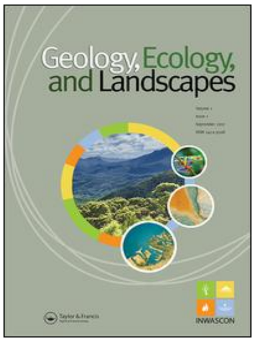

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RESEARCH ARTICLE

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Climate change effects on landscape and environment in glacierized Alpine areas: retreating glaciers and enlarging forelands in the Bernina group (Italy) in the period 1954–2007

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ABSTRACT

We analysed the recent involution of glaciers in the Bernina group (Italy), which are shrinking thus permitting a rapid enlargement of the forelands. We delimited glacier outlines upon aerial photographs (1954 and 1981 stereo pairs analysed through an optical system) and orthophotos (2003 and 2007 digital imagines directly managed via GIS software). All the obtained data were overlapped and compared. The estimated glacier area change during 1954–2007 was −36.5 ± 2.4% (−16.2 ± 0.4 km^2). The changes sped up more recently; in fact, during 1981–1954 (27 years) the variation was −0.206 km^2/y, against −0.387 km^2/y during 1981–2003 (22 years), and −0.535 km^2/y during 2007–2003 (4 years). In the 1954–2007 period, the forelands experienced a continuous increase (+14.7 km^2). Moreover, the analysis of the colour orthophotos allowed observations of: (i) changes affecting shape and geometry of glaciers (growing rock outcrops, tongue separations, increasing supraglacial debris and collapse structures) and (ii) main features of glacier forelands (bare rock exposures, debris and sediments and, in the latter case, occurrence of vegetation colonizing such pristine areas). Glacier forelands resulted also subjected to the action of melting water, debris transport, and periglacial processes, with consequences on landscape and geoheritage.

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KEYWORDS
Alpine glaciers; climate change impacts; glacier shrinkage; enlarging glacier forelands; remote sensing

1. Introduction

The retreat of glaciers, from Alpine areas (Haeberli & Beniston, 1998) to Antarctica (Cook, Fox, Vaughan, & Ferrigno, 2005; Frezzotti & Orombelli, 2014; Rott, Skvarca, & Nagler, 1996), during the last few decades, is widely reported as a clear and unambiguous sign of global warming (Oerlemans, 2005).

The recent rapid area and volume loss of mountain glaciers in response to climate warming has been reported at high and low latitudes all over the Planet (e.g., Falaschi, Bravo, Masiokas, Villalba, & Rivera, 2013; Gardent, Rabatel, Dedieu, & Deline, 2014; Kaser, Cogley, Dyurgerov, Meier, & Ohmura, 2006; Rabatel et al., 2013; Smiraglia et al., 2015; Wang, Siegert, Zhou, & Franke, 2013). The largest part of mountain glaciers and small ice caps have been generally retreating ever since the end of the Little Ice Age (LIA) but more recently glaciers began melting at rates that can hardly be explained only by natural climate variability (Dyurgerov & Meier, 2000; IPCC, 2013).

In particular, a tremendously rapid glacier retreat was found in the southernmost parts of Europe (Spain, Apennines of central Italy, and the Balkans) ever since the LIA (see Branda et al., 2010; D'Orefice, Pecci, Smiraglia, & Ventura, 2000; González Trueba, Martín Moreno, Martínez de Pisón, & Serrano, 2008; Hughes, 2009, 2010), dramatically decreasing therein glacier presence, reduced in some areas to a mere relic of the past coverage.

Glacier shrinkage is particularly severe upon the Alps and it is likely driven by the rapid increase in air temperature during the last few decades (IPCC, 2013). In facts, in the Alps atmospheric warming was found to more than double the global mean value over the last 50 years (Böhm et al., 2001), with a significant summer warming since 1970 (Casty, Wanner, Luterbacher, Esper, & Böhm, 2005; Leonelli et al., 2016).

Glacier geometry changes are key variables with respect to strategies for early detection of enhanced greenhouse effects on climate (Hoelzle, Haeberli, Dischl, & Peschke, 2003; Kuhn, 1980).

The terminus fluctuation data, collected in the Alps over the last two centuries, display a fairly constant retreating trend, with reduction of length from several hundreds of metres (in the case of smaller glaciers) to a few kilometres (in the case of larger ones, Citterio et al., 2007; Hoelzle et al., 2003). This dominating trend showed only one meaningful pause: between the Fifties and Nineties of the past century, a significant percentage of glaciers all over the World were found advancing (Patzelt, 1985; Wood, 1988) including 85% in Italy (Citterio et al.,

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2007). After this limited (in magnitude and rates) glacier advance, retreating became dominant again (Hoelzle et al., 2003).

The mass balance records, measured within the Alps over the last six decades, indicate strong ice losses accelerating more recently (i.e., 1985-hitherto, Zemp, 2008b; Zemp, Haeberli, Hoelzle, & Paul, 2006; Zemp, Paul, Hoelzle, & Haeberli, 2008a).

