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NICOLA COLOMBO (*), ELISA GIACCONE (*), LUCA PARO (**), GIORGIO BUFFA (***),
& SIMONA FRATIANNI (*,****)

THE RECENT TRANSITION FROM GLACIAL TO PERIGLACIAL ENVIRONMENT IN A HIGH ALTITUDE ALPINE BASIN (SABBIONE BASIN, NORTH-WESTERN ITALIAN ALPS). PRELIMINARY OUTCOMES FROM A MULTIDISCIPLINARY APPROACH

ABSTRACT: COLOMBO N., GIACCONE E., PARO L., BUFFA G. & FRATIANNI S., *The recent transition from glacial to periglacial environment in a high altitude alpine basin (Sabbione Basin, North-Western Italian Alps). Preliminary outcomes from a multidisciplinary approach.* (IT ISSN 0391- 9838, 2016)

High Alps are characterised by glacial and periglacial environments, which change sensitively in response to climatic changes. The global warming that has been witnessed over the last few decades has caused remarkable effects on high altitude mountain zones. In order to assess the ongoing transition from glacial to periglacial environments, due to climate change, and its effects on cryosphere, geosphere and biosphere, a multidisciplinary approach has been applied in the Sabbione Basin (Italy). In this study, attention has mainly been paid to two selected areas (pilot sites) representative of glacial-periglacial interactions in the investigated basin. Climatological and geomorphological studies have been conducted, together with analyses on the potential permafrost distribution. Furthermore, floristic surveys have been carried out to characterise the vegetation within the periglacial sites and *Artemisia genipi* has been selected as the monitoring species because of its abundance and its late flowering season. The climatic analyses have indicated that, over the last decades, air temperatures have increased and snow cover duration and thickness have decreased, thus causing a substantial regression of the glaciers. Periglacial processes and new permafrost-related landforms have been developing in recently deglaciated areas. The distribution, reproductive state and phenology of the monitoring species show a clear relationship with the permafrost-related landforms (i.e. rock glaciers). Moreover, the phenological delay observed in some of the *Artemisia genipi* individuals shows that micro-morphology and cold water sources have a considerable influence on their development. Finally, it has been found that lower altitude plant species have been colonising the basin, indicating an upward shift due to global warming conditions.

KEY WORDS: Periglacial processes, Climate change, Glaciers, Geomorphology, Vegetation, NW Italian Alps.

RIASSUNTO: COLOMBO N., GIACCONE E., PARO L., BUFFA G. & FRATIANNI S., *La recente transizione da ambiente glaciale a periglaciale in un bacino d'alta quota alpino (Bacino del Sabbione, Alpi italiane nord-occidentali). Risultati preliminari da un approccio multidisciplinare* (IT ISSN 0391-9838, 2016)

Le Alpi in alta quota sono caratterizzate da ambienti glaciali e periglaciali, che mutano sensibilmente in risposta ai cambiamenti climatici. Il riscaldamento globale verificatosi negli ultimi decenni ha provocato effetti notevoli sulle zone montane di alta quota. Un approccio multidisciplinare è stato applicato nel bacino del Sabbione (Italia) al fine di valutare la transizione in atto da ambiente glaciale a periglaciale, intervenuto a causa dei cambiamenti climatici, e comprendere i suoi effetti su criosfera, geosfera e biosfera. In questo studio l'attenzione è stata rivolta principalmente a due aree selezionate (siti pilota), rappresentative delle interazioni tra ambiente glaciale e periglaciale nel bacino indagato. Sono stati condotti studi climatologici e geomorfologici, insieme ad analisi sulla distribuzione potenziale del permafrost. Inoltre, sono state effettuate indagini floristiche per caratterizzare la vegetazione all'interno dei siti periglaciali, e *Artemisia genipi* è stata selezionata come specie di monitoraggio per la sua abbondanza e la sua stagione di fioritura tardiva. Le analisi climatiche hanno mostrato che, negli ultimi decenni, le temperature dell'aria sono aumentate e la durata e lo spessore del manto nevoso sono diminuiti, causando una regressione sostanziale dei ghiacciai. Processi periglaciali e nuove forme geomorfologiche legate alla presenza di permafrost si sono sviluppate nelle aree recentemente deglaciate. La distribuzione, lo stato riproduttivo e la fenologia delle specie di monitoraggio mostrano una chiara relazione con le morfologie legate al permafrost (ad esempio i rock glaciers). Inoltre, il ritardo fenologico osservato in alcuni individui di *Artemisia genipi* mostra che la micro-morfologia e le sorgenti di acqua fredda hanno una notevole influenza sul loro sviluppo. Infine, a causa del riscaldamento globale, è stata notata la presenza di specie vegetali di più bassa altitudine nel bacino studiato, indice di una risalita altitudinale delle specie.

TERMINI CHIAVE: Processi periglaciali, Cambiamento climatico, Ghiacciai, Geomorfologia, Vegetazione, Alpi Occidentali.

(*) *Dipartimento di Scienze della Terra, Università degli Studi di Torino, Via Valperga Caluso, 35 - 10125 Torino, Italy.*

(**) *Dipartimento "Geologia e Dissesto", Arpa Piemonte, Via Pio VII, 9 - 10135 Torino, Italy.*

(***) *Dipartimento di Scienze della Vita e Biologia dei Sistemi, Università degli Studi di Torino, Viale Mattioli, 25 - 10125 Torino, Italy.*

(****) *Centro di Ricerca sui Rischi Naturali in Ambiente Montano e Collinare (NatRisk), Via Leonardo da Vinci 44 - 10095 Grugliasco (TO)*

Corresponding author: simona.fratianni@unito.it

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INTRODUCTION

Between 1880 and 2012 global mean air temperatures increased on average by 0.85 °C (0.65 to 1.06 °C) (IPCC, 2013), while almost twice the global rate was recorded in the Alps (Auer & *alii*, 2007), and minimum air temperatures rose more than the maxima (Beniston, 2005). The rise in air temperatures has been associated with the decrease in solid precipitation (Garzena & *alii*, 2015); in the North-Western Alps, as recorded during the 1951÷2010 period, a considerable snowfall/snow depth reduction was measured (Terzago & *alii*, 2012, 2013; Acquaotta & *alii*, 2013, 2015; Fratianni & *alii*, 2015).

Climatic changes at high altitudes interact with glacial processes and cause important modifications of the geomorphology of valley heads. In the North-Western Italian Alps, recent glaciological surveys have shown a general reduction in the area and volume of glaciers (Baroni & *alii*, 2014, 2015), as has also been witnessed in other areas throughout the Italian Alps (Salvatore & *alii*, 2015; Smiraglia & *alii*, 2015), in the European Alps and at a global scale (WGMS, 2015; Zemp & *alii*, 2015). These changes have led to a gradual shrinkage of the cryosphere, with implications on human life structures, such as freshwater reductions due to retreating glaciers, rising slope instability caused by post-glacial tensional release and debris flows/slides caused by the degradation of unconsolidated and unvegetated glaciogenic sediments (Ballantyne, 2002; Curry & *alii*, 2006).

The regression of glaciers allows periglacial environmental conditions to form in deglaciated areas. These processes are related to ground freezing and permafrost formation, including the growth of segregated ice lenses and associated frost heaving, the development of cryostructures and cryotextures, thermal-contraction cracking and the growth of frost mounds (French, 2007). The development of periglacial processes is virtually inhibited underneath the glaciers, because of the insulating effect of the ice masses between atmosphere and lithosphere. Frost action is absent especially at the base of temperate glaciers, where the temperatures are too high and subglacial/basal meltwater exists. Furthermore, subglacial permafrost is absent if the glacial stress is high enough to overcome the resistance of the frozen rock and the release of frictional heat precludes its existence (Hart & *alii*, 1990). Nevertheless, the relationships between glaciers and permafrost are very complex and depend on the thermal regime of the glacier (warm or cold based), the topographic conditions (elevation, aspect and topography), the substrate typology (bedrock, blocky or fine-grained till) and the morphoclimatic history of the area (Guglielmin & *alii*, 2001; Haeberli, 2005; Haeberli & Gruber, 2008; Dobiński & *alii*, 2011).

