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

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Abstract

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

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

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

1. **Introduction**

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

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

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

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

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

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

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

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

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

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

In particular we tested the following hypotheses:

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

2. Materials and methods

2.1. *Site description*

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

The terrain slopes gently (4°), with a South aspect (195°N). The study area covers a surface of 2800 m^2.The site is characterized by an intra-alpine semi-continental climate, with a mean annual air temperature of +3.1 C° and a mean annual precipitation of about 880 mm. Generally the site is covered by snow from the end of October to late May, which limits the growing season to an average of five months (Galvagno et al., 2013).

The study site shows an undulating morphology, characterized by the presence of hummocks (15-30 cm high) alternate to interhummocks. On flat surfaces, the hummocks are organised in a non-sorted net; where the slope angle increases, they develop into parallel non-sorted stripes along the slope direction.

The studied subalpine grassland is a *Nardus stricta* formation, with the occurrence of other species as *Poa alpina, Trifolium alpinum, Arnica montana* and *Ranunculus pyrenaeus*, referred to the association *Sieversio-Nardetum strictae* Lüdi 1948.

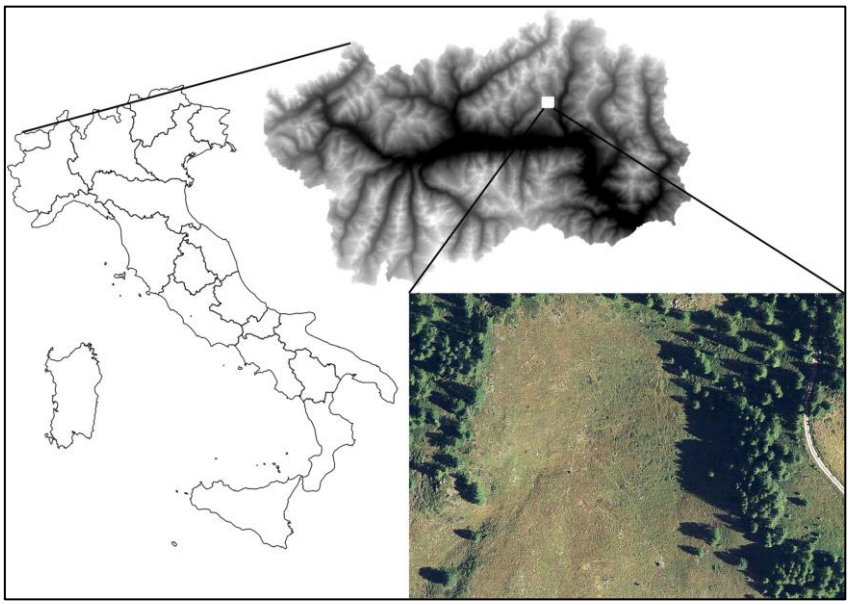

Fig. 1. The LTER experimental site of Tellinod in the Aosta Valley region, NW Italy.

2.2.*Meteorological patterns*

At the study site, air temperature and snow depth have been measured since 2010: the mean annual snow depth was 76 cm, while mean daily air temperatures varied from +15 to -10 °C (Fig. 2).

Soil temperature has been measured since 2010 in a non-hummocked area, at different depths (2, 10 and 35 cm). Moreover, in order to detect the thermal characteristics of hummocks, two soil temperature sensors (UTL1-2) were installed from November 2014 to June 2015 on hummock apex at 10 cm depth, and on hummock base at 30 cm depth. In the non-hummock area, frost penetration was limited to the surface (2 cm depth) and occurred for few days only in some years (Fig. 3A).

From the end of January to March (Fig. 3B) hummock apex remained constantly under 0 °C (-0.1 °C), while hummock base maintained a temperature close to +1 °C. At snowmelt a thermal inversion occurred, as

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

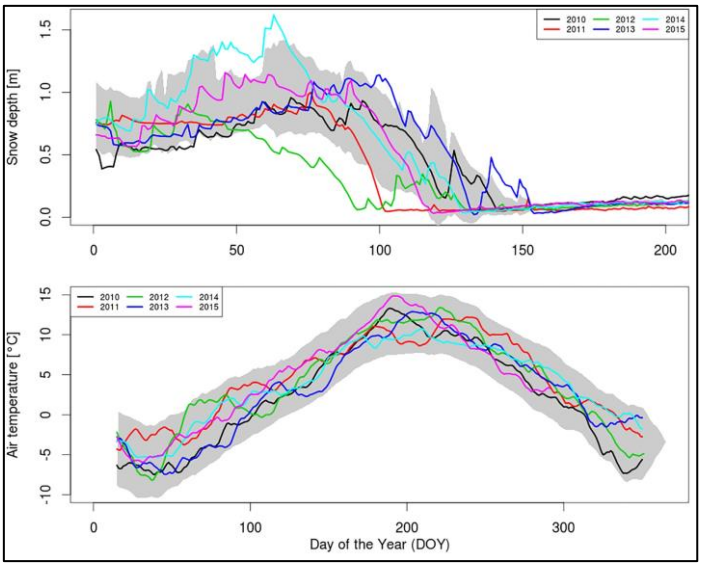

Fig. 2. Seasonal variation of snow depth and air temperature from 2010 to 2015. The grey polygon denotes the long-term (2008-2015) average (standard deviation).