The shrinkage of mountain glaciers is followed by a progressive increase of supraglacial debris coverage (Azzoni et al., 2018; Cannone, Diolaiuti, Guglielmin, & Smiraglia, 2008; Diolaiuti, D'agata, Meazza, Zanutta, & Smiraglia, 2009; Diolaiuti & Smiraglia, 2010) which contribute to the transformation from debris free glaciers to partially or totally debris covered ones. Supraglacial debris mantle frequently supports plant germination (Caccianiga et al., 2011), thus making grass and shrubs common features at the glacier surface also at high elevations (Pelfini & Leonelli, 2014). Moreover also trees can grow at the glacier surface whenever the following conditions are found: (1) the glacier terminus altitude is found below the treeline, (2) the rock debris is thick enough and, (3) the glacier surface velocity is low; in these cases actual forests at the glacier surface can be observed (Caccianiga et al., 2011, 2012; Pelfini, Santilli, Leonelli, & Bozzoni, 2007).

Other changes linked to glacier shrinkage are collapse structures at the glacier surface and a modified crevasse evolution which strongly influence glacier hazard and risk conditions (Diolaiuti et al., 2006) thus requiring accurate and updated surveys (Azzoni et al., 2017; Fugazza et al., 2018).

Concerning glacier area changes, the geometry features most used to evaluate glacier shrinkage and its magnitude, Maisch (2000) reported a general Alpine decrease of 27% from the mid-nineteenth century to the mid-1970s, and losses even stronger in some subregions of the Alps.

Glacier area data are generally available through glacier inventories, suitable tools to investigate mountain glaciation in a changing climate (Paul, Kääb, Maisch, Kellenberger, & Haeberli, 2004). In fact, glacier inventories should be carried out at intervals compatible with the characteristic response time of mountain glaciers (a few decades or less in the case of small glaciers), and the currently observed glacier down-wasting calls for frequent updates of inventories (Paul, Frey, & Le Bris, 2011; Paul, Kääb, & Haeberli, 2007; Pfeffer et al., 2014).

"The New Italian Glacier Inventory" published in 2015 represents an actual updated data base describing the whole Italian glaciation (Smiraglia et al., 2015; Smiraglia & Diolaiuti, 2015). A first comparison between the total Italian glacier area reported in this new inventory and the glacier coverage value from the past Italian national inventory (CGI-CNR, 1959, 1961a, 1961b, 1962) suggests an overall reduction of the glacier extent of about 30% (i.e., from 526.88 km^2 in the Sixties to 369.90 km^2 in the present time). The strongest area reduction was found affecting small glaciers (i.e., glaciers with area < 1 km^2), these latter cover roughly 80% of the census in the Alps and make an important contribution to water resources (Citterio et al., 2007; D'Agata, Bocchiola, Maragno, Smiraglia, & Diolaiuti, 2014; Diolaiuti, Bocchiola, D'agata, & Smiraglia, 2012b; Diolaiuti, Bocchiola, Vagliasindi, D'agata, & Smiraglia, 2012a; Bonardi et al. 2012). These data are in agreement with findings from previous European authors. Paul et al. (2004) evaluated that 44% of the Swiss glacier area decrease during 1973–1998/1999 was charged to glaciers smaller than 1 km^2, encompassing 18% of the total area in 1973. From the new Swiss Glacier Inventory (SGI2010, see Fischer, Huss, Barboux, & Hoelzle, 2014), the total glacierized area resulted 944.3 ± 24.1 km^2 and the area change is −362.6 km^2 (i.e., −27.7%) between 1973 and 2010. Lambrecht and Kuhn (2007) reported that the Austrian glaciers experienced an area change of about −17% during 1969–1998. Gardent et al. (2014) realized the first multitemporal French Glacier Inventory. They found that glaciers in the French Alps covered 369 km^2 in 1967/71 and 275 km^2 in 2006/09 thus giving an extent decrease by 25% between 1967–71 and 2006–09.

This strong and stronger glacier area retreat resulted coupled with fast and faster enlargement of glacier forelands. In fact, the ongoing retreat of the glacier snouts is driving the exposure of areas previously covered by ice. In these pristine territories, exogenous phenomena can operate through mass wasting action, melting and running water processes and gravitative phenomena (Pelfini & Bollati, 2014). Moreover, the widening of glacier forelands often reveals wood remnants crucial to reconstruct the past glacial and climatic history (e.g., Pelfini et al., 2014; St-Hilayre & Smith, 2017). The responses of the environmental systems to the retreat of glacier tongues are complex and with contributions from different biotic and abiotic features. The newly exposed areas are fast changing sites (Staines et al., 2015) where paraglacial and periglacial processes have implications for environmental hazard and risk conditions (Mergili, Kopf, & Muellebner, 2012). These latter are mainly due to the unconsolidated sediment present at the glacier forelands (in some cases also containing heterogenic ground ice) and susceptible of rapid modifications in relation to climate warming thus influencing both geomorphic processes and sediment supply to the processes acting down valley (Bosson et al., 2015); furthermore melting water as well as ground water may affect depositional landforms in areas of glacier retreat (Levy, Robinson, Krause, Waller, & Weatherill, 2015) and proglacial lakes and water ponds develop and undergo to spatial and temporal variations (Geilhausen, Morche, Otto, & Schrott, 2012; Salerno et al., 2014) with also biological consequences (Sommaruga, 2015). The newly exposed areas show the beginning of soil development (D'Amico, Freppaz, Leonelli, Bonifacio, & Zanini, 2015; Egli, Wernli, Kneisel, & Haeberli, 2006) both on sparse till deposits and on well-shaped moraine ridges (Kabala & Zapart, 2012); the chrono-sequences at the glacier forelands also represent favourable substrates for biological colonization; these pristine areas show successions of: arthropods (e.g., carabides, Schlegel & Riesen, 2012) also delayed by different environmental factors (Brambilla & Gobbi, 2014; Gobbi et al., 2007), bacterial communities (Meola, Lazzaro, & Zeyer, 2014), yeasts (Turchetti et al., 2008), plants (e.g., Cannone et al., 2008; Moreau, Mercier, Laffly, & Roussel, 2006) and trees (Garavaglia, Pelfini, & Bollati, 2010, Garavaglia, Pelfini, & Motta, 2010).