Like glaciers, periglacial environments are also affected by climate change (Leopold & *alii*, 2010; Avian & Kellerer-Pirklbauer, 2012). Glacier shrinkage becomes apparent in relatively short reaction times, whereas the response of mountain permafrost is equally sensitive, but somewhat delayed (Otto & Keuschnig, 2014). Some studies have confirmed that the increase in ground temperature during the last century (Vonder Mühll & Haeberli, 1990; Osterkamp & Romanovsky, 1999) has accelerated in recent years (Hoelzle & *alii*, 2002; Harris & *alii*, 2003) with a high interannual variability caused by variations in snowpack thickness and duration, and air temperature distribution (Hoelzle & Gruber, 2008). Therefore, because of the growing concern of warming-induced permafrost degradation and hazards related to the melting of ground ice, global warming and its impact on periglacial environments is a research topic of increasing importance (Gruber & Haeberli, 2007; Harris & *alii*, 2009).

Air temperature rising and regression of glaciers also affect the vegetation dynamics in high altitude areas. In the Alps, the upward migration of treeline together with alpine and nival plant species at a rate of 8÷10 m per decade was confirmed by several studies which demonstrated significantly changes in vegetal community compositions under climate change effects (e.g., Keller & *alii*, 2000; Walther & *alii*, 2005; Gehring-Fasel & *alii*, 2007; Cannone & *alii*, 2008). Plant communities in new deglaciated areas and on periglacial landforms are composed by pioneer species typical of unconsolidated substrates (Cannone & *alii*, 1997; Pirola, 2003). Some authors studied the vegetation distribution on periglacial landforms such as patterned grounds (Béguin & *alii*, 2006) and active, inactive and relict rock glaciers (Cannone & *alii*, 1995; Frauenfelder, 1997), highlighting the presence of specific associations and relations between permafrost and vegetation. Particularly, on rock glaciers the surface disturbances produced by permafrost creep and the presence of fine-grained materials in localised zones can be considered as the most important environmental factors controlling the plant growth and distribution (Burga & *alii*, 2004).

Climate and cryotic factors (e.g., air temperature, depth and persistence of snow cover, glacier mass evolution, processes in the active layer of permafrost, etc.) are the main features related to the evolution of the ground surface at high altitudes. Complex interactions among these factors, their feedback effects on abiotic and biotic processes, and the cold landscape evolution under climate change (French, 2007; Benn & Evans, 2010) underline the importance of studying the cryosphere through a multidisciplinary approach, overcoming the traditional conceptual separation in geosciences studies between glacial and periglacial (with or without permafrost) domains (Etzelmüller & Hagen, 2005). In order to assess the recent transition from glacial to periglacial environments and its consequences on abiotic and biotic ecosystems in the Sabbione basin, a multidisciplinary approach has been applied by analysing climatic, geomorphological, permafrost distribution and vegetational data. In particular, the aims of our research are:

– Analysis of the gradual transition from glacial to periglacial environments in the Sabbione Basin, over the last six decades, in relation to the evolution of the climatic and morphoclimatic characteristics in the context of global warming, by using local high altitude meteorological stations;

– Identification and quantification of ongoing periglacial and permafrost processes in selected areas (pilot sites), which are progressively getting ice-free, through detailed geomorphological analyses. In particular, we aimed for assessing the meso- and micro-geomorphological relationships between the glacial and periglacial domains;

– Investigation of the effects of glacial/periglacial process dynamics on the vegetation distribution in a transitional glacial catchment. Particularly, we studied the influence of the periglacial/permafrost landforms (active rock glaciers) on the vegetation colonisation and phenology of a monitoring species (*Artemisia genipi*) in selected areas (pilot sites).

The Sabbione basin is characterised by the largest glaciated area in the Piedmont Alps and by one of the largest hydroelectrical reservoirs in the Piedmont Region (NW Italy). The characteristics of the investigated area make this catchment an outstanding field laboratory for the study of the genesis of different processes and landforms, and their spatial/temporal relationships. In fact, the catchment morphology is the result of several different exogenous processes that have acted diachronically in some cases and simultaneously in others, such as glacial, periglacial and anthropogenic processes. Therefore, it is important that the processes influencing the dynamics of an alpine basin are described and understood through an integrated multidisciplinary approach.

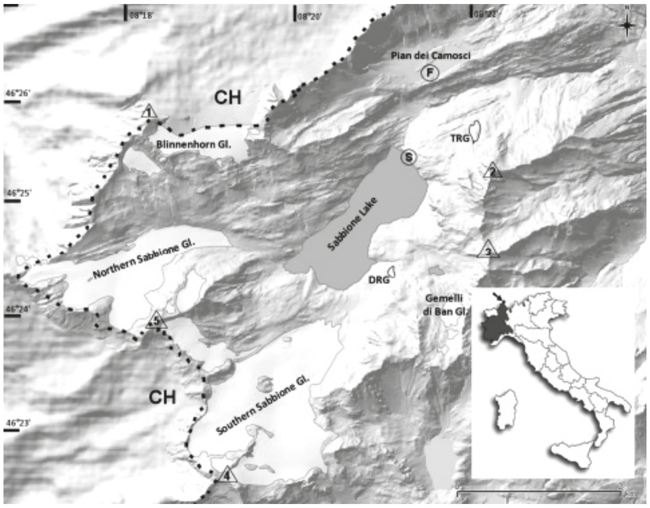

FIG. 1 - Shaded relief map of the study area with main characteristics. Dotted line: Italy-Switzerland cross border. Triangles: main peaks of the basin (1 - Blinnenhorn, 2 - Corno di Ban, 3 - Gemelli di Ban, 4 - Punta d'Arbola, 5 - Hohsandhorn). Circles: weather stations (F - Formazza, S - Sabbione). TRG: talus rock glacier. DRG: debris rock glacier.

STUDY AREA

The Sabbione basin is located in the North-West of Italy (46°25'N, 8°20'E) in the Ossola Valley (Piedmont Region), forming the upper basin of the Toce River, along the border to Switzerland (fig. 1). The study area is about 18 km^2 and ranges from 2300 to 3374 m a.s.l. of altitude. Several peaks surround the basin and the highest are Blinnenhorn (3374 m a.s.l.), Corno di Ban (3027 m a.s.l.), Gemelli di Ban (2946 m a.s.l.), Punta d'Arbola (3235 m a.s.l.) and Hohsandhorn (3182 m a.s.l.). The basin is characterised by the presence of an artificial lake of 1.23 km^2 (about 26 million m^3), built in the 1950's, and two of the biggest glaciers of Piedmont Region (Northern and Southern Sabbione Glaciers, about 3.8 km^2).

About 60% of the basin is covered by glaciers and bare bedrock. From a geological point of view, it is located in the Lower Penninic nappes composed by orthogneiss (Monte Leone Nappe), in the southern sectors, and Cretaceous silica-carbonate rocks (metamorphosed in calceschists during the Paleogene, Valais Units), in the northern sectors; amphibolites and prasinites occur in marginal zones of the study area (Rivella & *alii*, 2012). The most widespread deposits are recent till mainly referred to the LIA. Both soils and vegetation, with grasslands chiefly located on south-facing slopes, are poorly developed in the Sabbione catchment.

METHODS

Climate, glaciers and permafrost

Climate data were measured at two meteorological stations located in the study area (fig. 1): "Formazza" automatic station (2453 m a.s.l.) managed by Arpa Piemonte, providing a homogeneous time-series from 1988 to 2012, and "Sabbione" manned station (2470 m a.s.l) managed by power supplier company ENEL, with a homogeneous time-series from 1950 to 2012. A data quality control using the RClimDex software (Zhang & Yang, 2007) was performed prior to the analysis of air temperature, precipitation and snow time series. We used the monthly mean only if at least 80% of the daily data were available, equal to a gap of 6 non-consecutive days (Sneyers, 1990). Moreover, in order to recover metadata and analyse the degree of time-series homogenisation, historical researches and data comparison with nearby stations were carried out (for further details: Giaccone & *alii*, 2015).

The statistical analysis of daily data was performed using RClimDex and AnClim softwares (Stèpànek, 2007). Values from both stations were aggregated on monthly, seasonal and annual basis, and trends were calculated for the main climatic parameters for the longest time dataset of Sabbione station (1950÷2012). Maximum and minimum air temperatures, summer air temperatures, cumulated precipitation, number of rainy days, cumulated fresh snow, snow depth, number of snowy days, snow cover absence, number of frost days and ice days, growing season length, cold spell duration indicator and warm spell duration indicator were calculated using the Mann-Kendall non-parametric test to verify the statistical significance, assuming a 95% probability level (Sneyers, 1990, 1992).