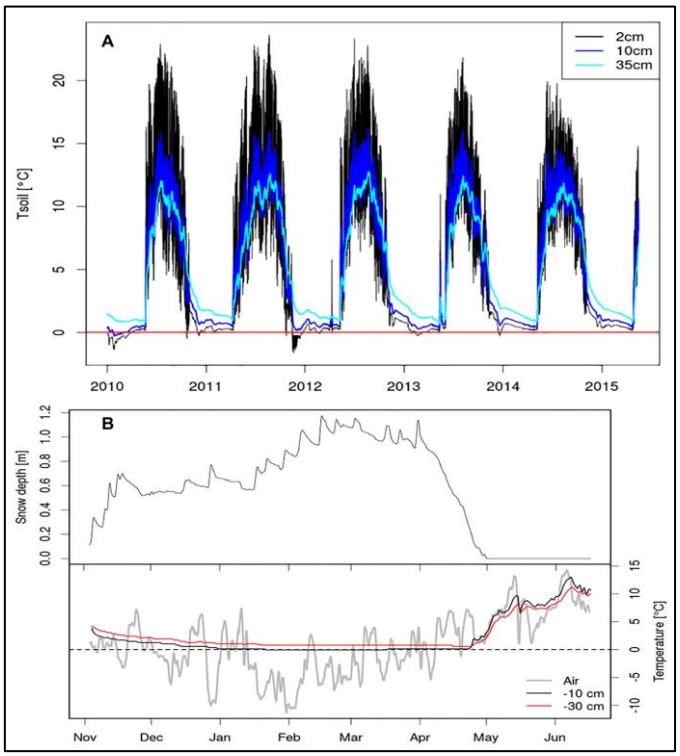

Fig. 3. Seasonal course of soil temperature in a non-hummocked area at different depths (2,10, 35 cm) from 2010 to the first part of 2015 (A); Hummocks apex and base temperature from November 2014 to June 2015 (B).

2.3. *Soil sampling and analysis*

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

The soil samples were air-dried, sieved to 2 mm and analyzed following the standard methods reported by Van Reeuwijk (2002). pH was measured in water (soil:water = 1:2.5); particle-size analysis was performed by the pipette method after organic matter destruction with H_2O_2 followed by dispersion with Na–hexametaphosphate; the cation exchange capacity (CEC) was determined in a $BaCl_2$ solution buffered at pH 8.1 (Rhoades, 1982); the exchangeable cations were measured by atomic absorption spectrometry (Analyst 400, Perkin Elmer, Waltham, MS, USA) on the $BaCl_2$ extracts. Total organic carbon (TOC) and nitrogen (TN) were analyzed by dry combustion with a CN elemental analyzer (CE Instruments NA2100, Rodano, Italy). Total soil P (TP) was determined by acid persulphate digestion (Nelson, 1987); available P (P_{Olsen}) was extracted with $NaHCO_3$ and determined colorimetrically by the ascorbic acid molybdate blue method (Murphy and Riley, 1962). In order to detect the spodic properties in the soil profile, the oxalate and dithionite extractable fractions of Fe and Al (Fe_o, Al_o, Fe_d) were measured. Total iron (Fe_{tot}) was determined after HCl–HNO_3 digestion and the Fe_o/Fe_d and Fe_d/Fe_{tot} ratios were calculated.

To evaluate water extractable organic carbon (WEOC) and water extractable total nitrogen (WETN) content 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 hours in 50 ml PE bottles. The soil samples were then centrifuged at 3000 rpm for 6 minutes, and the supernatant was filtered to <0.45 μm. Soil extracts were then acidified with HCl to remove the inorganic carbon fraction.

WEOC and WETN were determined with a TOC analyzer (Elementar, Vario TOC, Hanau, Germany). Ammonium in 1 M KCl extracts ($N\text{-}NH_4^+$) was determined colorimetrically (Crooke and Simpson, 1971) using

UV-vis spectrophotometer. Nitrate ($N\text{-}NO_3^-$) concentrations in the same extracts were determined following Miranda et al. (2001). Total extractable organic nitrogen (TEON) was determined as difference between WETN and dissolved inorganic N (DIN: $N\text{-}NH_4^+$+ $N\text{-}NO_3^-$) in the extracts.