In this contribution we summarized the ongoing (i.e., last 50 years) trend affecting an important Alpine glacierized group (namely, Bernina Group), characterized by strong and accelerating glacier decrease and the consequent widening of the glacier forelands.

The aims of this paper, after a brief review on the previous scientific researches carried out in the Bernina group, are: (1) to analyse in detail magnitude and rates of a) glacier areas decrease, and b) glacier forelands enlargement and, (2) to discuss implications for landscape and human environment (including geo-heritage and social/economic/touristic activities).

The Bernina glacierized group (Lombardy Alps) was chosen both due to the abundance of high quality aerial photos, useful to reconstruct the glacier history over the last half century (i.e., 1954–2007), and due to its representativeness, because the glaciers therein approximate in size, morphology and shape the "mean Italian glacier" (see Citterio et al., 2007; Smiraglia et al., 2015). Moreover, the Bernina massif has been previously studied by geologists, geographers, ecologists, botanists, etc. for the peculiarity of the region mainly with respect to its Swiss sector (see references cited in the following paragraph) thus suggesting to analyse and describe the Italian side as well.

2. The Bernina glaciers: main features and previous investigations

The Italian sector of the Bernina group covering about 60 km^2, is nested within the Municipality of Chiesa Valmalenco (upper Valtellina, Lombardy), near the Italian-Swiss border. It is the mountain group featuring the highest peak of Lombardy, Punta Perrucchetti 4020 m asl, the last Italian peak before Bernina, 4049 m asl on the Swiss side. The area is labelled as a "Site of Community Importance" (SCI), under the 92/43/EEC directive (ECC 92/43). Two SCIs are present here: they are named "Monte di Scerscen-Ghiacciaio di Scerscen-Monte Motta" (SCI code: IT2040016) and "Disgrazia-Sissone" (SCI code: IT2040017), respectively, and they are managed by the Sondrio Province Authority.

Presently, about forty (40) glaciers are located in the Italian sector of the Bernina Group, covering altogether an area of approx. 28 km^2, with different shapes, sizes and morphologies (Figure 1, Table 1 where the coordinates of each glacier are reported as well).

The size and features of Bernina glaciers are important, particularly when compared against other mountain groups with similar elevation range.

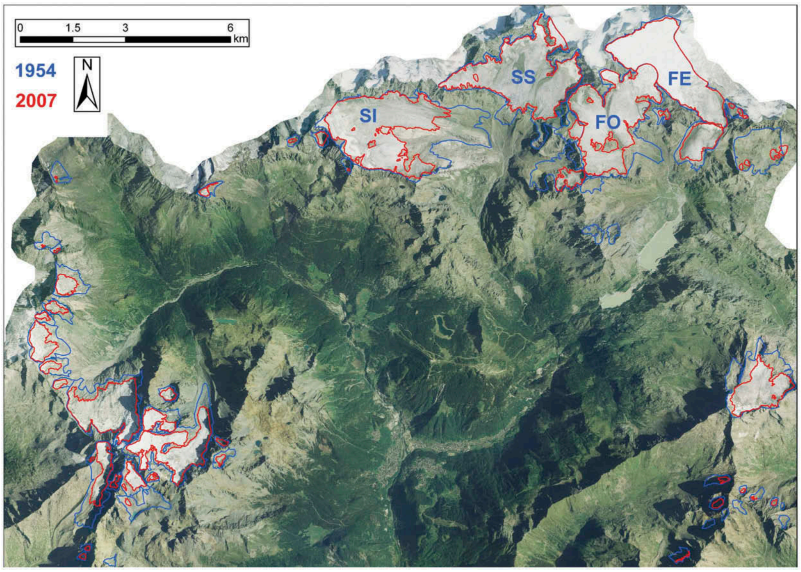

Figure 1. Location Map. The blue glacier boundaries described glacier limits in the 1954, instead the red outlines showed glaciers in the 2007. The base layer is the 2007 colour orthophotos (CGR BLOM). Scerscen Superiore, Scerscen Inferiore, Fellaria Est and Fellaria Ovest are the main glacier bodies of the Bernina group – Italian sector (4.92, 4.80, 4.85 and 4.35 km2, respectively, these glaciers are labelled as SS, SI, FE and FO, geolocation is reported in Tab.1).