In order to estimate the permafrost distribution, empirical models already available for the studied area were analysed: APMOD (alpine permafrost index map - APIM) (Boeckli & *alii*, 2012) (fig. 2a), PERMAROCK modified (mod.) (Guglielmin, 2009) (fig. 2b) and Swiss Permafrost Map (BAFU, 2005) (fig. 2c).

Finally, literature data review, photographic interpretation and historical maps were used to reconstruct the glacial evolution of the basin since the end of the LIA and to prepare the field surveys.

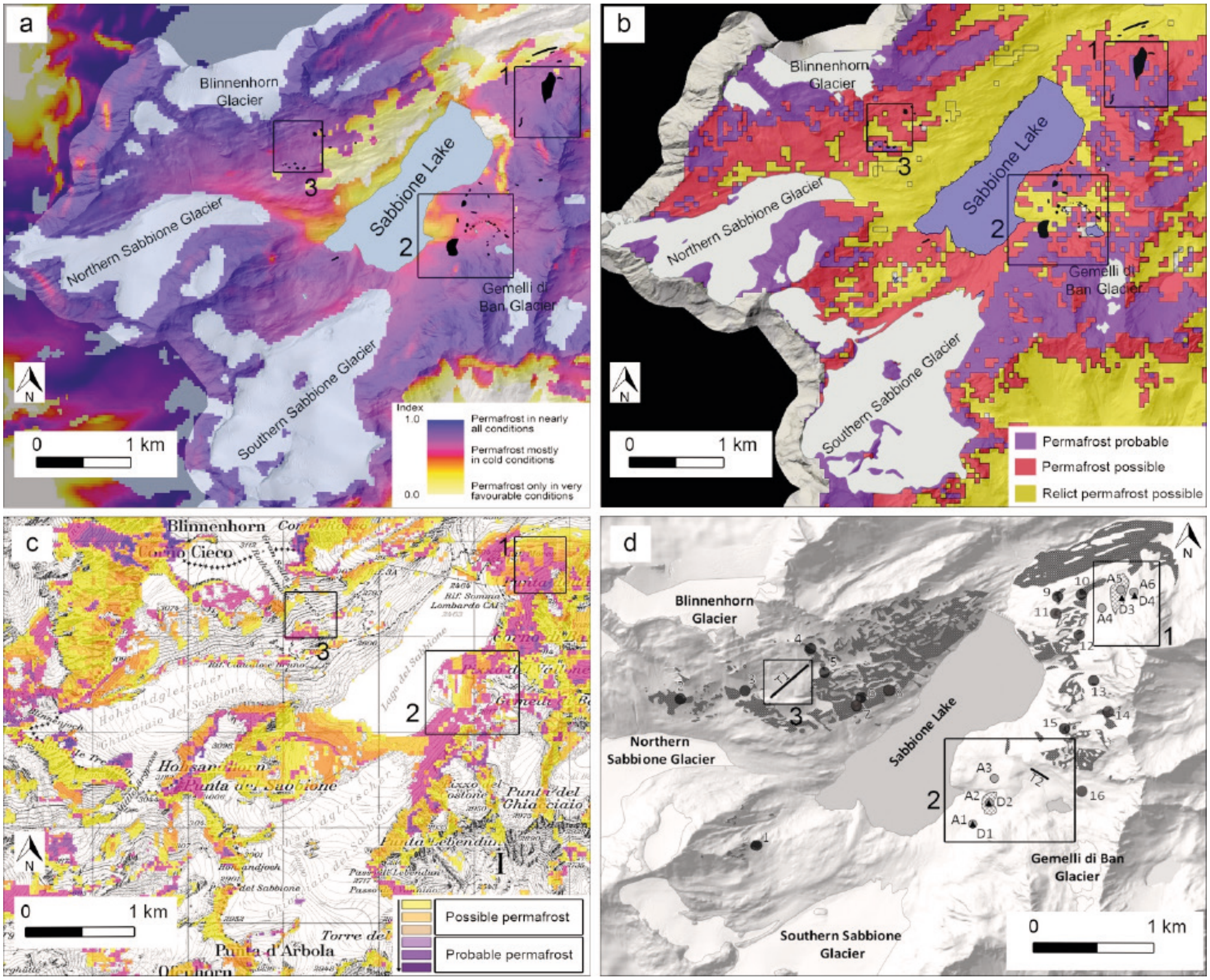

FIG. 2 - a) Alpine permafrost indexmap (APIM) of the basin. The map was processed within the alpine PermaNET project and is freely available at http://www.geo.uzh.ch/microsite/cryodata/. Further information about map interpretation key can be found in Boeckli & *alii* (2012). Legend: black polygons, periglacial landform; b) PERMAROCK mod. Map (Guglielmin, 2009). Legend: black polygons, periglacial landforms; c) Swiss Permafrost Map. Further information about map interpretation key can be found in BAFU (2005) and http://www.bafu.admin.ch/; d) Vegetation study sites in the Sabbione basin. Shaded area: grassland. Reticulated area: rock glaciers. Circles: vegetation samples (1÷16 floristic surveys, A1÷A6 *A. genipi* sample collecting sites). Black segments: vegetal transects. Triangles, code D1÷D5: ground surface temperature dataloggers. Details in the text.

Geomorphology

In order to describe the morphological characteristics of the basin and understand the evolution of the recently deglaciated areas, detailed geomorphological mapping and analyses were performed. Landforms and deposits were mapped through collection and analysis of technical and scientific literature, aerial and satellite photographic interpretation (images from 1954 to 2010) and field surveys (in 2012 and 2013). During the field investigations several control points were acquired with a GPS device in correspondence with relevant geomorphological features such as the periglacial micro-landforms. After this, all data were digitised using QuantumGIS allowing geo-referencing and morphometric elaboration. Particular attention was given to the classification of deposits/landforms and associated processes focusing on glacial, periglacial and permafrost landforms (e.g., active rock glaciers).

Main outputs of this working phase were: i) a general geomorphological map (1:10,000 scale), ii) detailed maps (1:3,000 scale) to highlight periglacial "meso-landforms" (rock glaciers and protalus ramparts) and "micro-landforms" (e.g., frost boils, stone-banked lobes, etc.), iii) a synthesis map (1:25,000 scale) of till distribution distinguished by glacial sub-basins (fig. 3) (for further details: Colombo & *alii*, 2015).

By the combination of glacial evolution reconstruction and geomorphological analysis results, two pilot sites were selected in the Sabbione basin because of their significance

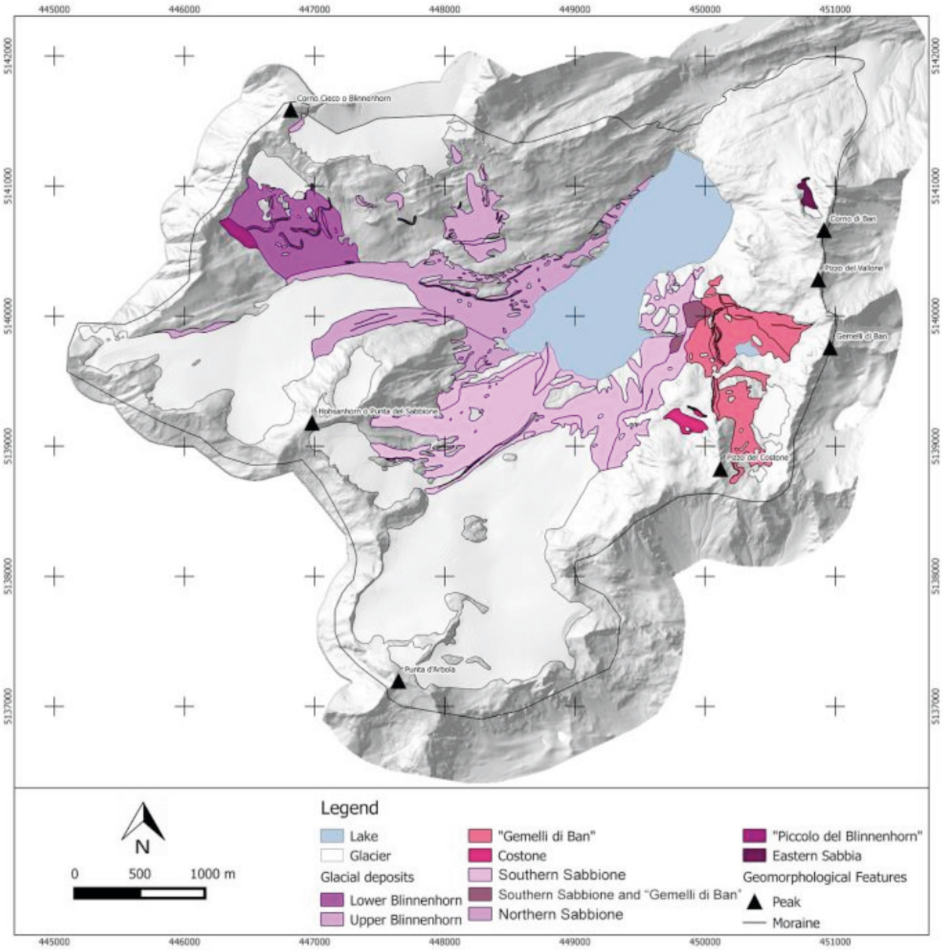

FIG. 3 - Synthesis map (1:25,000 scale) of till distribution distinguished by glacial sub-basins. The limits of till distribution areas represent the maximum extension of glaciers during the LIA.

