks are among the most common cryogenic mounds (Grab, 2005) and their presence has been
44 reported in a variety of high-latitude regions (e.g., Tarnocai and Zoltai, 1978; Luoto and Seppälä, 2002;
45 Kvéderová et al., 2011; Van Vliet-Lanoë et al., 1998). Earth hummocks frequently also occur in alpine and
46 subalpine environments both in the northern (e.g. Treml et al., 2010) and southern (e.g., Mark, 1994; Scott et
47 al., 2008; Grab, 1994, 2005) hemispheres and in tropical areas (Grab, 2002). For this reason, earth
48 hummocks have received much research interest.

49 There are many theories about mechanisms of hummock formation. Differential frost heave is the most
50 widely accepted model for hummock development (Van Vliet-Lanoë, 1991; Grab, 2005), but other theories
51 include cryoexpulsion of clasts (Van Vliet-Lanoë and Seppälä, 2002), hydrostatic or cryostatic pressure
52 (Lundqvist, 1969; Tarnocai and Zoltai, 1978) and the cellular circulation model (Mackay, 1980). Given the
53 great number of theories about their formation, hummocks likely have a polygenic development (Beschel,
54 1966; Grab, 2005).

55 Earth hummocks have been recorded in many types of fine-textured, frost-susceptible materials like peat
56 and mineral soils of colluvial and glacial origin (Grab, 2005), which often contain a high percentage of
57 silt/clay. Sectioned hummocks frequently display intrusions of surface horizons or lenses of organic matter at

58 depth that have been convoluted as a result of cryoturbation (e.g., Schunke, 1977; Zoltai and Tarnocai, 1981;
59 Scotter and Zoltai, 1982; Ellis, 1983; Schunke and Zoltai, 1988; Van Vliet-Lanoë, 1991; Gerrard, 1992; Van
60 Vliet-Lanoë et al., 1998). When hummocks lack obvious indications of current activity (contemporary to the
61 present climate conditions), they are regarded as inactive and stable relicts of past cooler climates (McCraw,
62 1959; Billings and Mark, 1961; Mark and Bliss, 1970).

63 Hummocks are most prevalent where snow cover is thin or redistributed by wind (Schunke and Zoltai, 1988):
64 in particular hummocks generally experience thinner and shorter lasting snow cover than interhummocks (i.e.
65 the depressions between consecutive hummocks). Thus, given the thermal insulating role of snow,
66 interhummock ground is generally warmer than hummocks (Mark, 1994; Grab, 1997) in middle-low latitude
67 periglacial environments, which remain frozen for several weeks while interhummock areas are
68 predominantly unfrozen (e.g., Van Vliet-Lanoë, 1991; Mark, 1994; Grab, 1997). The order of freezing
69 between hummocks and interhummock depressions may be more important than the freezing period
70 duration, because differential freezing spatial patterns create short-term temperature gradients that are
71 sufficient for hummock maintenance (Scott et al., 2008).

72 Vegetation has been considered an important factor involved in hummock formation (Tyrtikov, 1969) and
73 development (Schunke and Zoltai, 1988), but at the same time plant communities can be a result of the
74 interactions between hummock occurrence and environmental conditions rather than a factor directly
75 influencing hummock formation itself (Smith, 2011). In fact, microtopography influences small-scale changes
76 in soil nitrogen transformation and retention (Reddy and Patrick, 1984; Ford et al., 2007), soil texture
77 distribution (Grab, 1997), bulk density (Benscoter et al., 2005; Quinton and Marsh, 1998), drainage
78 (Lötschert, 1974), moisture and temperature within hummocks (Mark, 1994; Grab, 1997; Scott et al., 2008);
79 in addition, temperatures and amount of radiation differ between hummocks and interhummocks (Shen et al.,
80 2006). These factors contribute to create unique microenvironments in which some plants are better adapted
81 than others and influence plant species diversity (Smith, 2011). For example, Biasi et al. (2005) found that
82 interhummocks are usually dominated by mosses, which act as heat insulators and decrease summer soil
83 temperatures, thereby promoting further environmental heterogeneity (Longton, 1988), while hummocks are
84 mainly vegetated by sedges, grasses and dwarf shrubs, where warmer conditions are observed during the
85 growing season (Zoltai and Tarnocai, 1974; Quinton and Marsh, 1998; Admiral and Lafleur, 2007).
86 Hummocky microtopography may thus be a factor enhancing biodiversity at small spatial scales (Smith,
87 2011), which in turn affects litter decomposition and nutrient cycling.

88 Given the high geographical variability in the relationship between hummock microtopography, soil and
89 vegetation, a generalized conceptual model of their interconnections cannot be defined, and site-specific
90 analysis are needed, particularly in alpine areas.

91 Based on these considerations, the aims of this work are:

92 i) to investigate how hummock topographical features and activity history are reflected in pedon and topsoil
93 characteristics; ii) to analyze soil physical and chemical properties differences between hummocks and
94 interhummocks, and iii) to investigate the influence of hummock topography on plant communities and litter
95 decomposition rate.

96 In particular we tested the following hypotheses:

- 97 1. the hummock topography and activity are reflected in soil properties and pedogenesis, with large
98 differences between hummocks and interhummocks;
- 99 2. hummock/interhummock patterns influence plant species distribution, characterized by a different
100 rate of litter decomposition;
- 101 3. plant species distribution and their decomposition rates mutually influence the soil properties in the
102 hummocks and interhummocks.

103

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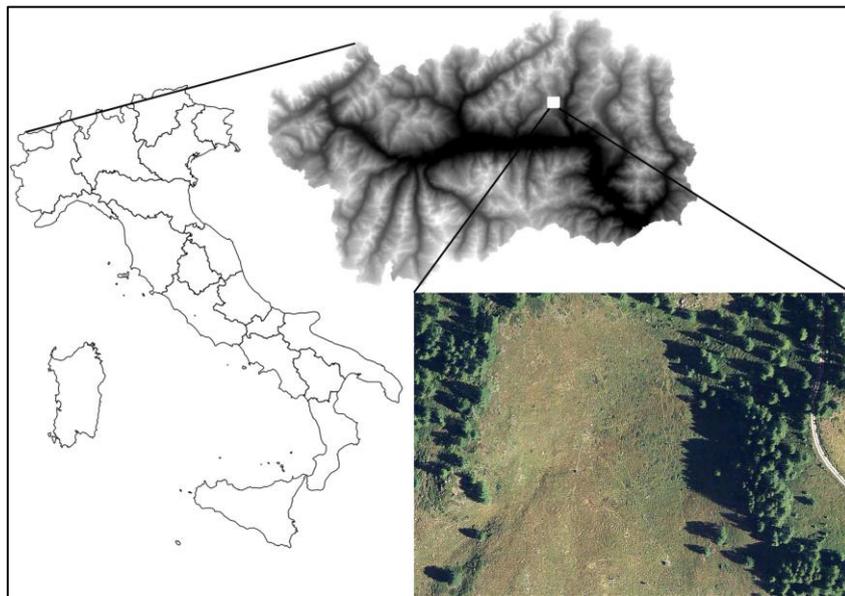
105 **2. Materials and methods**

106 *2.1. Site description*

107 The study was carried out in a subalpine grassland, which was grazed until 2007 and then abandoned, in the
108 north-western Italian Alps (Fig. 1). The site is located a few kilometres from the village of Torgnon in the
109 Aosta Valley region, at an elevation of 2160 m asl (45°50'40" N, 7°34'41" E). Since 2007 this experimental
110 site (ID: T19-005-T) belongs to the Long Term Ecological Research network (LTER - Italy).

111 The terrain slopes gently (4°), with a South aspect (195°N). The study area covers a surface of 2800 m². The
112 site is characterized by an intra-alpine semi-continental climate, with a mean annual air temperature of +3.1
113 C° and a mean annual precipitation of about 880 mm. Generally the site is covered by snow from the end of
114 October to late May, which limits the growing season to an average of five months (Galvagno et al., 2013).