Table 1. The 41 glaciers we analysed (since they are common to all the database). The coordinates here reported are referred to the WGS84 System and describe the mean geographic location of each glacier.

Long E	Lat N		Area 1954 (km^2)	Area 1981 (km^2)	Area 2003 (km^2)	Area 2007 (km^2)
564,208	5,132,243	Sassa d'Entova	0.08	0.05	0.01	0.004
563,439	5,133,163	Pizzo delle tre Mogge	0.16	0.13	0.11	0.08
565,177	5,133,396	Scerscen Inferiore	7.75	6.40	5.19	4.80
569,235	5,134,984	Scerscen Superiore	6.30	5.82	5.06	4.92
571,746	5,133,777	Fellaria Ovest	5.66	5.29	4.57	4.35
570,713	5,133,363	Marinelli	0.39	0.34	0.19	0.15
570,507	5,131,991	Caspoggio	1.09	0.72	0.38	0.33
573,234	5,133,837	Fellaria Centrale	0.13	0.15	0.06	0.05
573,364	5,135,156	Fellaria Est	5.51	5.48	4.99	4.85
575,574	5,132,441	Pizzo Varuna	1.42	0.97	0.22	0.07
562,596	5,133,081	Passo delle Tre Mogge	0.08	0.05	0.02	0.02
560,091	5,131,611	Sasso di Fora	0.16	0.13	0.08	0.05
555,874	5,131,923	Monte del Forno Nord Est	0.22	0.16	0.01	0.004
555,486	5,130,075	Monte Rosso Sud Est	0.19	0.12	0.02	0.004
555,879	5,129,943	Cima di Val Bona Nord	0.05	0.04	0.02	0.01
556,131	5,128,962	Vazzeda	0.62	0.46	0.32	0.27
555,838	5,128,308	Cima di Rosso Est	0.28	0.20	0.16	0.13
555,480	5,128,073	Cima di Rosso Sud Est	0.14	0.12	0.06	0.06
555,466	5,127,332	Sissone	0.94	0.83	0.60	0.60
555,681	5,126,635	Passo di Chiareggio	0.32	0.28	0.14	0.12
555,955	5,126,147	Punta Baroni	0.14	0.12	0.08	0.07
557,358	5,125,409	Disgrazia	2.90	3.14	2.44	2.25
559,065	5,125,839	Pizzo Ventina	0.17	0.16	0.12	0.11
558,729	5,125,085	Canalone della Vergine	0.61	0.49	0.40	0.35
559,287	5,124,334	Ventina	2.85	2.44	1.99	1.89
558,074	5,123,472	Cassandra Est	0.49	0.38	0.26	0.24
557,185	5,123,653	Preda Rossa	1.37	1.23	0.68	0.58
557,551	5,123,357	Corna Rossa	0.11	0.09	0.06	0.05
558,620	5,123,484	Cassandra Superiore	0.08	0.06	0.04	0.03
557,906	5,122,765	Cassandra Ovest	0.55	0.20	0.04	0.02
556,767	5,121,478	Corni Bruciati I	0.05	0.04	0.02	0.01
556,767	5,121,478	Corni Bruciati II	0.04	0.04	0.03	0.02
560,601	5,124,483	Pizzo Rachele	0.07	0.06	0.04	0.04
560,550	5,123,992	Sassersa	0.19	0.14	0.06	0.04
575,946	5,125,974	Pizzo Scalino	2.65	2.03	1.62	1.49
574,912	5,123,416	Cima Painale Nord Ovest	0.15	0.14	0.05	0.03
574,747	5,122,730	Pizzo Painale Sud Ovest	0.11	0.10	0.06	0.05
573,760	5,121,193	Corti	0.14	0.12	0.04	0.01
574,475	5,123,074	Pizzo Painale Nord Est	0.04	0.02	0.01	0.01
575,775	5,122,909	Passo di Val Molina	0.08	0.06	0.02	0.01
576,369	5,122,768	Cima di Forame Nord	0.04	0.04	0.03	0.02
		TOTAL	**44.37**	**38.82**	**30.32**	**28.18**

Scerscen Superiore, Scerscen Inferiore, Fellaria Est and Fellaria Ovest are the main glacier bodies of the Bernina group – Italian sector (4.92, 4.80, 4.85, and 4.35 km^2, respectively, see Figure 1 where these glaciers are labelled as SS, SI, FE, and FO, and Table 1 where the coordinates are reported as well).