2.4. *Vegetation survey and plant decomposition rate*

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

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

2.5. Statistical analyses

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

3. Results

3.1. *Topsoil characteristics in the hummocky grassland*

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

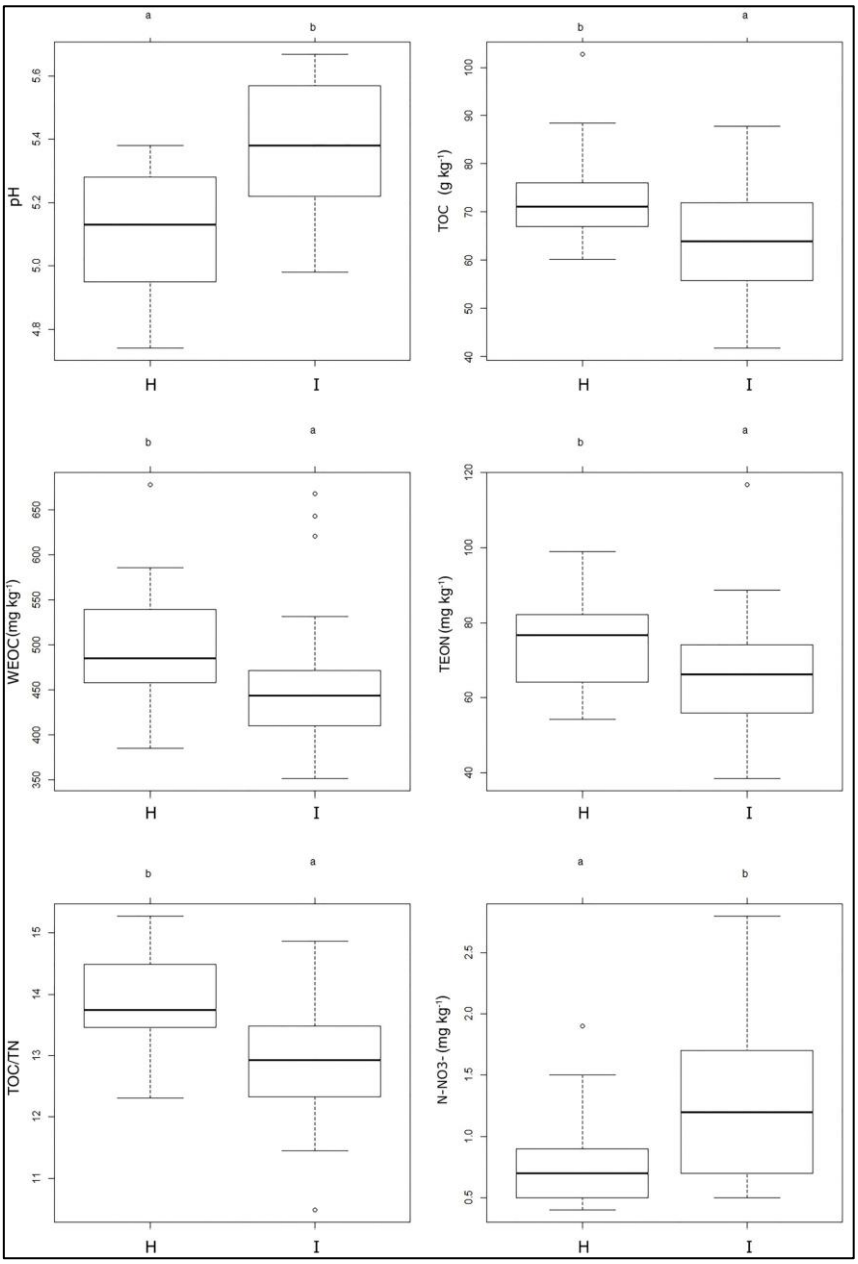

Fig. 4. Boxplots (n = 60) of pH values, TOC, WEOC, TEON, TOC/TN and $N\text{-}NO_3^-$ content of topsoils in hummock apexes (H) and interhummocks (I). Letters indicate statistically significant differences.

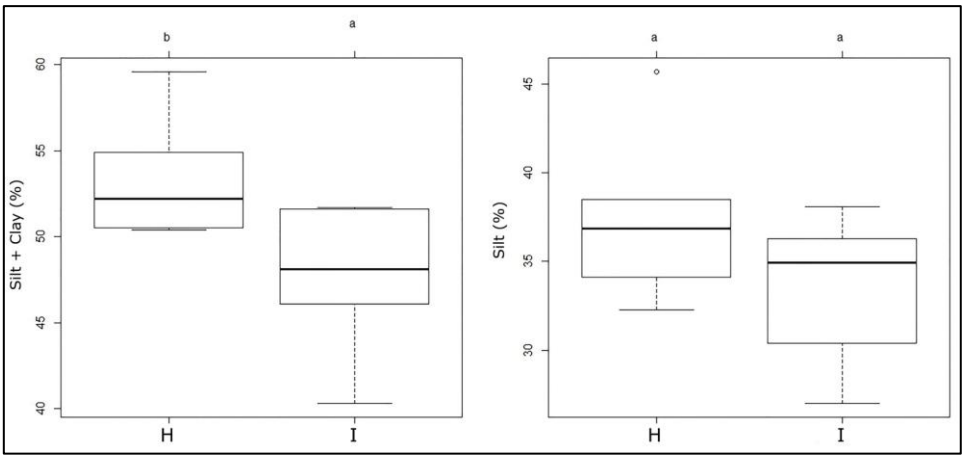

Fig. 5. Boxplots (n = 16) of silt and clay and silt content in hummock apexes (H) and interhummocks (I). Letters indicate statistically significant differences.