in glacial-periglacial transition investigations and the large amount of periglacial landforms mapped. In these two sites further geomorphological analyses and vegetational studies were carried out in order to perform an inter-comparison analysis. In particular, the Corno di Ban site (fig. 2, box n°1) was selected due to the presence of an active talus rock glacier (TRG in fig. 1) in a sector deglaciated since the end of the Last Glacial Maximum (LGM) and not affected by LIA glaciation. The Gemelli di Ban site (fig. 2, box n°2) was chosen because an active debris rock glacier was individuated (DRG in fig. 1) in an area deglaciated before the first decades of 20th century. An additional area was initially considered as third selected site, the Upper Blinnenhorn basin (fig. 2, box n°3), but detailed field surveys showed that the existing till had extensively been remodelled by fluvioglacial processes after glacier recession, entailing a probable disturbance on periglacial processes (*sensu stricto*) development.

Vegetation

During the 2012 and 2013 summer seasons a several vegetation survey were performed (fig. 2d) in order to integrate the floristic knowledge of this area (Antonietti, 2002; Antonietti, 2005; Crosa Lenz & Pirocchi, 2011) and to identify the main aspects of the plant communities in the lower part of the Sabbione catchment. 16 phytosociological surveys were carried out applying the Braun-Blanquet modified method (Pignatti, 1995) on a surface of 10x10 m for each plot.

The plot locations were chosen to investigate the characteristics of the main environmental settings where the vegetation could be found in the basin (grasslands, snowbeds and debris deposits). In order to achieve a more accurate representation of the scarce vegetation growing on LIA deposits, 2 transects within debris deposits with a low pioneer plant cover were investigated. On the 2 rock glaciers (TRG and DRG in fig. 1, boxes n°1 and n°2 in fig. 2) a complete floristic list with notes on the specific abundance was performed. Taxa nomenclature follows Pignatti (1982).

Generative and vegetative phenology of *Artemisia genipi* was recorded to investigate the influence of permafrost conditions on vegetation. This late-season flowering species was chosen because it is ubiquitous throughout the basin on till and undifferentiated debris deposits, and because of its widespread presence on the rock glaciers and their surrounding areas.

Five phenological stages were identified (fig. 4): 1) flowering stem shorter than basal leaves, 2) yet flowering spike, 3) pendent flowering spike, 4) erect flowering spike, and 5) faded spike. The number of basal rosettes without flowering stem was also noted.

For each individual collected with flowering stem in 2013 the corresponding phenological stage was noted. In total, 720 *A. genipi* individuals were picked up in six selected sites (2 sites on active rock glaciers, A2-A5 in fig. 2d, and 4 in adjacent areas, A1-A3-A4-A6 in fig. 2d). Because of the strong micromorphological variation at the rock glacier sites and its effect on phenology, for each site 40 individuals were identified and described in flat zones, in depression sectors and in ridge areas, respectively.

Furthermore, 5 mini-dataloggers were installed during the summer season 2013 to monitor ground surface temperature (dataloggers Tinytag Plus-2 with 2 temperature probes each) (fig. 2d). The dataloggers were located beneath the ground surface, protecting them from the direct solar radiation. The sensors were installed at depths of 2 and 10 cm and were programmed to record every hour. The basal-ripening date (RD), describing the time when a frozen ground surface is warmed to 0 °C by melt-water percolation (Schmid & *alii*, 2012) and the melt-out date (MD), describing the time when the snow cover is depleted and no further release of meltwater occurs allowing the ground surface to warm above 0 °C (Schmid & *alii*, 2012), were chosen to detect snow cover timing characteristics in the investigated sites.

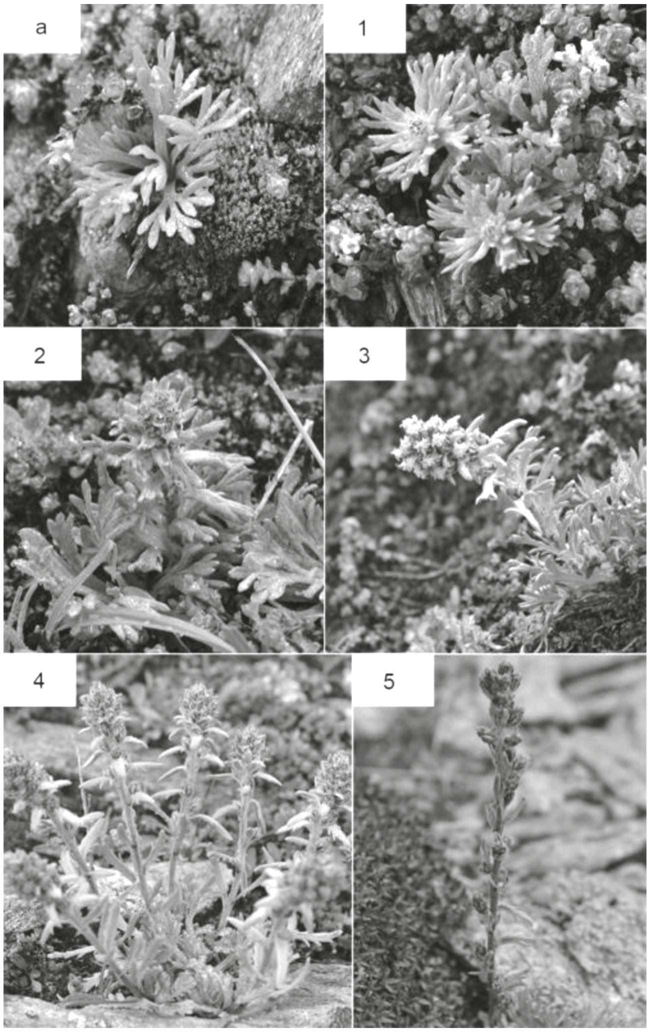

FIG. 4 - Phenological stages of *Artemisia genipi*: a) basal rosette without spike; 1) flowering stem shorter than basal leaves; 2) yet flowering spike; 3) pendent flowering spike; 4) erect flowering spike; 5) faded spike.

RESULTS

Climate, glaciers and permafrost

The analysis of climate data recorded by Formazza and Sabbione stations are synthesised in table 1. The climatic trends of Sabbione station (period 1951÷2011) indicate a significant increase for maximum and minimum air temperatures, +0.03±0.01 °C year^{-1} and +0.04±0.01 °C year^{-1}, respectively, and a decreasing snow depth (Hs) of -0.82±0.27 cm year^{-1}. Frost days (FD0) decreased significantly by -0.68±0.13 days year^{-1} and ice days (ID0) by -0.49±0.17 days year^{-1} (Colombo & *alii*, 2013). Growing season length (GSL) showed a significant positive trend (1.08±0.33 days year^{-1}). Cold spell duration indicator (CSDI) had a significant negative trend (-0,24±0,06 days year^{-1}). Warm spell duration indicator (WSDI) showed a non-significant increase (0.06±0.06 days year^{-1}), whereas the trend was significant in the period 1985-2011 (0.58±0.18 days year^{-1}) (fig. 5).