Previous studies on the Bernina massif, mainly performed in the Swiss territory, range from geology (e.g., Mohn, Manatschal, Beltrando, Masini, & Kusznir, 2012; Mohn, Manatschal, & Muntener, 2011), to geomorphology (e.g., reconstructions of the Holocene changes and glacier history, Hormes, Muller, & Schluchter, 2001; Joerin, Stocker, & Schluchter, 2006; Pelfini, 1999; Pelfini & Smiraglia, 1994; Pelfini, Smiraglia, & Diolaiuti, 2002), from remote sensing (Bolch & Kamp, 2006), to field glaciology (e.g., measurements of terminus fluctuations and mass balance data, Comitato Glaciologico Italiano, Comitato Glaciologico Italiano, 1914–1977; 1978–2016), from glacier modelling (Frank & Linsbauer, 2012; Klok, Greuell, & Oerlemans, 2003; Klok & Oerlemans, 2002; Linsbauer, Paul, Machguth, & Haeberli, 2013; Zekollari And Uybrechts, 2015), to glacier meteorology (Oerlemans, 2001; Oerlemans & Klok, 2002; Oerlemans & Knap, 1998), and glacier hydrology (Pellicciotti, Carenzo, Bordoy, & Stoffel, 2014).

Investigations at glacier forelands were performed on the Swiss sector of the Bernina Group, with a particular focus on weathering processes and soil properties and development (Arnaud, Temme, & Lange, 2014; Egli, Mavris, Mirabella, & Giaccai, 2010; Mavris et al., 2010), clay mineral evolution along soil chronosequences (Mavris et al., 2010), soil features which support plant colonization (Burga et al., 2010). In some cases, data from pollen and macrofossil allowed reconstruction of glacier fluctuations and reforestation of the forelands at Bernina Pass during the Late glacial period and the Holocene (Burga, 1999; Zoller, Athanasiadis, & Heitz-Weniger, 1998). The most recent researches have locally detected an upward shift of alpine plants (Gian-Reto, Beißner, & Burga, 2005), the consequent increasing floristic similarity of mountain summits (Jurasinski & Kreyling, 2007) and a shift of macroinvertebrate assemblage along the longitudinal alpine stream gradients at the base of Roseg and Tschierva glaciers (Sertić Perić, Robinson, Schubert, & Primc, 2015). Last but not least Fischer, Amann, Moore, and Huggel (2010), Frey, Haeberli, Linsbauer, Huggel, and Paul (2010), Garavaglia, Pelfini, Bini, Arzuffi, and Bozzoni (2009), analysed the implications for hazard and risk conditions of changes in the landscape and in particular they focus on: slope instability phenomena, glacier lake formation, and debris flow fans, respectively. Finally, the Bernina landscape has been considered also for peculiarities of its railway (the highest one of Europe) (Bebi, 2011; Boksberger, Anderegg, & Schuckert, 2011) and for the role it plays in promoting tourism in these areas. At the knowledge of the authors of this paper in the Italian sector of the Bernina Group no previous studies over long time frame (50 years or more) focusing on magnitude and rates of glacier changes and/or on expansion glacier forelands were performed.

3. Data collection and methods

In order to evaluate glacier area changes for the whole Italian sector of the Bernina group over the last 50 years, we analysed aerial photos and orthophotos dating back since 1954 until 2007. We compiled the 1954, 1981, 2003, and 2007 records by defining glacier outlines upon the aerial photographs (1954 and 1981 stereo pairs) and the orthophotos (2003 and 2007 digital colour images).

The 2003 and 2007 data were obtained by manually digitizing the glacier boundaries upon registered colour digital orthophotos (named Volo Italia, 2003 and Volo Italia, 2007, by Compagnia Generale Riprese Aeree – CGR (CGR 2003, 2007), featuring a planimetric accuracy equal to ± 1 m). These orthophotos are purchasable products (distributed by CGR), featuring a planimetric resolution specified by 1 pixel with size 0.5 m × 0.5 m.

Concerning the 1954 and 1981 records, they were obtained by analysing the stereo pairs (aerial photos at a scale of c. 1:20,000) with an optical stereoscopic system to obtain a 3D view of the glacierized area. Then, the glacier limits observed upon the photos were reported as polygons in a GIS environment. The 1:10,000 scale Technical Regional Map (CTR) of Lombardy Region was used as a raster base. The topographic data reported in the CTR are referred to the beginning of the Eighties of the past century, thus allowing the evaluation of the reliability and accuracy of our findings from the 1981 aerial photos. The planimetric accuracy of the 1954 and 1981 data is ± 5 m.

The glacier area records (i.e., 1954, 1981, 2003 and 2007) we developed were compared together to evaluate both glacier shrinkage and forelands expansion in the period 1954–2007 and in the time windows 1954–1981, 1981–2003, and 2003–2007.Furthermore, to describe features and characteristics of the glacier forelands we overlapped the 1954 and 2007 glacier boundaries using as base layer the 2007 orthophoto. Then by visual inspection we investigated the areas abandoned by ice in the 1954–2007 time window evaluating the extent of: (i) exposed rock areas, (ii) unconsolidated sediments, and (iii) water ponds and newly formed glacial lakes. This analysis permitted to describe not only the extent and the enlargement rates of the glacier forelands but also their features.