115 The study site shows an undulating morphology, characterized by the presence of hummocks (15-30 cm
116 high) alternate to interhummocks. On flat surfaces, the hummocks are organised in a non-sorted net; where
117 the slope angle increases, they develop into parallel non-sorted stripes along the slope direction.
118 The studied subalpine grassland is a *Nardus stricta* formation, with the occurrence of other species as *Poa*
119 *alpina*, *Trifolium alpinum*, *Arnica montana* and *Ranunculus pyrenaicus*, referred to the association *Sieversio-*
120 *Nardetum strictae* Lüdi 1948.
121

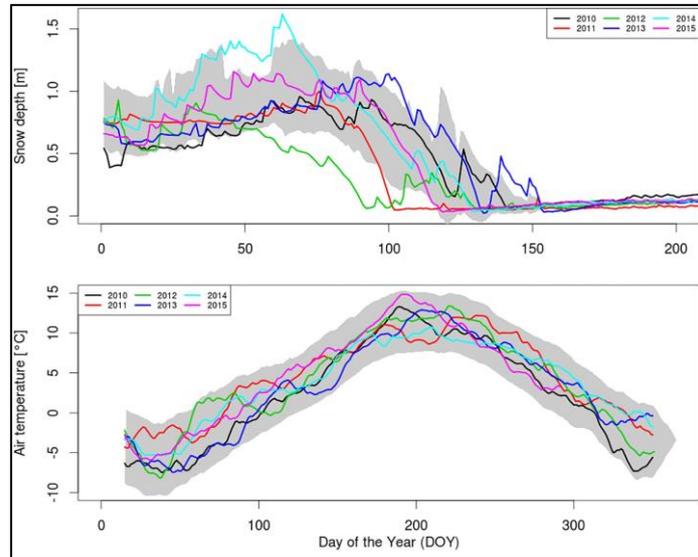


122
123 Fig. 1. The LTER experimental site of Tellinod in the Aosta Valley region, NW Italy.

124
125 *2.2. Meteorological patterns*

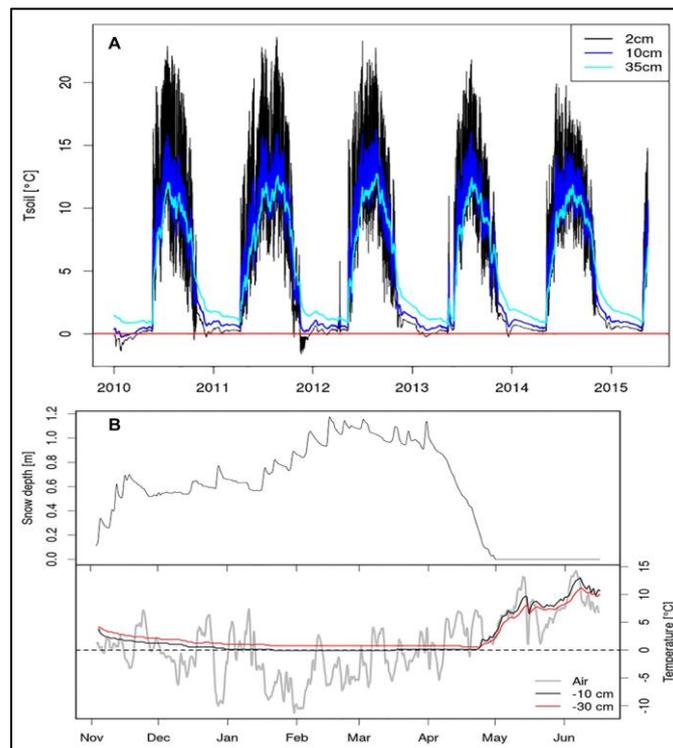
126 At the study site, air temperature and snow depth have been measured since 2010: the mean annual snow
127 depth was 76 cm, while mean daily air temperatures varied from +15 to -10 °C (Fig. 2).
128 Soil temperature has been measured since 2010 in a non-hummocked area, at different depths (2, 10 and
129 35 cm). Moreover, in order to detect the thermal characteristics of hummocks, two soil temperature sensors
130 (UTL1-2) were installed from November 2014 to June 2015 on hummock apex at 10 cm depth, and on
131 hummock base at 30 cm depth. In the non-hummock area, frost penetration was limited to the surface (2 cm
132 depth) and occurred for few days only in some years (Fig. 3A).
133 From the end of January to March (Fig. 3B) hummock apex remained constantly under 0 °C (-0.1 °C), while
134 hummock base maintained a temperature close to +1 °C. At snowmelt a thermal inversion occurred, as

135 hummock top became warmer than the base; it experienced more temperature daily fluctuations than the
136 base, which responded more slowly to the increase of air temperature.



137

138 Fig. 2. Seasonal variation of snow depth and air temperature from 2010 to 2015. The grey polygon denotes
139 the long-term (2008-2015) average (standard deviation).



140

141 Fig. 3. Seasonal course of soil temperature in a non-hummocked area at different depths (2, 10, 35 cm) from
142 2010 to the first part of 2015 (A); Hummocks apex and base temperature from November 2014 to June
143 2015 (B).

144 2.3. *Soil sampling and analysis*

145 Sixty soil samples (topsoil: 0-10 cm depth), corresponding to A horizons, were collected by drilling during
146 autumn 2014. These samples were collected from either hummock summits (n=30) and interhummock areas
147 (n=30). Moreover a soil pit was opened across two hummocks and the interhummock area to investigate the
148 soil characteristic and its spatial variability. The location of the soil profile was determined after having
149 performed 30 scattered pedological observations by soil probe, in order to determine the most common soil
150 types developed in the hummocky grassland. The field description of the soil profile was done according to
151 FAO (2006) while soil classification was done according to WRB classification system (FAO, 2014). Soil
152 material was collected from every horizon in the soil pit.

153 The soil samples were air-dried, sieved to 2 mm and analyzed following the standard methods reported by
154 Van Reeuwijk (2002). pH was measured in water (soil:water = 1:2.5); particle-size analysis was performed by
155 the pipette method after organic matter destruction with H₂O₂ followed by dispersion with Na-
156 hexametaphosphate; the cation exchange capacity (CEC) was determined in a BaCl₂ solution buffered at pH
157 8.1 (Rhoades, 1982); the exchangeable cations were measured by atomic absorption spectrometry (Analyst
158 400, Perkin Elmer, Waltham, MS, USA) on the BaCl₂ extracts. Total organic carbon (TOC) and nitrogen (TN)
159 were analyzed by dry combustion with a CN elemental analyzer (CE Instruments NA2100, Rodano, Italy).
160 Total soil P (TP) was determined by acid persulphate digestion (Nelson, 1987); available P (P_{Olsen}) was
161 extracted with NaHCO₃ and determined colorimetrically by the ascorbic acid molybdate blue method (Murphy
162 and Riley, 1962). In order to detect the spodic properties in the soil profile, the oxalate and dithionite
163 extractable fractions of Fe and Al (Fe_o, Al_o, Fe_d) were measured. Total iron (Fe_{tot}) was determined after HCl-
164 HNO₃ digestion and the Fe_o/Fe_d and Fe_d/Fe_{tot} ratios were calculated.

165

166 To evaluate water extractable organic carbon (WEOC) and water extractable total nitrogen (WETN) content
167 of topsoil samples, an aliquot of 10 g of fresh soil, sieved at 2 mm, was shaken with 50 ml 1 M KCl for two
168 hours in 50 ml PE bottles. The soil samples were then centrifuged at 3000 rpm for 6 minutes, and the
169 supernatant was filtered to <0.45 μm. Soil extracts were then acidified with HCl to remove the inorganic
170 carbon fraction.