The trends measured at the highest altitude historical stations in the Ossola Valley confirm those identified in the present paper (Vannino station, 2177 m a.s.l.: maximum temperature +0.03±0.01 °C year^{-1}, minimum temperature +0.06±0.01 °C year^{-1}, snow depth -1.0±0.4 cm year^{-1}; Toggia station, 2165 m a.s.l.: maximum temperature +0.04±0.01 °C year^{-1}, minimum temperature +0.02±0.01 °C year^{-1}, snow depth -1.01±0.4 cm year^{-1}) (Acquaotta & *alii*, 2013).

According to the three models already available for the study area used to estimate the permafrost distribution (APMOD, PERMAROCK modified and Swiss Permafrost Map) (fig. 2a-b-c), the highest probability of permafrost presence is above 2600 m a.s.l. for N-NW slopes and 2900 m a.s.l. for S-SE slopes. Permafrost is possible between 2400 and 2600 m a.s.l. for N-NW slopes and between 2700 and 2900 m a.s.l. for S-SE slopes. Permafrost is absent or relict below 2400 m a.s.l. on N-NW and below 2700 m a.s.l. on S-SE slopes. Moreover, modelling results were also compared to morphological evidences. Active rock glaciers, considered as indicators of permafrost presence (Barsch, 1996; Haeberli & *alii*, 2006), are located in sectors with probable permafrost. BTS (Bottom Temperature of the Snow cover, Haeberli, 1973; Hoelzle, 1992) measurements were also recorded on the Corno di Ban talus rock glacier by Arpa Piemonte (Paro, 2012), and they confirmed a high probability of permafrost presence in the talus rock glacier.

The analysis of the glacial evolution shows that the ice coverage of the basin has suffered an important reduction

TABLE 1 - Synthesis of main climate data (weather stations located in the study area)

Station	"Formazza" automatic station	"Sabbione" manned station
Altitude [m a.s.l.]	2453	2470
Time-frame [years]	1988÷2012	1950÷2012
Mean annual air temperature [°C]	-0.2	-0.9
Mean annual cumulate precipitation [mm]	995.1	1,034.8
Mean annual cumulate fresh snow [cm]	696.2	741.3
Mean annual snow depth [cm]	97.1	128.3
Snow days	60	64
Days without snow cover [number]	unavailable data	102

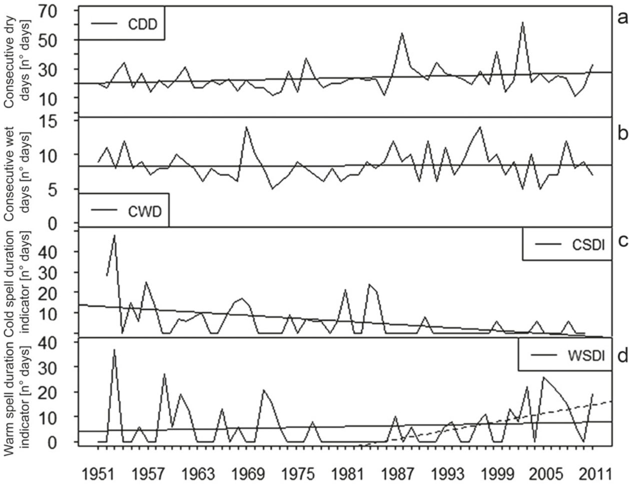

FIG. 5 - a) Growing season length, b) Cold spell duration indicator and c) Warm spell duration indicator in the period 1951-2011.

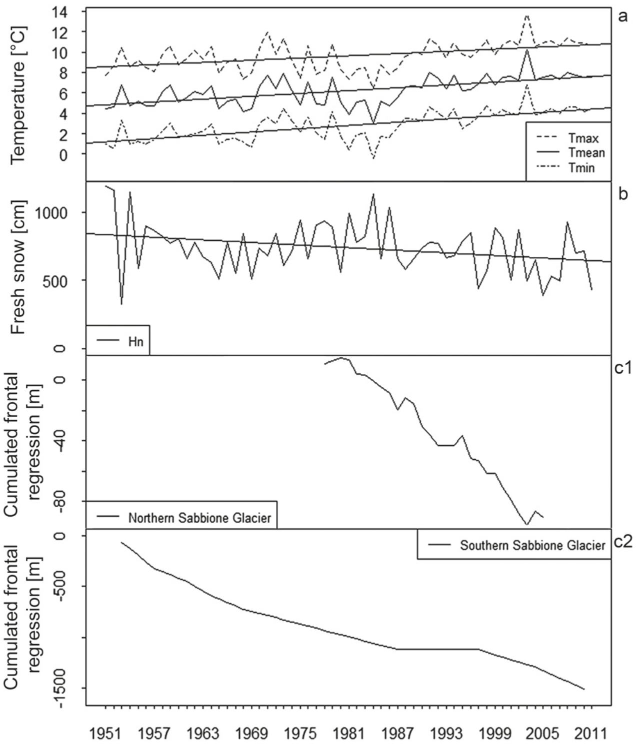

FIG. 6 - a) Summer Air Temperature and b) fresh snow trends from Sabbione station data series (period 1951÷2011); c) cumulated frontal regressions of Northern (1) and Southern (2) Sabbione glaciers in the period 1951÷2011.

since the second half of the 19th century. Southern Sabbione Glacier retreated by 2.2 km and Northern Sabbione Glacier recessed by 2 km in the period 1885÷2011 (Mazza & Mercalli, 1992; Casale, 2011; Italian Glaciological Committee Bulletin, 1992÷2012). The Northern Sabbione Glacier also suffered of significant volumetric shrinkage (time-frame 1885÷1991), estimated more than 50% (150 million m^3), and areal reduction, 40% (1.2 km^2) (Mazza, 1993). The creation of the large Sabbione artificial lake in 1953 additionally accelerated the reduction of these glaciers. Indeed, a stepped-up retreat rate was recorded for the Southern Sabbione Glacier (11.1 m $year^{-1}$ in the time-lapse 1923÷1940 → 64 m $year^{-1}$ in the time-lapse 1952÷1957) due to the calving effect (Bindschadler, 1980; Brown & *alii*, 1982; Funk & Röthlisberger, 1989), in the period between 1953 and 1991, when the glaciers tongues emerged from the pond (Mazza, 2007). Since the end of the LIA many other temperate glaciers have also suffered extremely high regression rates such as Gemelli di Ban Glacier, Blinnenhorn glaciers, Eastern Sabbia Glacier, and three glacial masses extinguished (Costone Glacier, Piccolo del Blinnenhorn Glacier and Central Sabbione Glacier).

The recession of glaciers is caused by changing in climatic forcing (Haeberli & *alii*, 1999; Hoelzle & *alii*, 2003; Hock, 2005). Glacier mass balance and length variations are mainly attributable to SAT (Summer Air Temperature, June-July-August-September) and Hn (fresh snow) modifications (Letréguilly, 1988; Dyurgerov, 2003; Nesje & *alii*, 2008). SAT and Hn were calculated using the Sabbione weather station data and compared to Northern and Southern Sabbione cumulated frontal regression time series (annual variations were not used because of the presence of several gaps in the data series, thus the comparison has to be interpreted on a quality level) (fig. 6c1 and fig. 6c2). Minimum SAT increased significantly by +0.06 °C $year^{-1}$,

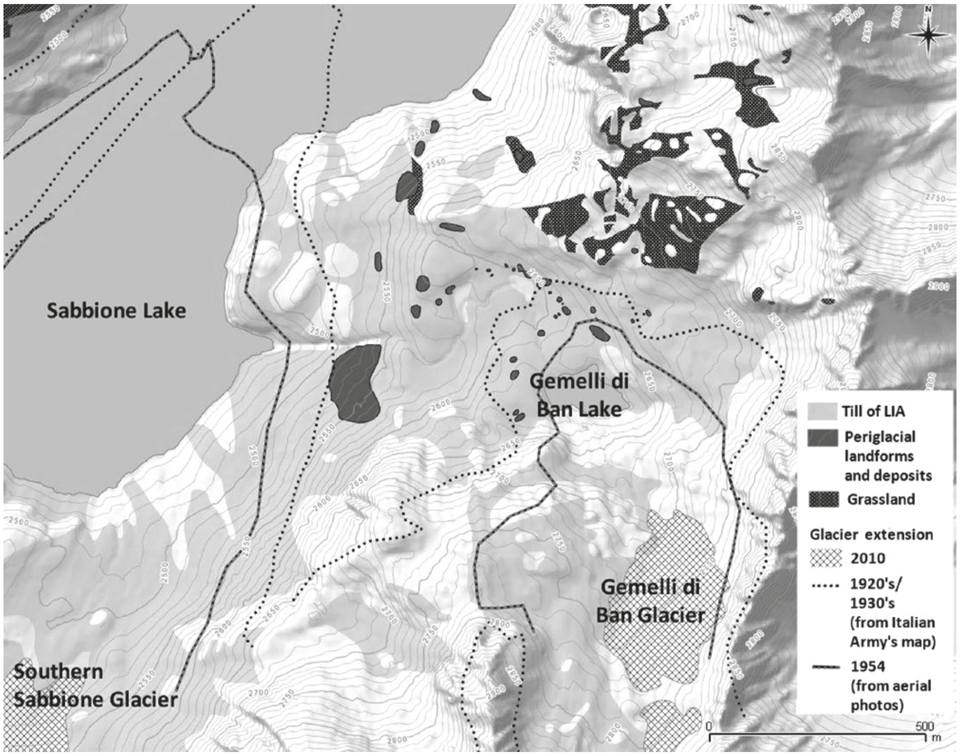

FIG. 7 - Sketch of geomorphological map (Gemelli di Ban area) with 1920's/1930's, 1954 and 2010 glacial limits.