3.2. Soil profile characteristics

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

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

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

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

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

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

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

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

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

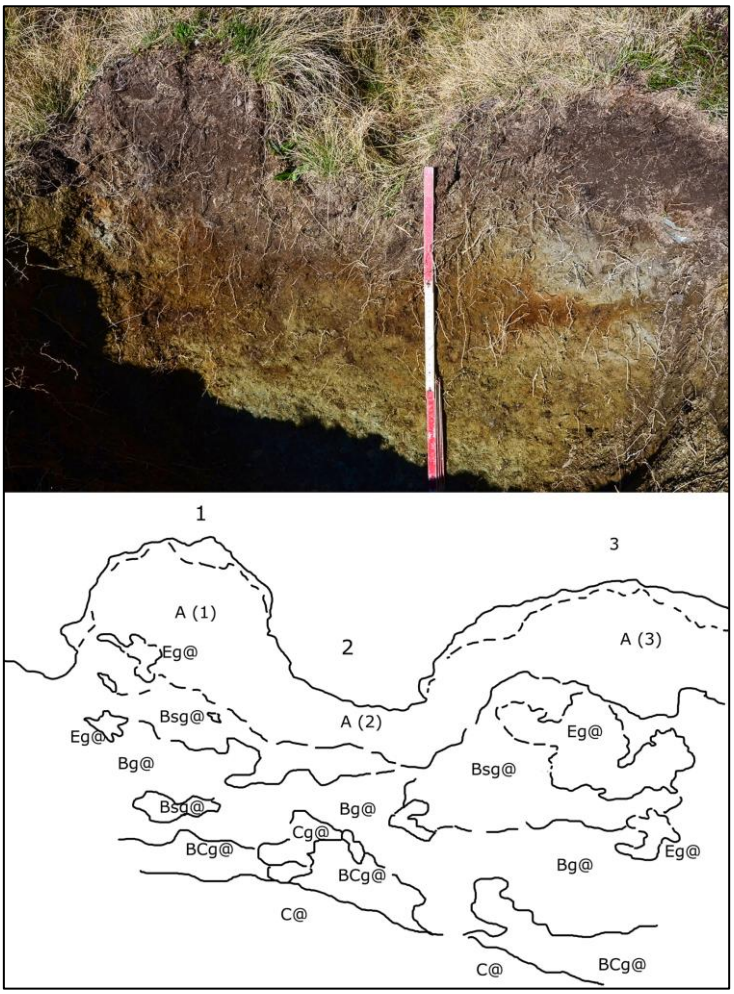

Fig. 6. The hummocky soil profile, with cryoturbated podzolic horizons; A (1), A (2) and A (3) are operationally numbered and correspond to the sectors used in the descriptions, with hummock apex horizons evidenced by 1 and 3, interhummock ones by number 2. Red and white tape sections are 20 centimetres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

3.3. *Vegetation survey*

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

3.4. *Plant decomposition rate*

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

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

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

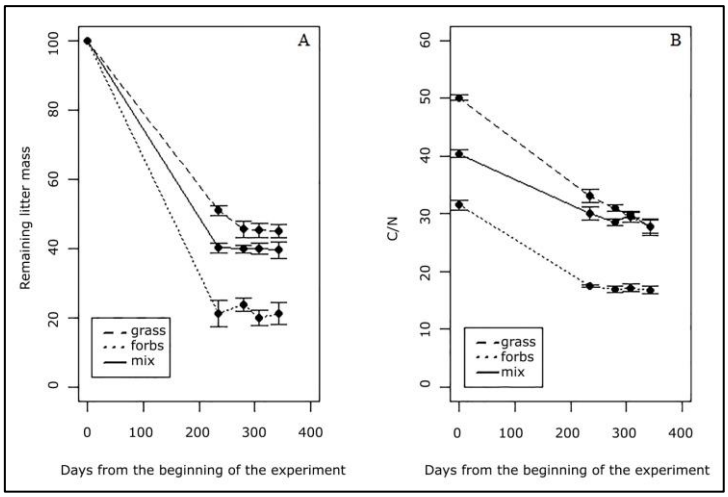

Fig. 7. Remaining litter mass (%) (A) and C/N ratio (B) for the three litter types (Grass, Forbs and Mix) during the one year long decomposition experiment.

In order to highlight the influence of the decomposition process on soil properties, N and C loss was calculated. The N loss differed for the litter types ($F_{2, 86} = 147.86$; $p<0.001$) (Fig. 8A): the highest amount was 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 all of the loss occurred during the snow-cover period.

The carbon loss differed in the three litter types ($F_{2, 86} = 141.90$; < 0.001) (Fig. 8B), but not between the microtopographic positions. The highest amount of C was lost during the snow cover period by the forbs (a 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).