171 WEOC and WETN were determined with a TOC analyzer (Elementar, Vario TOC, Hanau, Germany).

172 Ammonium in 1 M KCl extracts (N-NH₄⁺) was determined colorimetrically (Crooke and Simpson, 1971) using

173 UV-vis spectrophotometer. Nitrate (N-NO₃⁻) concentrations in the same extracts were determined following
174 Miranda et al. (2001). Total extractable organic nitrogen (TEON) was determined as difference between
175 WETN and dissolved inorganic N (DIN: N-NH₄⁺+ N-NO₃⁻) in the extracts.

176

177 2.4. *Vegetation survey and plant decomposition rate*

178 In order to verify plant species distribution eight vegetation surveys were carried out in hummocks and eight
179 in interhummock areas, indicating the total percent cover of herbs and shrubs, and listing all the plant
180 species occurring in each sampling area and the percentage cover of each species by visual estimation.

181 The annual decomposition rate of the plant species was investigated by the litter bag method. Three different
182 litter types were enclosed in litter bags according to species occurrence in the study area (Filippa et al.,
183 2015): 1) grasses (mainly *Nardus stricta*), 2) forbs, 3) a mixture composed by grasses (80%) and forbs (20%)
184 hereinafter indicated as mix. Twenty-four litter bags for each litter type were filled with 4 g of dry plant
185 material. Twelve bags of each litter type were laid in interhummocks and twelve on hummocks, in order to
186 highlight the differences in decomposition rate due to the microtopographic position. The litter bags were
187 placed on the grassland surface in order to recreate the natural conditions in which the plant material decomposes
188 after the end of the growing season. Litter bags were laid on site in October 2013 and subsamples were
189 collected at snow melt (June 2014) and then monthly until October 2014. After each sampling, the collected
190 litter was oven dried (60 °C for 48 hours) and then weighted. Carbon and N content of the remaining
191 materials was then measured by the CN analyzer.

192

193 2.5. *Statistical analyses*

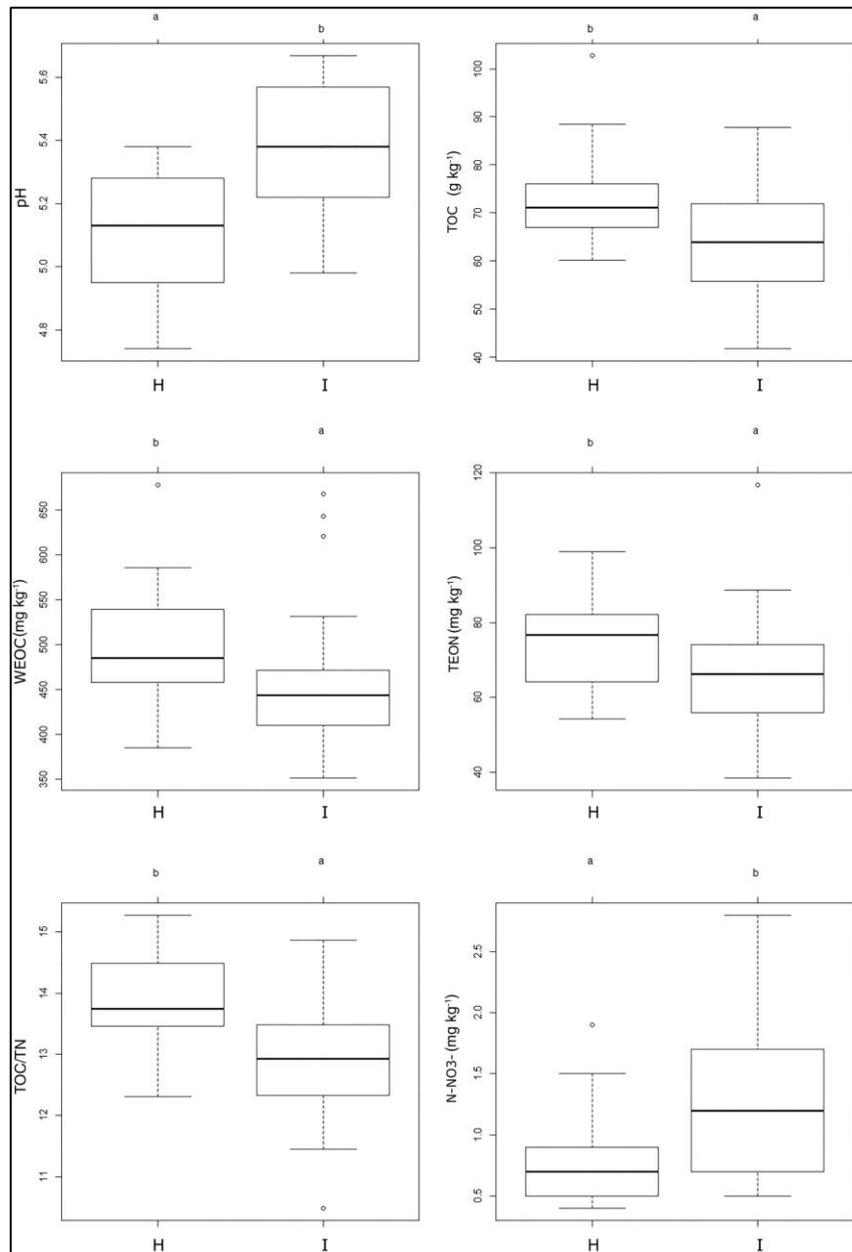
194 Differences in soil and vegetation properties between hummocks and interhummocks were evaluated
195 through a one-way analysis of variance (ANOVA). Before performing the ANOVA, Tukey HSD was used to
196 test differences in soil properties while Fisher test was used for vegetation data, at a significance level of
197 $p < 0.05$. Data analyses were performed using R (R Core Team 2015).

198

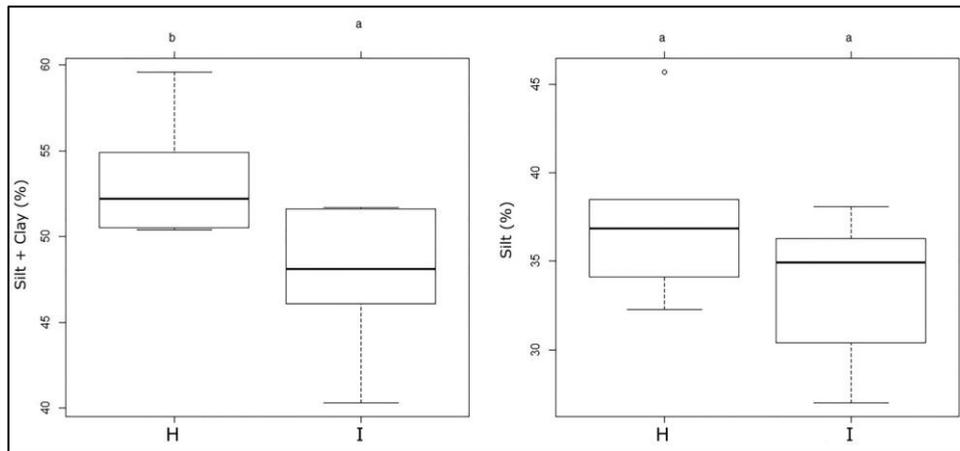
199 **3. Results**

200 3.1. *Topsoil characteristics in the hummocky grassland*

201 Significant differences ($p < 0.05$) existed in some physical and chemical parameters between hummocks and
 202 interhummocks topsoil (Fig. 4). Other not significantly different topsoil properties are reported in Table 1. In
 203 particular, given a general loamy-sandy soil texture, hummocks showed a significantly greater silt + clay
 204 content than interhummocks (Table 1, Fig. 5). Hummocks were characterized by lower pH values, higher
 205 TOC, WEOC, TEON and TOC/TN ratio, while a higher content of N-NO_3^- was found in soils of
 206 interhummocks than in hummocks.