maximum +0.04 °C $year^{-1}$ and average +0.05 °C $year^{-1}$ (fig. 6a) while Hn decreased significantly by -3.17 cm $year^{-1}$ (fig. 6b). Cumulative variations in both glacier fronts appear directly dependent on Hn decrease and negatively correlated with SAT, particularly since the early 1990's, when the glacier terminus emerged from the artificial lake.

Geomorphology

A large amount of glacial deposits outcropped after the glaciers regression. Over 3 km^2 (about 20% of the study area) were deglaciated from the LIA glacial maximum to the year 2010. Detailed surveys allowed to observe the presence of periglacial landforms and their relationships with glacial deposits. 61 periglacial elements were observed and mapped; 58% of these were gelifluction lobes, 39% were patterned ground and deposits remodelled by cryoaction (especially frost heaving and frost sorting) and 3% were active rock glaciers and protalus ramparts.

All the periglacial landforms are mainly concentrated in three areas (Corno di Ban, Gemelli di Ban and Upper Blinnenhorn, boxes n°1-2-3 in fig. 2) and about 70% are located in LIA glacial deposits, and most of these in areas deglaciated between the LIA glacial maximum and the 1920's/1930's (e.g., Gemelli di Ban area, fig. 7). In particular, typical frost sorting- and frost heaving-related landforms, such as sorted/non-sorted circles and frost boils (fig. 8b), were observed within lodgement/basal till composed by boulders varying from decimetric to metric size with high contents of fine-grained material. Sorted and non-sorted circles occurred commonly as single forms and rarely as group, and their diameters were less than 2 m; frost boil diameters were less than 1.5 m and the height varied from 20 to 30 cm. Moreover, non-sorted stripes (fig. 8c) were mainly identified in till characterised by low contents of fine-grained sediments. Finally, turf-banked lobes and stone-banked lobes (fig. 8d) were individuated in glacial, weathering, and talus deposits.

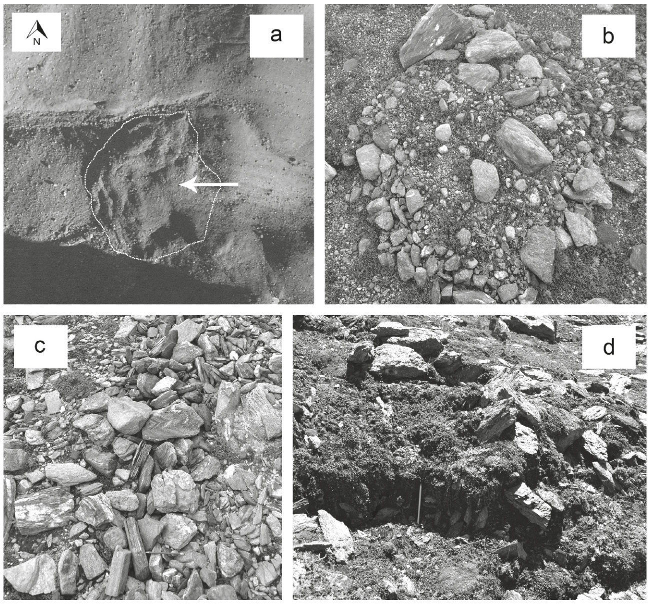

FIG. 8 - a) Active debris rock glacier (the white arrow indicates the flow direction); b) frost boil; c) non-sorted stripe; d) frontal zone of a stone-banked lobe with a little amount of vegetated fine-grained sediment.

The largest periglacial elements are two rock glaciers, one developed in talus/landslide deposits in the Corno di Ban area (pilot site n°1) and the second one in LIA glacial deposits in the Gemelli di Ban area (pilot site n°2). Particular attention was given to the description of these landforms because of their role in the vegetational analyses within the selected pilot sites.

In the study area, an active rock glacier was recognised in the Corno di Ban zone (TRG in fig. 1, box n°1 in fig. 2), within a sector deglaciated since the end of the Last Glacial Maximum (LGM), outside LIA glacial deposits. It develops from a talus slope located at the toe of the NW steep rock face of the Corno di Ban (already identified as talus rock glacier or ice cemented rock glacier in the Arpa Piemonte regional inventory, Paro, 2012), on which mechanical weathering provides significant quantities of debris. Cyclic snow avalanches and snow patches with long permanence (8÷10 months per year) within the depression zones allow for snowmelt water to infiltrate through the debris and freeze to form an ice-debris matrix in the talus deposit. The rock glacier is characterised by a tongue-shaped body, very steep frontal and lateral scarps, and few flow features such as small longitudinal and transverse ridges. The longitudinal profile is mainly convex with a smooth-shaped depression in the middle sector of the rock glacier. The minimum altitude of the front is 2475 m a.s.l, maxima width and length are 120 and 300 m respectively, for a total area of about 28,000 m^2; the slope is between 14 (middle sector of the body) and 37° (terminus). The surface of the rock glacier is covered by clasts varying from centimetric to pluri-decimetric size (many boulders of tens of m^3 could also be identified), with outcropping of finer sediments primarily at the terminus, but also in the lateral zones.

The active debris rock glacier in the Gemelli di Ban sector (DRG in fig. 1 and fig. 8a, box n° 2 in fig. 2) was identified in an area deglaciated before the first decades of 20th century (as shown in the topographic map of the Italian Army) and it is developed on a LIA moraine complex (moraine rock glacier, Lindner & Marks, 1985) of the Southern Sabbione-Gemelli di Ban glaciers. The rock glacier is characterised by a lobate body and a fluidal surface texture, showing a succession of well-developed arcuate ridges and furrows, placed side by side and perpendicular to the main axis of the deposit, just below a small spoon-shaped depression in the upper part. The elevation of the front is 2505 m a.s.l., maxima width and length are 170 and 95 m respectively, covering a total area of about 16,000 m^2; the slope is between 13° (depression located in the rooting zone) and 34° (terminus). A well reverse-graded grain size distribution was noted in vertical section, with coarse debris cover (from centimetric to pluri-decimetric dimensions) and low content of fine-grained sediments. The latter are mainly concentrated at the lateral scarps of the landform.

Vegetation

The description of vegetation plots and the main observed species are summarized in the table 2 and table 3. The results of our study showed a prevalence of communities influenced by the presence of calcium in the bedrock and in glacial deposits, with calciphilous grasslands dominated by *Carex curvula* ssp. *rosae*, mainly on the southern slope, and other grasslands dominated by *Sesleria varia* and *Elyna myosuroides*, sometimes with *Dryas octopetala*, on different aspects. In few cases there were acidic soils on terraces, with grasslands dominated by *Carex curvula* ssp. *curvula*, as in small parts of the terraces under the Corno di Ban peak (northern slopes) or on small terraces in the lower part of the grasslands on the southern slopes. The same influence of the substratum acts on scree vegetation, characterised by *Saxifraga biflora*, *Saxifraga oppositifolia*, *Arabis alpina*, *Arabis caerulea* and *Artemisia genipi.* Acidophilous species as *Geum reptans, Androsace alpine* and *Oxyria digyna* were limited to amphibolites or prasinites bedrocks, and to silicate glacial deposits (e.g., proglacial areas of Southern Sabbione glacier).