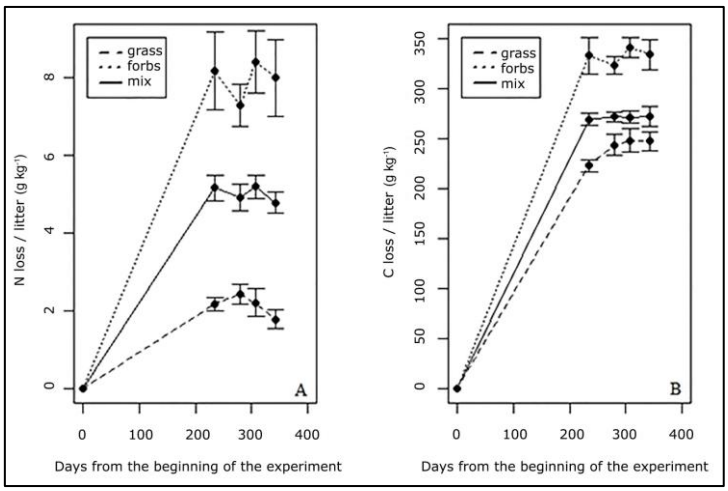

Fig. 8. Nitrogen (A) and carbon (B) loss of the three litter types (Grass, Forbs and Mix) during the one year long decomposition experiment.

4. Discussion

4.1. *Interactions between topsoil properties and vegetation*

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

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

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

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

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

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

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

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

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

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

4.2 *Pedogenesis in hummock soils*

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

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

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

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

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

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

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

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

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

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

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

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

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

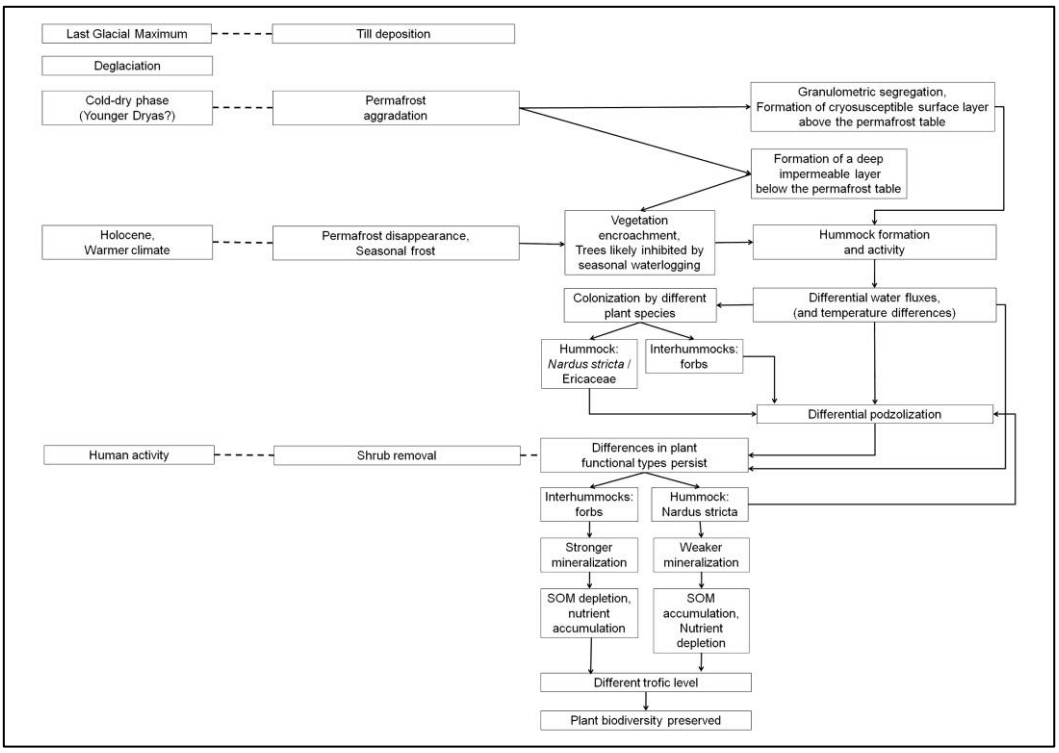

Fig. 9. Conceptual model of eco-pedological functioning of present-day grassland.

5. Conclusions

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

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

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

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References

Admiral, S.W. and Lafleur P.M., 2007. Partitioning of latent heat flux at a northern peatland. Aquat. Bot. 86, 107-116.

Baptist, F. and Choler P., 2008. A Simulation of the Importance of Length of Growing Season and Canopy Functional Properties on the Seasonal Gross Primary Production of Temperate Alpine Meadows. Ann. Bot. 101, 549–559, 2008 doi:10.1093/aob/mcm318.

Baptist, F., Yoccoz, N.G., Choler ,P., 2010. Direct and indirect control by snow cover over decomposition in alpine tundra along a snowmelt gradient. Plant Soil 328, 397 – 410. DOI 10.1007/s11104-009-0119-6.

Benscoter, B.W., Wieder, R.K. and Vitt, D.H., 2005. Linking microtopography with post-fire succession in bogs. J. Veg. Sci. 16, 453-460.

Beschel, R.L., 1966. Hummocks and their vegetation in the high Arctic. Washington, DC: US National Academy of Science, National Research Council Publication 1287, 13–20.