The area values we computed feature a final planimetric precision value which was evaluated according to Vögtle and Schilling (1999) and Minora et al. (2016). The area precision for each glacier was evaluated by buffering the glacier perimeter, considering the area uncertainty (Linear Resolution Error or LRE). The LRE is generally considered as half the resolution of the image pixel, that is, in our case 0.5 m for the 2003 and 2007 imagines and 2.5 m for the 1954 and 1981 data. This error may be too low for debris pixels, because glacier limits are more difficult to distinguish when ice is covered by debris (Paul et al., 2009). Therefore, we set the error for debris pixels to be three times that of clean ice. The precision of the whole Bernina glacier coverage was estimated as the root squared sum (RSS) of the buffer areas for 1954, 1981, 2003, and 2007:

$$\mathrm{AE}_{\mathrm{yr}} = \sqrt{\sum\nolimits_{i=1}^{N} \left(pi * LRE_{yr}\right)^{2}} \tag{1}$$

where $\mathrm{AE}_{\mathrm{yr}}$ is the areal error of year (1954 or 1981 or 2003 or 2007), pi is the i^{th} glacier perimeter, $\mathrm{LRE}_{\mathrm{yr}}$ is the LRE of year (1954 or 1981 or 2003 or 2007), and N is the total number of glaciers in the record.

Finally, the total error in area change (AEarea change 1954–1981, 1981–2003, 2003–2007, and 1954–2007) was then calculated as the RSS of the areal errors related to each glacier in the 1954 and 1981, 2003 and 2007 and 1954–2007 (Equation 2 where we computed the RSS for the changes in the time window 1954–2007).

$$\mathrm{AEarea\ change}_{\,1954-2007} = \sqrt{\left(AE_{1954}^{2} + AE_{2007}^{2}\right)} \tag{2}$$

4. Results

4.1. Glacier area changes

The Bernina glacierized area was 45.18 km^2 in 1954 (50 ice bodies), 39.58 km^2 in 1981 (54 ice bodies), 30.58 km^2 in 2003 (59 ice bodies), and 28.19 km^2 in 2007 (49 glaciers) (Figure 2).

Albeit the Bernina glaciers generally underwent losses in area (losing the largest part of their tongues) an increase in their number was observed at times (i.e., 1954–1981 and 1981–2003). This increase is caused by fragmentation of previous larger glaciers, which

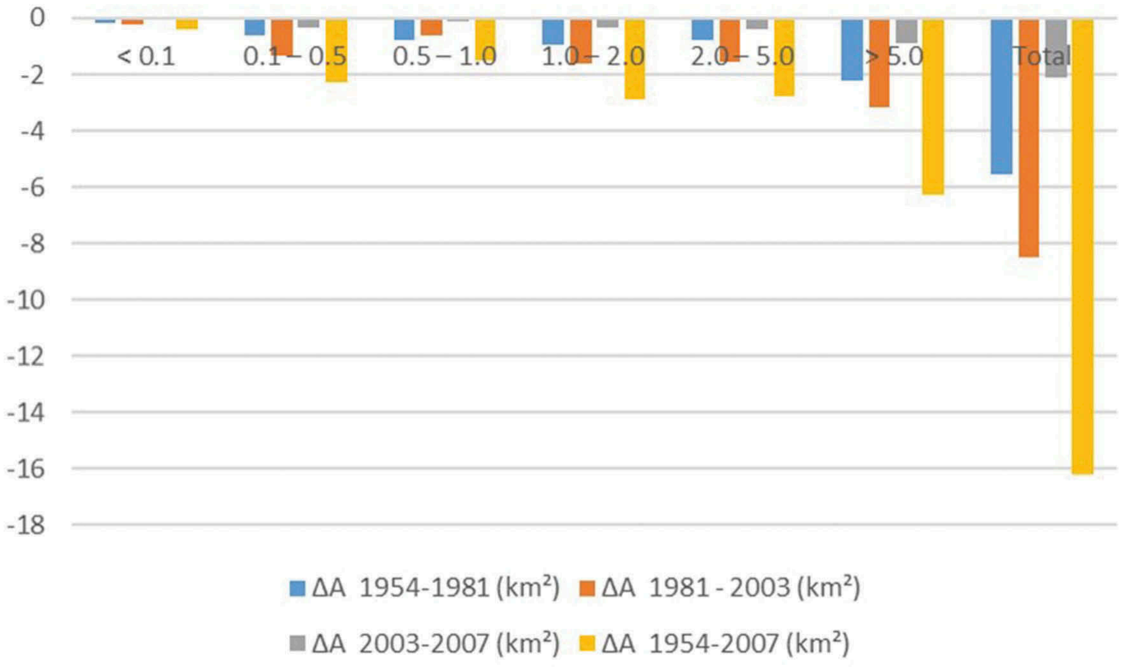

Figure 2. Glacier area change (values are reported as km^2) per size classes over time.

generates smaller ones, and it is typical of the ongoing deglaciation phase. A similar behaviour was reported, for example, by Knoll and Kerschner (2009) for the Tyrolean glaciers (Eastern Alps) where more than smaller 50 glaciers derived from the disintegration of previously larger ones, and by Diolaiuti, Maragno, D'Agata, Smiraglia, and Bocchiola (2011) for Dosdè Piazzi glaciers analysed in the time window 1954–2003.