207
 208 Fig. 4. Boxplots (n = 60) of pH values, TOC, WEOC, TEON, TOC/TN and N-NO_3^- content of topsoils in
 209 hummock apexes (H) and interhummocks (I). Letters indicate statistically significant differences.



210

211 Fig. 5. Boxplots (n = 16) of silt and clay and silt content in hummock apices (H) and interhummocks (I).

212

Letters indicate statistically significant differences.

213

214 *3.2. Soil profile characteristics*

215 The probing campaign showed that Podzols were widespread in the hummock area. In the interhummocks,
 216 E horizons were always absent. A much higher stone content in the interhummocks than in the hummocks
 217 was detected as well.

218 The typical hummock soil showed a complex and well developed profile indicating the occurrence of different
 219 processes such as podzolization and gleyzation over the centuries. Under hummocks, the soils showed a
 220 sequence of A-Eg@-Bsg@-Bg@-Bcg@-C@ horizons (Table 2, Fig. 6), with convolutions and disruptions
 221 demonstrating intense cryoturbation (Bockheim and Tarnocai, 1998). E horizons were absent in the
 222 interhummock (Fig. 6), where the expression of the Bsg was weaker as well.

223 The soil properties of the profile generally confirmed what was observed in the topsoil samples. In particular,
 224 the texture was generally sandy-loamy except in the A (1), A (3) and C@ horizons, where it was loamy and
 225 loamy-sandy respectively. Although the sandy fraction was prevalent in the soil, the clay-silt fraction was
 226 substantial. The clay and silt contents were higher in hummock surface A (1) and A (3) horizons and lower in
 227 the interhummock surface A (2), confirming the results shown in Fig. 5. From the Eg@ horizons, the clay
 228 content tended to irregularly decrease with depth reaching minimum values in Bcg@ and C@ horizons. Silt
 229 had the highest content in the Eg@ horizon, then it decreased with depth and reached minimum value in the
 230 C@. Conversely, the sand content was considerably higher in interhummock horizon A (2) than in hummock
 231 horizons A (1,3), then it increased with depth and reached maximum values in the C@ horizon. The deep
 232 C@ horizon was observed below an abrupt structural and granulometric discontinuity, and it was

233 characterized by a dense, hard consistence, high stone content; it did not show any lateral variations in
234 texture or structure below hummock or interhummock. Most horizons showed a weak platy structure that
235 became abruptly coarser and more strongly developed in the C@ horizon, which also presented thick silt
236 caps on the stone fragments; the Bsg@ horizons were blocky subangular. All the horizons below the A ones
237 showed evidences of waterlogging, with the presence of reddish iron mottles alternating to light greyish
238 zones. Dark brown patches of organic matter-rich materials indicated cryogenic displacement of surface
239 materials. Examining the entire soil profile (hummock-interhummock-hummock) it was possible to observe a
240 tongue-like pattern of horizons, which created a sort of mirror image of surface topography. This structure
241 was observed in other studies about earth hummock in permafrost environments (e.g. Tarnocai and Zoltai,
242 1978; Schunke and Zoltai, 1988).

243 pH values were very strongly or strongly acidic (Table 2); the lowest pH values were found in the A horizons,
244 they slightly increased with depth until the Bsg@ and Bg@ horizons, below which they tended to remain
245 stable (Table 2).

246 TOC reached the maximum values in the A horizons, and it was higher in hummock horizons A (1,3) than in
247 interhummock horizon A (2). In addition, as expected for podzolic soils, TOC was lower in the Eg@ horizon
248 than in the underlying illuvial Bsg@, then decreased with depth and reached minimum values in C@ horizon
249 (Table 2). TN was always very low. The TOC/TN ratio reached minimum values in the eluvial Eg@ horizons
250 and maximum ones in the illuvial Bsg@; high values were also measured in BCg@ horizons.

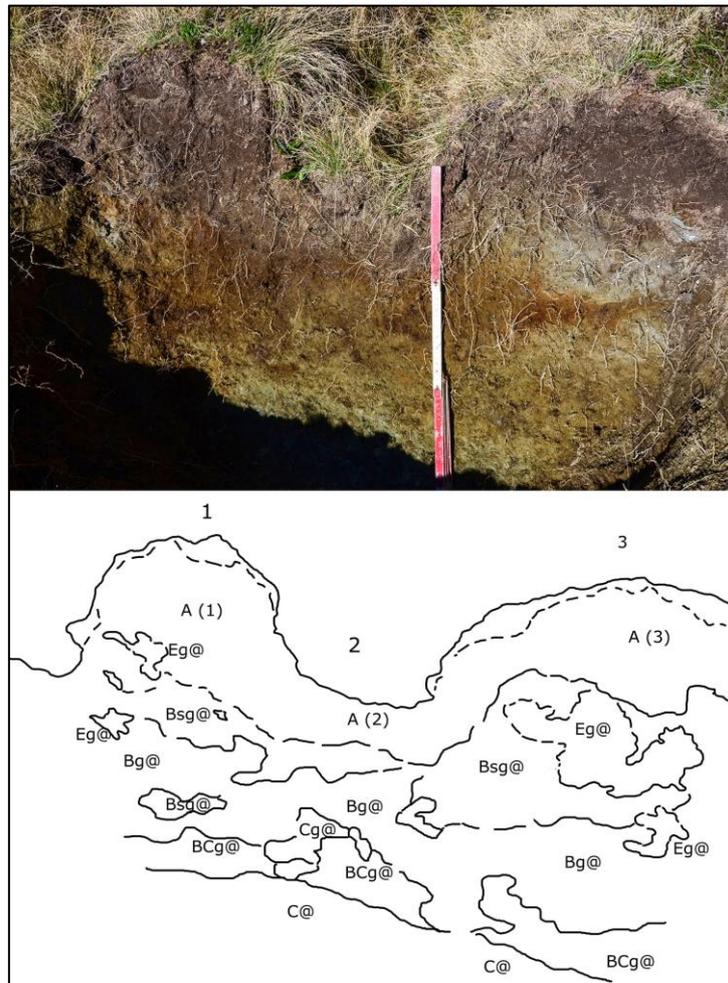
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252 The amorphous Fe and Al (hydro) oxides (Fe_o and Al_o) reached minimum values in the Eg@ and C@
253 horizons, while the highest contents occurred in the Bsg@ horizons (Table 2). Fe_o predominated in the
254 spodic Bsg@ horizons while crystalline Fe oxides (Fe_d - Fe_o) in the Eg@ and C@ (Table 2). A similar trend
255 characterized the dithionite-extractable Fe (Fe_d) (free pedogenic oxides), which was always greater than Fe_o ,
256 and reached minimum and maximum values in Eg@ and Bsg@ horizons, respectively. This trend was
257 related to large amounts of Fe_{tot} in Bsg@ horizons, associated with lower values in Eg@ and C@ horizons,
258 as often observed in podzolic soils (e.g., D'Amico et al., 2008). The Fe_d/Fe_{tot} ratio, which is an index about
259 the weathering of minerals that provide Fe to soil, indicated that a large part of Fe in illuvial Bsg@ horizons
260 was of pedogenic illuvial origin.

261 The values of the activity ratio (Fe_o/Fe_d) found in Bsg@ horizons under hummocks (≥ 0.55) indicated that the
262 podzolization process is still active (Burt and Alexander, 1996).

263 Based on the morphological and chemical evidences, the whole profile can be considered a complex
264 between Albic Gleyic Podzol (Relictiturbic) in hummocks, and Entic Gleyic Podzol (Relictiturbic) in the
265 interhummocks, according to WRB classification system (FAO, 2014).