Biasi, C., Wanek, W., Rusalimova, O., Kaiser, C., Meyer, H., Barsukov, P. and Richter, A., 2005. Micro-topography and plant-cover controls on nitrogen dynamics in hummock tundra ecosystems in Siberia. Arctic Alpine Res. 37, 435–443. DOI: 10.1657/1523-0430(2005)037[0435:MAPCON]2.0.CO;2.

Billings, W.D., Mark, A.F., 1961. Interactions between alpine tundra vegetation and patterned-ground in mountains of southern New Zealand. Ecology 42, 18–31.

Bockheim, J.G., Tarnocai, C., 1998. Recognition of cryoturbation for classifying permafrost-affected soils. Geoderma 81 (3–4), 281–293.

Boeckli, L., Brenning, A., Gruber, S., Noetzli, J., 2012. Permafrost distribution in the European Alps: calculation and evaluation of an index map and summary statistics. Cryosphere 6, 807–820.

Burt, R., Alexander, E.B., 1996. Soil development on moraines of Mendenhall Glacier, southeast Alaska. 2. Chemical transformations and soil micromorphology. Geoderma 72, 19–36.

Cornelissen Johannes, H.C., Pérez-Harguindeguy N., Díaz S., Grime J.P., Marzano B., Cabido M., Vendramini F. and Cerabolini B., 1999. Leaf Structure and Defence Control Litter Decomposition Rate Across Species and Life Forms in Regional Floras on Two Continents. New Phytol. Vol. 143, No. 1, Special Issue: Variation in Leaf Structure (Jul., 1999), pp. 191-200.

Crooke, W.M. & Simpson, W.E., 1971. Determination of ammonium in Kjeldahl digests of crops by an automated procedure. J. Sci. Food Agric. 22, 9-10.

D'Alessandro S., 2009. Tesi di laurea "Relazioni tra fenologia della comunità vegetale e bilancio del carbonio in un pascolo subalpino a Nardus stricta L.".

D'Amico, M.E., Julitta F., Previtali F., Cantelli D., 2008. Podzolization over ophiolitic materials in the western Alps (Natural Park of Mont Avic, Aosta Valley, Italy). Geoderma 146,129–137.

D'Amico, M.E., Freppaz, M., Filippa G., Zanini E., 2014. Vegetation influence on soil formation rate in a proglacial chronosequence (Lys Glacier, NW Italian Alps). Catena 113, 122–137.

Edwards, A.C. and Cresser, M.S., 1992. Freezing and its effect on chemical and biological properties of soil. Adv. Soil Sci. 18, 61–79.

Egli, M., Fitze P., Mirabella A., 2001. Weathering and evolution of soils formed on granitic, glacial deposits: results from chronosequences of Swiss alpine environments. Catena 45, 19–47.

Ellis, S., 1983. Stratigraphy and 14C dating of two earth hummocks, Jotunheimen, South Central Norway. Geogr. Ann. 65A, 279–87.

FAO, 2014. World Reference Base for Soil Resources 2014. World Soil Resources Reports 106. FAO, Rome.

FAO, 2006. Guidelines for soil description, Fourth edition. FAO, Rome.

Filippa, G., Cremonese, E., Galvagno, M., Migliavacca, M., Morra di Cella, U., Petey, M., & Siniscalco, C., 2015. Five years of phenological monitoring in a mountain grassland: inter-annual patterns and evaluation of the sampling protocol. Int. J. Biometeorol. http://doi.org/10.1007/s00484-015-0999-5.

Ford, D.J., Cookson, W.R., Adams, M.A., Grierson, P.F., 2007. Role of soil drying in nitrogen mineralization and microbial community function in semi-arid grasslands of north-west Australia. Soil Biol. Biochem. 39, 1557-1569.

Galvagno, M., Wohlfahrt, G., Cremonese, E., Rossini, M., Colombo, R., Filippa, G., Migliavacca, M., 2013. Phenology and carbon dioxide source/sink strength of a subalpine grassland in response to an exceptionally short snow season. Environ. Res. Lett. 8(2), 25008.

Gensac, P., 1990. Plant and soil groups in the alpine grassland of the Vanoise Massif, French Alps. Arct. Alp. Res. 22 (2), 195–201.

Gerrard, A. J., 1992. The nature and geomorphological relationships of earth hummocks (thufur) in Iceland. Z. Geomorphol. Suppl. 86, 173–182.

Grab, S.W., 1994. Thufur in the Mohlesi Valley, Lesotho, Southern Africa. In: Permafrost Periglacial Process. 5, 111–118. DOI: 10.1002/ppp.3430050205.

Grab, S.W., 1997. Thermal regime for a thufa apex and its adjoining depression, Mashai Valley, Lesotho. Permafrost Periglacial Process. 8, 437–45.

Grab, S.W., 2002. Periglacial phenomena in Ethiopia: a review. In: Permafrost and Periglacial Processes 13, 71–76 DOI: 10.1002/ppp.405.

Grab, S.W., 2005. Aspects of the geomorphology, genesis and environmental significance of earth hummocks (thúfur, pounus): miniature cryogenic mounds Prog. Phys. Geogr. 29 (2), 139–155. DOI: 10.1191/0309133305pp440ra.