In order to evaluate the area changes of Bernina glaciers we only compared the surface coverage of glaciers present in all the datasets. The records for 1954, 1981, 2003, and 2007 were considered, thus allowing to evaluate the evolution of 41 glaciers common to all the records and listed in Table 1 (with the coordinates in the WGS84 System).

To analyse in more depth the relations between glacier size and area changes, the Bernina area data were analysed by classifying the glaciers according to the following size classes: < 0.10 km^2, 0.10–0.5 km^2, 0.5–1 km^2, 1–2 km^2, 2–5 km^2, 5–10 km^2, and >10 km^2. These are the same as those applied in previous studies upon Lombardy glaciers' shrinking (Citterio et al., 2007, 2012b; Diolaiuti et al., 2012a, 2011) upon Adamello glaciers' variations during 1981–2003 (Maragno et al., 2009) and analysing Ortles Cevedale glaciers in the time window 1954–2007 (D'Agata et al., 2014). The same classes were initially introduced by Paul et al. (2004) for Swiss glaciers, were used by Knoll and Kerschner (2009) for analysing Austrian glacier changes and were used here to allow a proper comparison with the results therein.

Our data also underline that several glaciers have shifted from the largest size classes to the smallest ones. In fact, analysing glacier size distribution, it can be noticed that in the Bernina group of the 31 glaciers (Table 2) with areas over 0.1 km^2 in 1954, only 17 remained in 2007.

To avoid inconsistencies like the apparent gain in area for those classes that acquired more glaciers from the larger classes than they lost to the smaller ones, the area change values plotted in Figure 2 were obtained by crediting the contribution of each glacier according to the class it belonged to in 1954. Thus, the evaluations of area changes were not affected by class shifts.

Considering these 41 common glaciers, the Bernina glacierized area results 44.37 km^2 ± 0.7% in 1954, 38.82 km^2 ± 0.6% in 1981, 30.32 km^2 ± 0.3% in 2003, and 28.18 km^2 ± 0.3% in 2007 (Tables 1 and 3). The area changes between

Table 2. Number of glaciers in the Bernina Group over time.

Size class (km^2)	Number of glaciers in 1954	Number of glaciers in 1981	Number of glaciers in 2003	Number of glaciers in 2007
< 0.1	10	11	22	24
0.1–0.5	17	19	10	8
0.5–1.0	4	3	2	2
1.0–2.0	3	1	2	2
2.0–5.0	3	3	3	5
> 5.0	4	4	2	0
Total	**41**	**41**	**41**	**41**

Table 3. Area coverage of glaciers in the Bernina Group over time.

Size class (km^2)	1954 Area (km^2)	1981 Area (km^2)	2003 Area (km^2)	2007 Area (km^2)
< 0.1	**0.62**	**0.47**	**0.23**	**0.17**
0.1–0.5	3.51	2.87	1.57	1.25
0.5–1.0	2.73	1.97	1.37	1.24
1.0–2.0	3.88	2.92	1.29	0.98
2.0–5.0	8.4	7.61	6.05	5.63
> 5.0	25.23	22.98	19.81	18.91
Total	**44.37**	**38.82**	**30.32**	**28.18**

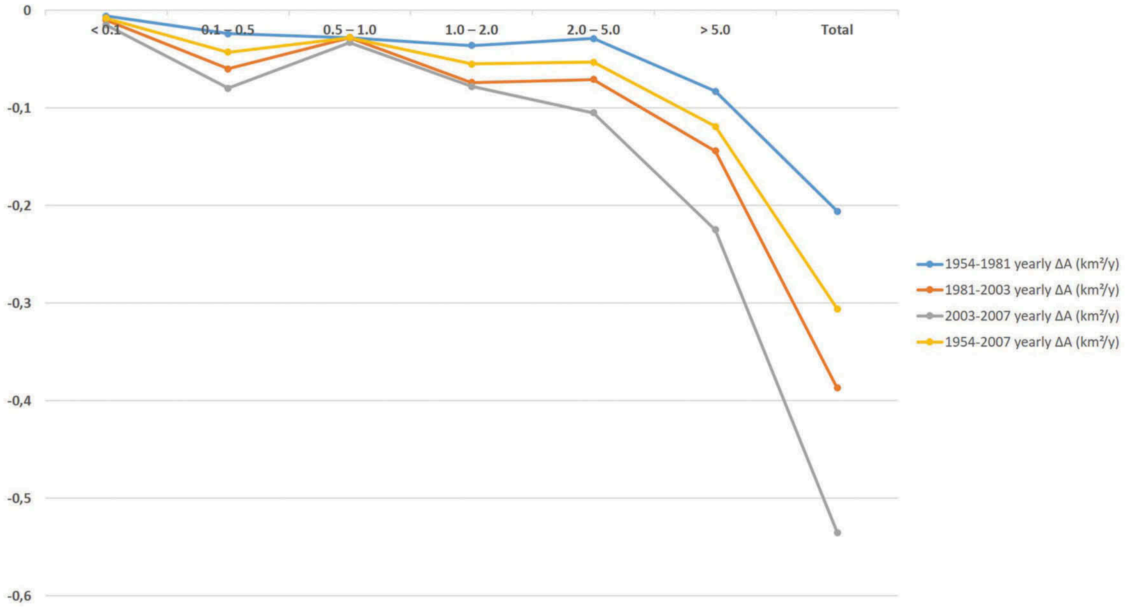

Figure 3. Mean yearly area change (km^2/yr, y axis) evaluated in the different time windows (see the legend) and considering the size classes (x axis).