266



267

268 Fig. 6. The hummocky soil profile, with cryoturbated podzolic horizons; A (1), A (2) and A (3) are
269 operationally numbered and correspond to the sectors used in the descriptions, with hummock apex
270 horizons evidenced by 1 and 3, interhummock ones by number 2. Red and white tape sections are 20
271 centimetres long.

272

273

274

275 3.3. Vegetation survey

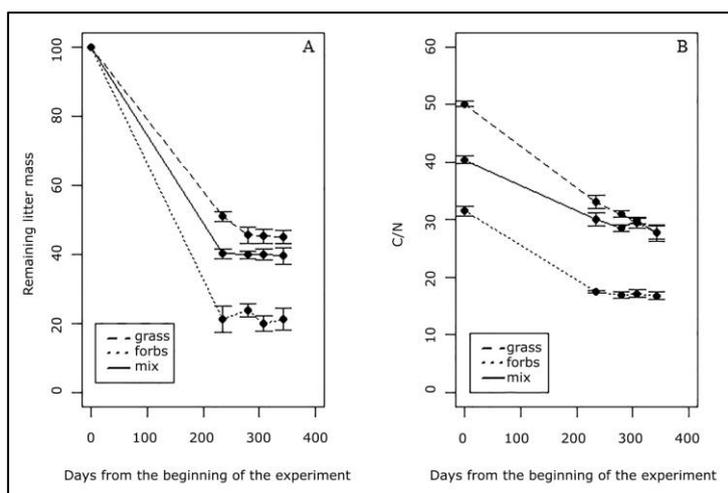
276 The grassland had 100% vegetation cover in all sampling plots (Table 3). The vegetation surveys showed
277 that *Nardus stricta* was dominant on the hummocks (H), with a cover ranging from 78 to 93%; locally, on
278 hummocks, an early colonization by shrubs, and in particular by *Calluna vulgaris*, was detected, showing a
279 trend towards more mature vegetation dynamic stages. On the hummocks the forbs cover was always very
280 low. Conversely, in the interhummocks (I) a higher cover of forbs species, such as *Geum montanum*, *Arnica*
281 *montana*, *Trifolium alpinum* occurred, while *Nardus stricta* showed lower cover, ranging from 5 to 25 %.

282 3.4. Plant decomposition rate

283 Significant differences in decomposition rate ($F_{2, 86} = 278.3$; $p < 0.001$) were observed between the three litter
284 types, expressed as remaining litter mass (Fig. 7A): on an annual scale, forbs decomposed faster than the
285 grass/forbs mixture and grasses. At the end of experiment, the remaining mass of forbs was around 20%
286 while it was 40 and 52% for mix bags and grasses bags, respectively.

287 The great majority (ca. 50-80%) of the decomposition process occurred during the snow-cover period that
288 lasted 235 days and not during the growing season (110 days), when the remaining mass of all litter types
289 showed a very slow decrease of about 10-20% (Fig. 7A). The microtopographic position did not determine
290 differences in decomposition rates.

291 The C/N ratio in the litter type was significantly different in grasses, mix and forbs ($F_{2, 86} = 584.08$; $p < 0.001$)
292 (Fig. 7B) and did not show any differences if located in hummocks and interhummocks. The C/N values were
293 around 50 for the grasses, 42 for the mix and 32 for the forbs at the beginning of the experiment and then
294 decreased to values around 35 after the snow cover period for grass and grass-forbs mixture and to 18 for
295 the forbs. A slight decrease was detected during the snow free period for grasses and mix while the value for
296 the forbs was almost stable.



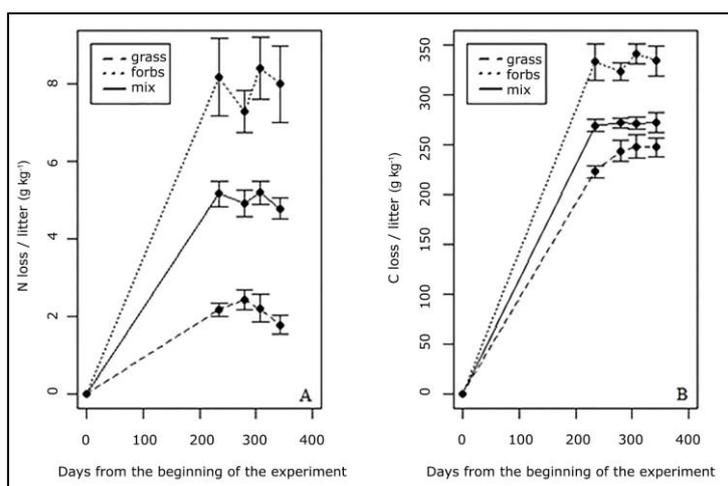
297

298 Fig. 7. Remaining litter mass (%) (A) and C/N ratio (B) for the three litter types (Grass, Forbs and Mix) during
 299 the one year long decomposition experiment.

300

301 In order to highlight the influence of the decomposition process on soil properties, N and C loss was
 302 calculated. The N loss differed for the litter types ($F_{2, 86} = 147.86$; $p < 0.001$) (Fig. 8A): the highest amount was
 303 lost by forbs (around 8 g kg^{-1} litter) while the lowest was lost by the grasses (less than 2 g kg^{-1} litter); almost
 304 all of the loss occurred during the snow-cover period.

305 The carbon loss differed in the three litter types ($F_{2, 86} = 141.90$; < 0.001) (Fig. 8B), but not between the
 306 microtopographic positions. The highest amount of C was lost during the snow cover period by the forbs (a
 307 mean of 330 g kg^{-1} litter) while a lower amount was lost by the grass litter (a mean of 230 g kg^{-1} of litter).



308

309 Fig. 8. Nitrogen (A) and carbon (B) loss of the three litter types (Grass, Forbs and Mix) during the one year
 310 long decomposition experiment.

311 4. Discussion

312 4.1. Interactions between topsoil properties and vegetation

313 The differences in soil properties detected between hummocks and interhummocks are consistent with those
314 found in other studies. The higher silt and clay content in hummocks results from sorting associated with
315 differential freeze-thaw activity (Van Vliet-Lanoë, 1991; Grab, 1997; Smith, 2011) and cryoturbation (e.g.,
316 Tarnocai and Zoltai, 1978; Schunke, 1981; Schunke and Zoltai, 1988; Grab, 1997, 2005; Smith, 2011) ..

317 Many chemical differences were observed as well, explained by different microtopography and different plant
318 communities, which are characterized by different nutrient requirements and decomposition rates. In
319 particular, the pH difference between hummock and interhummock was consistent with that measured in
320 hummock tundra ecosystems (e.g. Biasi et al., 2005) and it could be related with differential leaching
321 associated with microtopography and/or with the presence of acidifying and weakly degradable plant
322 species. The different podzolic expression under hummocks and interhummock areas is also compatible with
323 the observed pH differences. The same effect on pH could also be created by the greater organic matter
324 content in hummock soils. In fact, the significantly higher TOC content found in hummock topsoil (already
325 noticed in hummocks by Grab, 1997), could be linked to different litter type and plant productivity. The slower
326 decomposition rate of hummock plants was reflected in the higher TOC/TN ratio in hummock topsoils.

327 Other differences observed between hummock and interhummock topsoils included a significantly higher
328 WEOC and TEON in hummocks, probably related to the lower rate of organic matter mineralization (Kalbitz
329 et al., 2000) and to the greater litter quantity, due to the dominance of *Nardus stricta* and to its weaker
330 decomposability (high C/N ratio) documented by the litter bags experiment. At the end of autumn and during
331 snowmelt, lower soil temperatures and possible freeze-thaw cycles induced by differential snowpack
332 accumulation, likely active during colder winters, may also cause an increase in extractable WEOC, following
333 physical disruption of the litter layer and consequent leaching from the organic horizons (Kalbitz et al., 2000;
334 Grogan et al., 2004; Vestgarden and Austnes, 2009).