TABLE 2 - Description of the vegetation surveys

Plot no.	Total cover (%)	No. species	Altitude (m)	Slope (°)	Asp.
1	70	27	2720	25	NE
2	60	26	2855	40	S
3	70	21	2810	30	SE
4	80	30	2860	20	E
5	20	15	2760	5	N
6	70	13	2612	10	SSE
7	80	16	2608	5	SE
8	80	29	2590	15	SE
9	90	15	2520	various	various
10	90	22	2525	0	/
11	90	19	2565	20	N
12	30	14	2605	5	WNW
13	80	21	2700	35	W
14	70	29	2775	40	W
15	70	20	2740	5	S
16	25	21	2665	30	SW
T 1	/	27	2750-2800	/	SE
T 2	/	38	2580-2600	/	/

Grasslands were located in zones not affected by LIA glacial processes or by other interfering phenomena such as constant contribution of debris originating from rock face detrition processes, whereas in recently deglaciated areas a debris pioneer vegetation was found with presence of calcicole or (rarely) silicate species depending on the predominant lithology of the substratum. Surprisingly, the presence of lower altitude species (*Acinos alpinus*, *Gentiana purpurea* and *Silene nutans*) (Pignatti, 1982) was also noted on the southern slopes of the catchment.

On the rock glaciers the most common species are: talus rock glacier (TRG in fig. 1) - *Saxifraga oppositifolia*, *Arabis alpina*, *Arabis caerulea* and *Saxifraga exarata*, with *A. genipi* mainly located on the lateral and frontal borders of this landform; debris rock glacier (DRG in fig. 1) - *Saxifraga*

TABLE 3 - Relative abundance of species in vegetation plots and transects. Note: +, <1%; 1, 1-20%; 2, 20-40%; 3, 40-60% (Braun-Blanquet mod. Pignatti, 1995)

	Relative abundance by plots																	
Species	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	T 1	T 2
Carex curvula ssp. rosae	2	3	3							3			1		3		+	+
Sesleria varia		+		+									3		+			
Elyna myosuroides	1	+		+					3		2		2	1	1			
Dryas octopetala											+							
Loiseleuria procumbes											2							
Carex curvula ssp. curvula				2				2				1		2				+
Geum montanum	+	+	1			1	1	1						1				
Salix herbacea	1		1				1			+		1		1				
Arabis alpina																		2
Arabis caerulea				2									+				1	2
Artemisia genipi				1						+			1				1	1
Saxifraga biflora				1													2	2
Saxifraga oppositifolia		1		1	+					+			1				3	1
Androsace alpina																		3

TABLE 4 - *Artemisia genipi* sample characteristics. Values referred to flat, ridge and depression sampling sites are the averages of 1 to 5 phenological stages (see also fig. 5) calculated for 40 individuals

Sampling site	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**
Altitude (m)	2520-2550	2520-2550	2520-2550	2550-2580	2520-2560	2520-2570
Aspect	NW	N-NW	W-SW	N-NW	N-NW	NW
Slope (°)	20	20-40	30	30	30-35	20-50
Flat	3.6	3.1	4.4	2.2	3.7	4.4
Ridge	4.0	4.4	5.0	3.6	3.9	4.6
Depression	2.9	2.3	3.4	2.3	2.2	1.9
Average	3.5	3.3	4.3	2.7	3.3	3.6
Variance	0.8	1.2	0.6	0.8	0.9	1.8

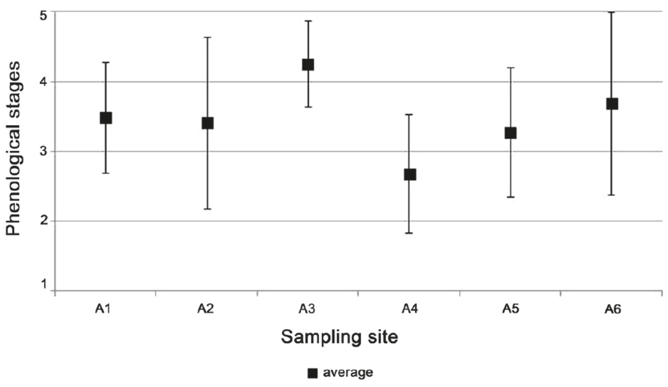

FIG. 9 - Phenological average stages (1÷5) for each sampling site (A1÷A6) with distribution error associated.

biflora, *Saxifraga oppositifolia*, *Poa laxa*, *Arabis alpina* and *Artemisia genipi*. Rock glaciers showed a lower vegetation cover (< 10%) in comparison to the other investigated sites, however, typical stress tolerant vascular plants (pioneer species) were widespread, due to their tolerance to stressful conditions associated with relatively coarse substrate granulometry and surface movements. Among the individuated species, *Saxifraga oppositifolia* and *Arabis alpina* can be defined as "movement indicators" (Burga & *alii*, 2004).

A phenological delay was found in *Artemisia genipi* individuals growing in rock glacier depressions (tab. 4); here, a high number of shoots without flowering stems was counted (10% - Corno di Ban TRG and 32.5% - Gemelli di Ban DRG). Generally all samples had a smaller maturation degree in comparison to sample number A3 (fig. 9), which showed a greater maturation degree because of its location in a SW aspect area where, according to permafrost distribution models, permafrost could be absent.

In the analysed period (2013÷2015) the snow cover duration did not show strong differences among the 5 ground surface temperature datalogger sites. In particular, timing and duration of the snow cover during winter season 2013÷2014 was similar in all 5 data logger sites, from October 2013 to mid-July 2014 (MD), and the continuous snowmelt period (RD) started on the 11th of April (DRG area) and on the 20th of May 2014 (TRG area). The snow timing during the winter season 2014÷2015 showed a similar evolution even though the MD was reached earlier (mid-June 2015) in comparison to 2014, due to the low amount of snow accumulated during the snow season. The mean annual ground surface temperature was lower on rock glaciers than neighbouring sites of 0.7 °C on average.

DISCUSSION

The Sabbione basin hosts one of the most important glaciated areas in the Piedmont Alps. Since the end of the LIA, the climatic conditions in the investigated area have caused a substantial decrease in glacial masses. Increasing temperatures (approximately +2 °C), decreasing snow depth (about -50 cm) and a pronounced glacier retreat (e.g., Northern and Southern Sabbione glaciers, frontal regression of ca. 1 km) have been recorded, in particular over the last six decades. The creation of an artificial lake and climatic changes are the main causes of the pronounced glacial decline, which has been caused by an augmentation of ablation, due to the increase in summer air temperatures (SAT average ca. +3 °C), and by a reduced alimentation caused by a decrease in solid precipitation (Hn about -190 cm).

According to the climatic analyses and definitions proposed by several authors (e.g., André, 2003; Boelhouwers, 2003; Guglielmin, 2004; French, 2007), the basin is part of the periglacial s.l. domain (Mean Annual Air Temperature - MAAT<+3 °C) and the climatic characteristics are typical of a permafrost context (MAAT<0 °C and total liquid/liquid-equivalent precipitation<2,000 mm year^{-1}). The geomorphological analysis has shown that the forefields, which are becoming ice-free due to glacier recession, have been exposed to climate conditions that favour permafrost occurrence (Kneisel 1998; Kneisel & *alii*, 2000) and the development of cryotic processes, in agreement with the permafrost maps derived from the permafrost models used in this work.

Patterned grounds, frost boils and gelifluction lobes were recognised above all in LIA glacial deposits, a few of them in sites deglaciated before the 1950's, and the majority was found in sites deglaciated before the 1920's. Therefore, it would seem that several decades (more than 50 years at least) are necessary for a sizeable development of cryotic processes in loose glacial deposits, because temperate and polythermal glaciers interfere significantly with the thermal conditions of the substrate. Several cryotic micro-landforms, derived from frost heaving and frost sorting processes, were localised in till within newly deglaciated areas, while there was very little evidence in other debris deposit typologies. This is probably related to the presence of sub-surface polygenetic ice (Dobiński & *alii*, 2011) in the glacier forefields that have been exposed since the end of the LIA (Kneisel, 2003), which favours the development of frost heave-related landforms. The ground ice here is likely derived from recent ground freezing in the cold microclimates of formerly temperate bed parts after glacier retreat (intrasedimental ice: segregated ice, intrusive ice), burial of dead ice from the glacier (buried glacier ice: firn-derived glacier ice, basal glacier ice) or a combination of these processes (Kääb & Kneisel, 2006).