Grogan, P., Michelsen A., Ambus P., Jonasson S., 2004. Freeze–thaw regime effects on carbon and nitrogen dynamics in sub-arctic heath tundra mesocosms. Soil Biol. Biochem. 36, 641–654.

Güsewell S., Jewell, P.L, Edwards P.J., 2005. Effects of heterogeneous habitat use by cattle on nutrient availability and litter decomposition in soils of an Alpine pasture. Plant Soil 268, 135-149.

Kalbitz, K., Solinger S., Park J.H., 2000. Controls on the dynamics of dissolved organic matter in soils: a review. Soil Sci.165, 277–304.

Kvíderová, J., Elster, J. and Šimek, M., 2011. *In situ* response of *Nostoc commune* s.l. colonies to desiccation in Central Svalbard, Norwegian High Arctic. Fottea 11, 87–97.

Longton, R.E., 1988. Biology of polar bryophytes and lichens. Cambridge: Cambridge University Press. 391 pp.

Lötschert, W., 1974. Über die Vegetation frostgeformter Böden auf Island. Ber. a. d. Forschungsstelle 'Nedri As', 16, Hveragerdi, Iceland, 15 pp.

Lundqvist, J., 1969. Earth and ice mounds: a terminological discussion. The periglacial environment, ed. Péwé, T.L., Montreal: McGill-Queen's University Press, pp. 203–15.

Luoto, M. and Seppälä, M., 2002. Characteristics of earth hummocks (pounus) with and without permafrost in Finnish Lapland. Geogr. Ann. 84A, 127–136.

Mackay, J.R., 1980. The origin of hummocks, western Arctic coast, Canada. Can. J. Earth Sci. 17, 996–1006.

Mark, A.F., 1994. Patterned ground activity in a southern New Zealand high-alpine cushionfield. Arctic Alpine Res. 26, 270–280. DOI: 10.2307/1551939.

Mark, A.F., Bliss L.C., 1970. The high-alpine vegetation of Central Otago, New Zealand. N. Z. J. Bot. 8, 381–451.

McCraw, J.D., 1959: Periglacial and allied phenomena in western Otago. N. Z. Geog. 15, 61–68.

Miranda, K.M., Espey, M.G, Wink, D.A., 2001. A rapid, simple spectrophotometric method for simultaneous detection of nitrate and nitrite. Nitric Oxide-Biol Ch 5(1), 62-71.

Murphy, J., Riley, P., 1962. A modified single-solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27, 31–36.

Nelson, N.S., 1987. An acid-persulfate digestion procedure for determination of phosphorus in sediments. Commun. Soil Sci. Plant Anal. 18, 359–369.

Pornon, A., Doche, B., 1996. Age structure and dynamics of Rhododendron ferrugineum L. populations in the Northwestern French. Alps. J. Veg. Sci. 7 (2), 265–272.

Quinton, W. L., 2000. Subsurface drainage from hummock-covered hillslopes in the Arctic tundra. J. Hydrol. 237, 113–125.

Quinton, W.L. and Marsh P., 1998. The influence of mineral earth hummocks on subsurface drainage in the continuous permafrost zone. Permafrost Periglacial Process. 9, 213–228.

Reddy, K. R. and Patrick W.H., 1984. Nitrogen transformations and loss in flooded soils and sediments. CRC Crit. Rev. Environ. Control 13, 273–309.

Rhoades, J.D., 1982. Cation exchange capacity. In: Page, A.L., et al. (Eds.), Methods of Soil Analysis. Part 2, 2nd edn. Agron. Monogr. vol. 9. ASA and SSSA, Madison, WI, pp. 149– 157.

Schaetzl, R., Anderson, S., 2005. Soils. Genesis and Geomorphology. Cambridge University Press (Ed), Cambridge (UK).

Schunke, E., 1977. Zur genese der thufur Islands und Ost-Grönlands. Erdkunde 31, 279–87.

Schunke, E., 1981. Zur kryogenen Bodendynamik der arktischen Tundren Nordamerikas und Nordeuropas, Polarforschung, 51, 161-74.

Schunke, E. and Zoltai, S.C., 1988. Earth hummocks. In Clark, M.J., Adv. Periglac. Geomorphol. Chichester: Wiley, 231–45.

Scott, M.B., Dickinson, K.J.M., Barratt, B.I.P. and Sinclair, B.J., 2008. Temperature and moisture trends in non-sorted earth hummocks and stripes on the Old Man Range, New Zealand: implications for mechanisms of maintenance. Permafrost Periglacial Process.19, 305–314. DOI: 10.1002/ppp.627.

Scotter, G.W. and Zoltai, S.C., 1982. Earth hummocks in the Sunshine area of the Rocky Mountains, Alberta and British Columbia. Arctic 35, 411–16.

Sharp, R.P., 1942. Soil structures in the St. Elias Range, Yukon Territory. J. Geomorphol. 5, 274–301.

Shen, H., Tang, Y. and Washitani I., 2006. Morphological plasticity of *Primula nutans* to hummock-and-hollow microsites in an alpine wetland. J. Plant Res. 119, 257–264.

Smith, M., 2011. Characteristics of hummocks and hummocked wetlands in Colorado.