335 Nitrogen soluble forms, such as NO_3^- and TEON were also different, with respectively higher values in
336 interhummocks and hummocks. In particular, the higher NO_3^- content found in interhummocks was in
337 agreement with those reported by Biasi et al. (2005), who suggested that inorganic N forms tend to
338 accumulate in interhummock depressions, as a result of lateral flow of water from elevated hummocks
339 (Quinton, 2000). In the study area the higher NO_3^- content is also a result of the occurrence of higher N rich

340 plant species in the interhummocks, their decomposition rate and N loss which are respectively faster and
341 higher than those of the grass and mix litters, as documented also in other sites (Baptist et al., 2010).

342

343 The observed chemical differences between hummocks and interhummocks are correlated with differences
344 in vegetation cover. In fact, floristic surveys show that a selective distribution of plant species occurs in
345 hummocks and interhummocks: *Nardus stricta* is dominant on the convex areas and the concave areas are
346 dominated by forbs, as observed in other areas with similar microtopographic conditions (e.g. Güsewell et
347 al., 2005; Admiral and Lafleur, 2007). Several plant species were found only where hummocks created
348 favourable habitat due to their heterogeneous microtopography (Smith, 2011). Grasses and forbs functional
349 traits are distinctly different: *Nardus stricta* exhibits a high C/N ratio and a high leaf dry matter content which
350 are known to be associated with recalcitrant litter (Baptist and Choler, 2008) while forbs exhibit a lower C/N
351 ratio and a relatively higher specific leaf area (SLA) which allow for a faster decomposing litter (Cornelissen
352 et al., 1999). This distribution influenced the soil properties by means of the different rate of litter
353 decomposition and associated C and N release.

354 All these parameters, together with leaching associated to podzolization, may reduce trophic levels of
355 hummock soils, thus promoting oligotrophic species like *Nardus stricta*, which is an herbaceous species
356 characterized by a relatively high lignin content, therefore more recalcitrant to decomposition compared to
357 other herbaceous species (Güsewell et al., 2005).

358 In addition D'Alessandro (2009) and Solly (2009) found high phytomass values in the same study areas, as a
359 consequence of the high productivity and slow rate of decomposition of *Nardus* (Güsewell et al., 2005) and
360 consequent litter accumulation. *Nardus stricta* also forms extended root systems with comparatively long-
361 lived, slowly decomposing roots (Van der Krift and Berendse, 2002), which may contribute to the long-term
362 accumulation of C in hummocks soils. Moreover the lignin present in *Nardus stricta* may interact with NH_4^+ ,
363 giving rise to recalcitrant amino-derivatives, with consequent accumulation of organic matter and reduction of
364 available N forms for plants and microbial communities, which may promote a further *Nardus* abundance on
365 hummocks.

366 In interhummock areas, the greater water content in soils observed in the field some weeks after snowmelt,
367 could be able to influence thermal inertia, reducing temperature range. Interhummock areas experienced
368 less thermal fluctuation allowing for a higher microbial activity. This aspect, coupled with the greater litter
369 decomposability of forbs, may favour a greater mineralization rate of organic matter (C/N reduction) with

370 consequent increase of the nutrient pool. In interhummock areas, the lower presence of WEOC and TEON
371 suggests that these labile forms are subjected to a greater mineralization. This, associated with translocation
372 processes of nutrients from hummocks to interhummocks (for e.g. nitrates) related to water flow and texture
373 (loamy-sand), may produce favourable conditions for more exigent plant species (e.g. *Arnica montana*,
374 *Trifolium alpinum*, etc.). These species, dominant in interhummock areas, are characterized by precocity and
375 higher development rates than *Nardus stricta*. In interhummock soils, the greater NO_3^- content may be due to
376 higher mineralization rate linked to greater litter decomposability and higher microbial activity.

377

378 4.2 Pedogenesis in hummock soils

379 The topsoil and vegetation gradients observed between hummocks and interhummocks were mutually
380 reflected in the pedogenesis.

381 According to the WRB taxonomic system (FAO, 2014), the hummock soil can be fully classified as Podzol,
382 based on both the morphological and chemical diagnostic properties; a strong Fe redistribution is evidenced
383 by the high $\text{Fe}_d/\text{Fe}_{\text{tot}}$ in Bsg@ horizons. Podzolization is still active, as shown by the activity ratio (Fe_o/Fe_d).
384 However, morphological evidences indicate that the degree of podzolization differs significantly in hummock
385 and interhummock areas: Eg@ horizons are developed only in hummocks and the Bsg@ in the
386 interhummock is much shallower and paler than in hummocks.

387 The internal morphology, which shows convoluted, disrupted and displaced horizons and a weak platy
388 structure, and the general undulating trend of soil profile, evidence cryoturbation of these soils. This pattern
389 is in agreement with other studies on earth hummocks both in permafrost and non-permafrost environments
390 (e.g. Tarnocai and Zoltai, 1978; Scotter and Zoltai, 1982; Schunke and Zoltai, 1988). As soil horizons are
391 strictly associated with hummock topography, and pedogenic horizons are cryoturbated, we assume that
392 cryoturbation has been active contemporarily, or during alternating periods, with podzolization, i.e. during the
393 Holocene or parts of it. Given the strong Fe-Al redistribution measured in the hummocks and the average
394 time required for Podzol development in the Alps, which is between 500 (D'Amico et al., 2014) and 3000
395 years (Egli et al., 2001), we can assume that podzolization and cryoturbation have been active together, or
396 during alternating periods, for many thousands of years across the Holocene. Hummock formation,
397 associated with cryoturbation, facilitated soil colonization by different plant species in relation with

398 microtopography and different water fluxes. The higher leaching conditions on hummock facilitated the
399 colonization by oligotrophic and acidifying species, such as *Nardus stricta* and Ericaceae.

400 In addition to podzolization and cryoturbation, the presence of light greyish mottles in most horizons
401 suggests the occurrence of gleyzation processes caused by seasonal waterlogging and alternation of
402 reductive and oxidative conditions, thanks to the high water input during snowmelt (e.g. Gensac, 1990), the
403 overall concave topography of the grassland and the presence of a dense C@ horizon at shallow depths.

404 This dense C@ horizon with thick silt caps on stone fragments and well developed, coarse platy structural
405 aggregates, represents an important paleoclimatic signature, as it typically developed below a past
406 permafrost table (Van Vliet-Lanoë, 1998), even if permafrost is actually absent in this site (Boeckli et al.,
407 2012). Above this unsorted, dense horizon, the surface layers show an important textural differentiation, with
408 a higher silt and clay content in hummocks. A high granulometric lateral sorting is visible as well, with stone
409 and sand-rich interhummocks and stone and sand-poor hummocks. This textural differentiation was likely
410 caused by intense cryoturbation above an ancient permafrost table, which created the accumulation of frost-
411 susceptible materials in the surface; this silt and clay rich material (frost-susceptible) is necessary for
412 hummock formation and development under a complete vegetation cover, under milder conditions. In fact,
413 earth hummocks often contain a high percentage of silt/clay, even if their absolute content varies
414 considerably between regions (Grab, 2005).

415 Cattle grazing for many centuries should have caused hummocks regression, but they are still well
416 preserved: other factors promoting hummock current conservation and development are likely present. For
417 example, Mark (1994) and Grab (1997) suggested that, when temperature differentials between frozen
418 hummocks and generally unfrozen interhummock areas are significant, a basis for the maintenance of the
419 existing microtopography may be provided; in addition vegetation development seems to be an important
420 factor enhancing growth (Van Vliet-Lanoë and Seppälä, 2002). Seasonal water-table fluctuations, associated
421 with localized frost penetration, could be other factors responsible for hummocks maintenance.