The largest periglacial landform observed in the study area is the active talus rock glacier in the Corno di Ban area, outside the LIA glaciated area, which is characterised by a long-term morphological evolution that has remained undisturbed by the most recent glacial processes; the geomorphological analyses, BTS measurements and permafrost maps from models have confirmed the high probability of the presence of permafrost in this landform. Conversely, the landform that has been interpreted as an active debris rock glacier derived from a LIA moraine, thus showing a short-term morphological evolution. Although the climate evolution over the last decades has caused an impressive regression of the investigated glaciers, the results of the climatic analyses and permafrost model simulations show that the ice-marginal zones at pilot site 2 (fig. 2, box n°2) have been cold enough to prevent the gradual decay of the frozen deposit. The coarse debris cover on the top of this landform has also favoured ground cooling, due to enhanced heat transfer between the atmosphere and the rock glacier (Harris & Pedersen, 1998; Delaloye & *alii*, 2003; Vonder Mühll & *alii*, 2003; Gorbunov & *alii*, 2004; Hanson & Hoelzle, 2004). Moreover, the existence of fluting ground moraines, i.e. water-saturated ground deposits developed under basal ice in temperate conditions (Benn, 1994; Haeberli, 2000; Menzies, 2002; Benn & Evans, 2010), in the Gemelli di Ban Glacier area just above the rock glacier indicates the absence of a buried glacier ice core. The genetic connotation of this landform could be related to the former presence of a polythermal glacier, with a cold margin potentially frozen to the ground in permafrost conditions and warm-based ice behind the frozen margin on the water-saturated deformable sediment bed. The surface flow features, which are organised in a sequence of ridges and furrows, confirm the hypothesis of a frozen glacial deposit deformed by an ongoing permafrost creep; in particular, the gradual emphasizing of its morphological evidence (ridges and furrows) has been observed in aerial images since the 1950's, probably due to the rising air temperatures, which are known to be extremely important for rock glacier dynamics, as they entail speed acceleration and movement modifications (Kääb & *alii*, 2007; Delaloye & *alii*, 2008). The permafrost distribution simulations from the three models also indicated the high probability of the presence of permafrost in the rock glacier (e.g., fig. 2a-b-c, box n° 2).

The recent evolution of the glaciers has also influenced the vegetation spread. The recently deglaciated areas are colonised by pioneer vegetation, whereas the ice-free LIA areas are covered with stable grasslands, as demonstrated by other studies on vegetation in glacier forelands (Caccianiga & *alii*, 1994; Caccianiga & Andreis, 2004; Cannone & *alii*, 2008). The vegetation of active rock glaciers is characterised by low coverage (< 10%) and is influenced by presence of localised fine-grained material sites, water supply and favourable microclimatic conditions in consolidated sites (Burga & *alii*, 2004). In particular, the majority of plants are located in depressions or in lateral/frontal zones of rock glaciers, where a higher content of fine material is available.

Some lower altitude species (Pignatti, 1982) were noted in the catchment as a result of temperature warming as highlighted by the decrease of cold spells and increase of warm spells, especially during the last three decades. This recent climate warming has caused the extending of growing season length, allowing the single individuals to have a greater probability of development and colonisation of new free surfaces.

Owing to the local weather conditions in the summer 2013, which resulted in a delayed snow melt, the *Artemisia genipi* phenological study did not produce any significant results that could confirm the direct influence of permafrost on its phenology. However, topographic factors appear to be predominant for the maturation of individuals, especially the aspect and the presence of depressions and ridges. The number of individuals without flowering spikes in depressed positions is clearly higher on the two rock glaciers (10.8% and 3.3%, compared to a mean presence of less than 0.5% in the other sites in depressed positions) and this is probably related to the degree of physical and micro-climatic stress. The presence of individuals that had not reached maturation at the end of the season is an indicator of an environment with hard conditions that did not permit a sufficient accumulation of energy to allow the species to bloom.

The rock glacier samples have shown a more marked heterogeneity, due to the cryotic landform morphology, because the abundance of pluri-centimetric clasts only allows a high content of fine-grained sediments in depressed portions or on the lateral sides. In particular, the Corno di Ban rock glacier sample has shown a bimodal distribution, with several localised individuals in more premature and advanced stages, the former at the rock glacier base, the latter on the upper and middle part of the lateral escarpments. The absence of *A. genipi* over the body of this landform could indicate an excessive degree of physical and micro-climatic stress in the depressions with fine-grained sediments. The monitored species in this area is represented by only few individuals that grow on the top of rock blocks >2 m^2. The phenological delay in the depressions might be attributed to the longer permanence of snow in spring and to cold water sources at the rock glacier base or from snow patch melting; in fact, the timing of snowmelt can be included to the key factors for plant occurrence, abundance and phenology in these habitats because snowbed species usually grow and reproduce during a very short growing season (Hülber & *alii*, 2011; Carbognani & *alii*, 2012). However, since the snow has similar duration in all analysed pilot sites, the inter-comparison analysis indicated that others factors, such as micromorphology, influence the vegetation distribution on rock glaciers and reference sites. The highest percentage of non-flowering individuals in the DRG depressions can prelude the future rarefaction or disappearance of the monitored species in the central part of this landform (as already occurred on TRG) and the segregation of individuals on the peripheral escarpments that are richer in fine-grained sediments.

CONCLUSION

The analysis of Sabbione Basin glaciers performed in this study has revealed a strong reduction of glacier coverage during the last decades. Widespread glacier shrinkage is markedly changing the mountain landscapes and ecosystems of the Italian Alps (Baroni & *alii*, 2013). The strong glacial recession in the basin during the last decades has been mainly caused by the local summer warming combined with reduced solid precipitation. Moreover, the Northern and Southern Sabbione glacier regression has been enhanced by the strong anthropogenic impacts through the creation of the artificial Sabbione Lake.

Generally, the impact of climate evolution on glaciers and periglacial environments can clearly be seen from the remains of the recent LIA glaciation and the large number of periglacial meso/micro-landforms individuated within recently deglaciated sites in the Sabbione Basin. Here we showed that a close relationship between glacial deposits and landforms, and periglacial geomorphological features exists, where a transition from glacial to periglacial processes took place after the regression of glaciers. Thus, the Sabbione Basin is evidently undergoing the transition from a glacial to a paraglacial/periglacial system (Ballantyne & Benn, 1996; Curry & Ballantyne, 1999).

In accordance with climate change scenarios in the alpine region and the climatic trends individuated in this study, a further glacial retreat must be expected in the next decades. The present investigation suggests that extended areas of unconsolidated glacial deposits, which emerge after the disappearance of surface ice, will probably be affected by cryotic processes, considering the cooling effect on the ground thermal regime in newly exposed proglacial zones due to the retreat of alpine temperate and polythermal glaciers. In these glacial deposits, periglacial- and permafrost-related landforms, such as debris rock glaciers, sorted/non-sorted circles, frost boils and non-sorted stripes, will develop, as highlighted in this paper. Simultaneously, the lower permafrost limit may rise as a consequence of the climatic trends that have been identified. For instance, due to the effects of climate change since the LIA maximum (about 1850), the lower permafrost limit in the Alps was estimated to have risen vertically by about 1 m year^{-1} (Frauenfelder, 2005).

A gradual stabilisation of the lower altitude areas, where the frost action will be less intense because of the increase in air temperatures, might also be expected. Typical vegetal species of more mature stages might replace the pioneer species in these areas, while a progressive upward shift of lower altitudinal species might be possible in already stabilised areas (Walther & *alii*, 2005; Pauli &

alii, 2007; Wipf & *alii*, 2013), as highlighted in the present work. Furthermore, plant species phenology and colonisation will be affected, especially on the rock glaciers, not only by physical and micro-climatic stress (e.g., low ground surface temperature, Hülber & *alii*, 2010), but also by the surficial micro-morphological features of the rock glaciers (driven by their dynamics and local morphology and micro-morphology). These characteristics seem to be extremely important for the distribution of vegetation on these permafrost-related landforms, especially the grain size, which is correlated with soil organic matter content (Gobbi & *alii*, 2014).

Finally, the results of this work provide a better description and understanding of the widespread effects of climate change on Alpine landscapes and on high altitude vegetation. However, a more extensive research and monitoring period is necessary to refine conclusions and to broaden the perspectives regarding the future evolution of the Sabbione Basin environment and ecosystems in the context of the glacial-periglacial transition.

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