Solly, E., 2009. Tesi di laurea “Monitoraggio della fenologia in un pascolo subalpino a Nardus stricta L.: un approccio integrato.”

Tarnocai, C. and Zoltai, S.C., 1978. Earth hummocks of the Canadian Arctic and Subarctic. Arctic Alpine Res. 10, 581–94.

Treml, V., Krizek, M. and Engel, Z., 2010. Classification of patterned ground based on morphometry and site characteristics: a case study from the High Sudetes, Central Europe. Permafrost Periglacial Process. 21, 67–77. DOI: 10.1002/ppp.671

Tyrtikov, A.P., 1969. Effects of vegetation on the freezing and thawing of soils. New Delhi: Amerind Publishing Co. 192 p.

Van Reeuwijk, L.P., 2002. Procedures for Soil Analysis. Technical Paper n. 9. International Soil Reference and Information Centre, Wageningen, Netherlands.

Van der Krift, T.A.J., Berendse F., 2002. Root life spans of four grass species from habitats differing in nutrient availability. Funct. Ecol. 16, 198-203.

Van Vliet-Lanoë B., 1991. Differential frost heave, load casting and convection: converging mechanisms: a discussion of the origin of cryoturbations. Permafrost Periglacial Process. 2, 123–39.

Van Vliet-Lanoë, 1998. Frost and soils. Implications for paleopedology. Catena 34, 157–83.

Van Vliet-Lanoë, B., 2014. Patterned ground and climate Change. *Permafrost: distribution, composition and impacts on infrastructure and ecosystems*". Ed. Oleg Podrovsky, chap 2 pp.67-106, Nova Science Publishers, Inc, Results of the IPEV CRYOCLIM 2004 program.

Van Vliet-Lanoë, B., Bourgeois, O. and Dauteuil, O. 1998. Thufur formation in northern Iceland and its relation to Holocene climate change. Permafrost Periglacial Process. 9, 347–365. DOI: 10.1002/(SICI)1099-1530(199810/12).

Van Vliet-Lanoë, B. and Seppälä, M. 2002. Stratigraphy, age and formation of peaty earth hummocks (pounus), Finnish Lapland. Holocene 12, 187–99.

Vestgarden, L.S., Austnes K., 2009. Effects of freeze-thaw on C and release from soils below different vegetation in a montane system: a laboratory experiment. Glob. Chang. Biol. 15, 876–887.

Williams, P.J. and Smith, M.W., 1989. The Frozen Earth. Fundamentals of Geocryology. Studies in Polar Research Series. xvi + 306 pp. Cambridge, New York, Port Chester, Melbourne, Sydney: Cambridge University Press. ISBN 0 521 36534 1.

Zoltai, S.C. and Tarnocai, C., 1974. Soils and vegetation of hummocky terrain: Environmental-Social Committee, Task Force on Northern Oil Development, Government of Canada. Report 74-5, 86 pp.

Zoltai, S.C. and Tarnocai, C., 1981. Some nonsorted patterned ground types in northern Canada. Arctic Alpine Res. 13, 139 – 51.

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	$N\text{-}NH_4^+$	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**	**I1**	**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
Nardus stricta L.	94	85	80	90	85	78	40	35	10	10	10	5	20	10	25	15
Geum montanum L.	2	10	3	2	5	.	3	5	10	35	5	20	30	5	20	25
Crocus albiflorus Kit.	2	1	2	.	5	.	.	.	58	30	20	.	25	25	12	15
Ranunculus pyreneus L.	1	2	.	2	.	.	.	.	10	2	20	5	2	13	5	7
Poa alpina L.	.	.	8	2	2	2	2	2	10	5	30	.	.	.	5	5
Arnica montana L.	.	.	.	.	.	.	.	.	.	.	.	5	5	5	10	15
Leontodon helveticus Merat	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Potentilla grandiflora L.	1	2	4	2	.	.	.	.	2	15	13	40	10	10	5	10
Potentilla aurea L.	.	.	.	.	.	.	.	.	.	.	.	.	.	3	5	.
Trifolium alpinum L.	.	.	3	.	.	.	.	.	.	3	2	10	.	5	5	5
Achillea millefolium L.	.	.	.	1	1	.	.	.	.	.	.	.	.	2	.	.
Phleum alpinum L.	.	.	.	.	.	.	.	.	.	.	.	15	8	10	5	3
Galium pumilum Murray	.	.	.	1	.	.	.	.	.	.	.	.	.	5	3	.
Veronica officinalis L.	.	.	.	.	.	.	.	.	.	.	.	.	.	5	.	.
Campanula barbata L.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Carexsempervirens Vill.	.	.	.	.	2	10	5	5	.	.	.	.	.	.	.	.
Calluna vulgaris (L.) Hull	.	.	.	.	.	10	25	40	.	.	.	.	.	.	.	.
Vaccinium myrtillus L.	.	.	.	.	.	.	10	10	.	.	.	.	.	.	.	.
Vaccinium gaultherioides Bigelow	.	.	.	.	.	.	15	3	.	.	.	.	.	.	.	.