422 Soil temperatures measured during the particularly warm winter of 2015, characterized by a thicker than
423 average snow cover, confirmed the existence of a differential between hummock apex and base; in fact,
424 hummock summits (at a 10 cm depth) had a stable temperature of about -0.1°C for many weeks, while the
425 temperature was above 0°C 20 cm below; this temperature differential may provide a basis for the
426 maintenance of the existing microtopography (Mark, 1994). Edwards and Cresser (1992) indicated that soil
427 freezing usually commences at just below 0° C in relation with soil texture: sandy soils normally freeze at

428 temperature closer to 0 °C, while fine-textured soils at lower temperatures; silt-rich soils freeze at about -0.1
429 °C (Williams and Smith, 1989). Thus, the temperature at the hummock apex likely corresponded with the
430 freezing temperature of pore water in sandy loam soils such as the studied ones. This temperature
431 differential could thus induce thermodynamic forces leading to cryosuction, accretion of ice in the hummock
432 crests and differential ground heave (Grab, 1997). The temperatures are likely lower, and the differentials
433 between hummocks and interhummocks are likely larger during colder, average winter climate conditions
434 (e.g. 2010, 2012, Fig. 3), as a thick snow cover reduced frost penetration in the soil (Schunke and Zoltai,
435 1988) during the year of measurements.

436

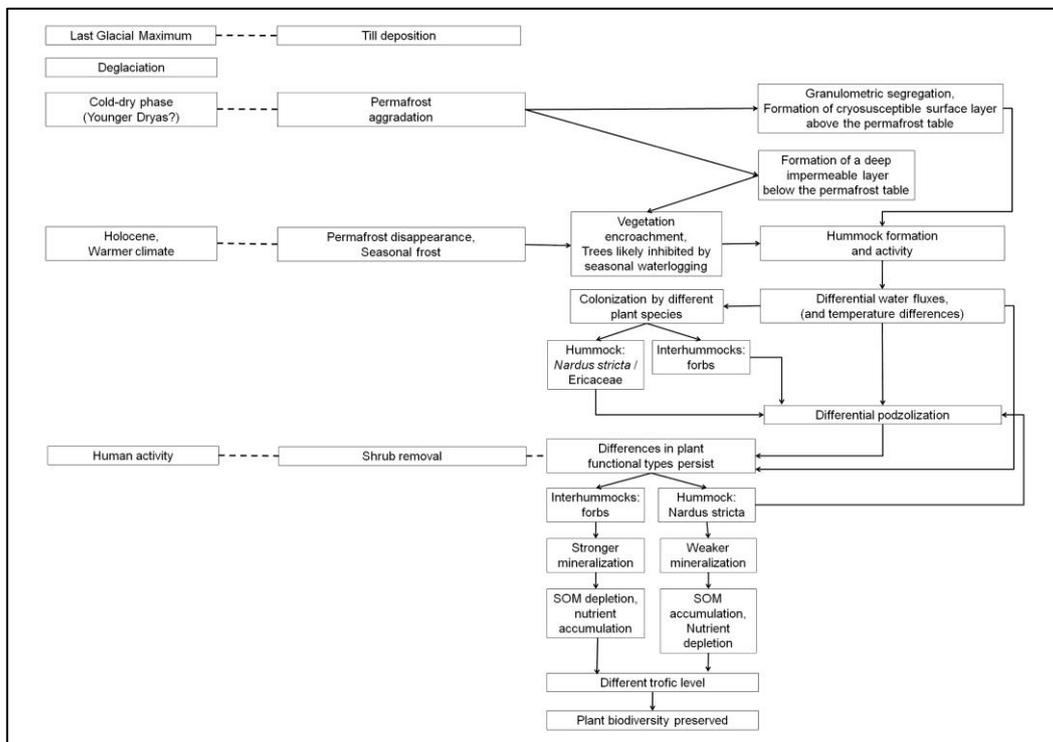
437 Van Vliet-Lanoë and Seppälä (2002) suggested that podzolization was active before a period of intense
438 cryoturbation in the Finnish Lapland, related to the existence of a higher pine timber-line than today during
439 the Holocene Climatic Optimum. Thus, the dilemma of determining whether podzolization was active prior,
440 contemporarily or after cryoturbation exists. The doubt if podzolization was the product of present day or past
441 vegetation exists as well. In fact, if hummocks were relict features formed thousands of years ago under a
442 much colder climate (Scotter and Zoltai, 1982; Van Vliet-Lanoë et al., 1998), present-day plant communities
443 likely do not represent those that were growing at the time of hummock formation (Smith, 2011). In addition,
444 different plant species are present at different stages of hummock development (Tyrtikov, 1969). The profile
445 didn't show evidences (e.g. charcoal, roots, etc.) of a sharp change in vegetation cover from coniferous tree
446 to herbaceous species, but high carbon content and TOC/TN values found in deep mineral horizons may
447 indicate the past abundance of more recalcitrant species such as Ericaceae (e.g. *Rhododendron*
448 *ferrugineum*, *Calluna vulgaris*, etc.) and/or Pinaceae. Ericaceous shrubs are normally eliminated from
449 subalpine pastures in the Italian Alps. The past presence of forest vegetation in the study site is not likely,
450 thanks to the high soil humidity caused by topography and by the presence of a dense layer at shallow
451 depths. In fact, after snowmelt, water normally covers most of the interhummocks area for many weeks and
452 a small temporary lake forms in the centre of the studied grassland. Gleyic properties in the soil also
453 demonstrated waterlogging. Moreover, the presence of trees usually excludes the possibility of hummock
454 formation and preservation (Van Vliet-Lanoë and Seppälä, 2002).

455 Although podzolization is typical under coniferous trees, Ericaceae are able to begin a quick podzolization
456 process in previously non-podzolic soils (D'Amico et al., 2014). This is caused by the slow decomposition
457 rates of the litter of ericaceous shrubs, due to their high amount of lignin, cellulose and other recalcitrant

458 substances, such as phenolic compounds, which reduce the soil biological activity (Pornon and Doche,
 459 1996). The litter of Ericaceae produces large quantities of low molecular weight and fulvic acids, which cause
 460 intense mineral weathering (Schaetzl and Anderson, 2005).

461

462 Based on field observations and soil analysis, a complex set of environmental processes can be
 463 hypothesized in the formation and conservation of present day hummock soils (Fig. 9). During the Last
 464 Glacial Maximum till deposition occurred. After deglaciation, during the Younger Dryas, the coldest and drier
 465 conditions favoured the permafrost genesis, which was responsible for the granulometric segregation and
 466 the formation of the underlying dense and poor permeable C@ horizon. After permafrost degradation,
 467 seasonal waterlogging coupled with frost penetration and the presence of cryosusceptible materials
 468 favoured hummock formation. The hummocks microtopography generated different microenvironmental
 469 conditions, which promote selective plant species distribution, characterized by specific litter characteristics,
 470 which in turn have favoured a diverse degree of podzolization under hummocks and interhummocks.
 471 Differential podzolization and leaching, different decomposability of organic matter produced by plant species
 472 distribution and different edaphic topsoil properties (and also sporadic cryoturbation processes) mutually
 473 interact in the preservation of this present-day subalpine hummocky grassland.



474

475 Fig. 9. Conceptual model of eco-pedological functioning of present-day grassland.

476 **5. Conclusions**

477

478 Data deriving from soil analysis, distribution of plant species and plant decomposition rates contribute in
479 explaining the reasons why soil parameters and distribution of plant species differ significantly in the two
480 microtopographic positions: lower mineralization rates and accumulation of organic matter due to grass litter
481 type in hummocks may be the cause for the lower pH, the greater TOC, WEOC and TEON contents and the
482 higher TOC/TN ratio found in hummock than in interhummock topsoils.

483 The results also show a faster decomposition of forbs in the nutrient-richer interhummock topsoils compared
484 to the podzolized hummocks positions, and an overall slower decomposition rate of *Nardus* litter.

485 These differences are reflected in soil pedogenesis, in fact, according to the WRB taxonomic system (FAO,
486 2014), the hummocky soil can be fully classified as Podzol, based on both morphological and chemical
487 diagnostic properties, however, morphological evidences indicate that the degree of podzolization differs
488 significantly under hummock and interhummock areas. The internal morphology, which shows convoluted,
489 disrupted and displaced horizons and a weak platy structure, and the general undulating trend of soil profile
490 evidence cryoturbation of these soils. In addition soil temperatures measured during a particularly warm
491 winter, characterized by a thicker than average snow cover, confirmed the existence of a differential between
492 hummock apex and base. Hummocks microtopography establishes specific pedoclimatic conditions
493 promoting selective plant species distribution, which in turn, as a function of litter characteristics, produces
494 variations on topsoil properties and different soil development under hummocks and interhummocks. The
495 interaction of all these factors supports the conservation of plant biodiversity in the grassland system
496 considered as a whole and represents a continuous feedback among the interconnected compartments,
497 contributing to create a unique pedo-environment.

498

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502

503

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Table 1

Not significantly different physical and chemical properties in hummock (H) and interhummock (I) topsoil samples; values in brackets are the standard errors.

	Sand	Silt	Clay	TN	CEC	Ca exc.	Mg exc.	K exc.	Base sat.	TP	P _{Olsen}	WETN	N-NH ₄ ⁺	DIN
	%			g kg ⁻¹	cmol ₍₊₎ kg ⁻¹				%	mg kg ⁻¹		mg kg ⁻¹		
H	46.7 (1.4)	37.4 (1.9)	15.9 (1.0)	5.3 (0.1)	34.4 (1.4)	2.4 (0.2)	0.8 (0.0)	0.3 (0.0)	10.1 (0.9)	601 (58.4)	40.7 (1.9)	88.9 (2.4)	12.7 (0.7)	13.5 (0.7)
I	52.4 (1.7)	33.6 (1.7)	14.0 (1.0)	5.0 (0.2)	31.3 (1.9)	2.5 (0.3)	0.8 (0.1)	0.3 (0.0)	11.8 (1.6)	637 (47.8)	36.1 (3.6)	81.7 (3.2)	14.2 (0.9)	15.5 (1.0)

Table 2

Morphological, physical and chemical properties of the soil horizons. Structure: GR= granular; PL= platy; PS=subangular polyhedral. Textural class: L= loam; LS= loamy sand; SL= sandy loam. (1), (2), (3) are operational numbers and correspond to the sectors used in the descriptions, with hummock apex horizons evidenced by 1 and 3, interhummock ones by number 2.

Horizon	Munsell colour, moist (mottles, %)	Stone fragments	Clay	Silt	Sand	Structure	Textural class	pH	TOC	TN	TOC/TN	Fe _o	Al _o	Fe _d	Fe _{tot}	Fe _d /Fe _{tot}	0.5*Fe _o +Al _o	Fe _o /Fe _d
		%	%						g kg ⁻¹			g kg ⁻¹				%		
A (1)	10YR 2/2	5	14.0	44.7	41.3	GR	L	4.4	74.6	4.7	16	5.21	3.11	5.51	23.22	0.24	0.57	0.95
A (2)	2.5Y 3/3	50	11.3	34.8	53.9	GR	SL	4.7	68.1	5.2	13	4.79	2.49	6.33	30.16	0.21	0.49	0.76
A (3)	10YR 2/2	5	13.9	45.7	40.4	GR	L	4.5	73.0	5.1	14	3.72	2.76	4.88	23.54	0.21	0.46	0.76
Eg@ (3)	5Y 4/2 (10YR 5/3, 2%)	5	6.3	49.5	44.2	PL	SL	4.9	8.7	0.7	12	1.15	1.16	3.14	25.76	0.12	0.17	0.36
Bsg@ (1)	7.5YR 4/4 (10YR 5/2, 5%)	10	-	-	-	PS	-	-	42.4	2.2	19	19.70	9.19	31.50	52.81	0.60	1.90	0.63
Bsg@ (3)	7.5YR 3/4 (10YR 5/2, 5%)	10	6.0	45.4	48.5	PS	SL	5.3	36.2	1.7	21	16.63	11.07	30.40	55.31	0.55	1.94	0.55
Bg@ (2)	2.5Y 3/3 (7.5YR 5/4, 10%)	40	1.9	42.0	56.2	PL	SL	5.4	19.9	1.0	20	4.01	5.15	8.03	41.78	0.19	0.71	0.50
Bg@ (3)	5Y 4/3 (7.5YR 5/4, 10%)	10	4.4	36.3	59.3	PL	SL	5.4	14.7	0.8	18	4.12	4.74	8.92	38.71	0.23	0.68	0.46
BCg@	5Y 5/3 (10YR 5/4, 10%)	40	1.0	28.1	70.9	PL	SL	5.4	17.4	0.9	19	3.56	4.65	7.00	36.97	0.19	0.64	0.51
C@	7.5Y 4/3	70	2.0	25.4	72.6	PL	LS	5.4	4.6	0.3	15	0.82	1.60	3.03	34.64	0.09	0.20	0.27

Table 3

Vegetation survey on hummocks (H) and interhummocks (I). Percent cover of grasses and forbs, shrubs, and each species have been indicated.

Survey number	H 1	H 2	H 3	H 4	H 5	H 6	H 7	H 8	I 1	I 2	I 3	I 4	I 5	I 6	I 7	I 8
grasses and forbs (% cover)	100	100	100	100	100	90	50	47	100	100	100	100	100	100	100	100
shrubs (% cover)	0	0	0	0	0	10	50	53	0	0	0	0	0	0	0	0
<i>Nardus stricta</i> L.	94	85	80	90	85	78	40	35	10	10	10	5	20	10	25	15
<i>Geum montanum</i> L.	2	10	3	2	5	.	3	5	10	35	5	20	30	5	20	25
<i>Crocus albiflorus</i> Kit.	2	1	2	.	5	.	.	.	58	30	20	.	25	25	12	15
<i>Ranunculus pyreneus</i> L.	1	2	.	2	.	.	.	.	10	2	20	5	2	13	5	7
<i>Poa alpina</i> L.	.	.	8	2	2	2	2	2	10	5	30	.	.	.	5	5
<i>Arnica montana</i> L.	.	.	.	.	.	.	.	.	.	.	.	5	5	5	10	15
<i>Leontodon helveticus</i> Merat	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
<i>Potentilla grandiflora</i> L.	1	2	4	2	.	.	.	.	2	15	13	40	10	10	5	10
<i>Potentilla aurea</i> L.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	5	.
<i>Trifolium alpinum</i> L.	.	.	3	.	.	.	.	.	.	3	2	10	.	5	5	5
<i>Achillea millefolium</i> L.	.	.	.	1	1	.	.	.	.	.	.	.	.	2	.	.
<i>Phleum alpinum</i> L.	.	.	.	.	.	.	.	.	.	.	.	15	8	10	5	3
<i>Galium pumilum</i> Murray	.	.	.	1	.	.	.	.	.	.	.	.	.	5	3	.
<i>Veronica officinalis</i> L.	.	.	.	.	.	.	.	.	.	.	.	.	.	5	.	.
<i>Campanula barbata</i> L.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
<i>Carex sempervirens</i> Vill.	.	.	.	.	2	10	5	5	.	.	.	.	.	.	.	.
<i>Calluna vulgaris</i> (L.) Hull	.	.	.	.	.	10	25	40	.	.	.	.	.	.	.	.
<i>Vaccinium myrtillus</i> L.	.	.	.	.	.	.	10	10	.	.	.	.	.	.	.	.
<i>Vaccinium gaultherioides</i> Bigelow	.	.	.	.	.	.	15	3	.	.	.	.	.	.	.	.