2007 and 1954 were −16.19 km^2 ± 1.3 % (−36.5 % of the area coverage in 1954), with a fastest rate in the last period; in fact, calculating the mean rate it resulted: −0.206 km^2/y during 1954–1981, against −0.387 km^2/y during 1981–2003, and −0.535 km^2/y during 2003–2007 (Figure 3).

From Table 4 it is seen that during 1954–2007 glaciers smaller than 0.1 km^2 lost c. 71.6% of their initial areas. However, this strong decrease accounts for 2.7% only of the whole glacier area loss. In the 50-year long period, glaciers with their area in the range 0.1–0.5 km^2 lost c. 64.4% of the surface they covered in 1954, thus contributing for 14% of the whole area loss. If we consider larger glaciers, like those in the size class 0.5–1.0 km^2, they lost about 54.6% of their surface, that is, 9.2% of the total glacier reduction.

Glaciers in the class 1.0–2.0 km^2 reduced their area by 74.8%, and their loss represents c. 17.9% of the whole glacier retreat.

Eventually, the contribution to the total area loss given by glaciers with area smaller than 1 km^2 during the period 1954–2007 was 25.9% (with respect to their total coverage in 1954), lower than the contribution the greater (area > 1 km^2) glaciers (which was 74.1%).

The largest glaciers (area > 5 km^2) reduced their area by 25.1%, and their loss represents c. 39.1% of the whole area retreat.

Considering the different time windows of the analysis (i.e., 1954–1981, 1981–2003, and 2003–2007) one finds that the first class (<0.1 km^2) always considerably decreased with respect to its previous surface coverage (by 24.5%, 50%, and 24.8% against the 1954, 1981, and 2003 area value), but still it contributed slightly to the total loss (always about 2.7%). Differently, the size class >5 km^2 was the most influent upon the overall reduction. The glaciers therein decreased by 8.9% during 1954–1981, by 13.8% during 1981–2003, and by 4.6% during 2003–2007, with a contribution to the overall loss of 40.6%, 37.3%, and 42.2% respectively.

This behaviour is partially due to the different reaction times (*sensu* Hoelzle et al., 2003) characterizing each glacier size-class. In addition it may be linked to a shorter persistence of snow accumulation (Pelto, 2010) and is also influenced by the ongoing glacier morphological evolution (e.g., growing rock

Table 4. The area changes of the 41 glaciers we analysed reported as percentage with respect to the size class change and the total area change.

Size class (km^2)	ΔA 1954–1981 as % with respect to the size class value	ΔA 1954–1981 as % with respect to the total change value	ΔA 1981–2003 as % with respect to the size class value	ΔA 1981–2003 as % with respect to the total change value	ΔA 2003–2007 as % with respect to the size class value	ΔA 2003–2007 as % with respect to the total change value	ΔA 1954–2007 as % with respect to the size class value	ΔA 1954–2007 as % with respect to the total change value
< 0.1	−24.5	2.7	−50.0	2.7	−24.8	2.7	−71.6	2.7
0.1–0.5	−18.1	11.5	−45.5	15.4	−20.3	14.9	−64.4	14.0
0.5–1.0	−27.8	13.7	−30.7	7.1	−9.2	5.9	−54.6	9.2
1.0–2.0	−24.8	17.3	−55.9	19.2	−24.2	14.6	−74.8	17.9
2.0–5.0	−9.4	14.2	−20.5	18.3	−7.0	19.7	−33.0	17.1
> 5.0	−8.9	40.6	−13.8	37.3	−4.6	42.2	−25.1	39.1
Total	**−12.5**	**100.0**	**−21.9**	**100.0**	**−7.0**	**100.0**	**−36.5**	**100.0**

outcrops, tongue separations, formation of pro-glacial lakes, increasing supraglacial debris and collapse structures down wasting processes) and the subsequent positive feedbacks (albedo lowering, increasing long wave radiation from rock outcrops, heat storage due to supraglacial water ponds) affecting most glaciers can act as drivers of the increasing reduction rates of recent years (Table 4). These results are consistent with those reported by Paul et al. (2004, 2007), Maragno et al. (2009), Pelto (2010) and Diolaiuti et al. (2011), Azzoni et al. (2017, 2018). Several of these papers underlined that increased rock outcrops are key indicators of down wasting and if these occur in the upper half-former accumulation zone a temperate glacier is expected to not survive.

4.2. Evolution of glacier forelands

As regards the ongoing widening of glacier forelands we evaluated the changes in their extent over time and we analysed features and processes.

In the time window of our analyses the Bernina glaciers abandoned an area of about 16.2 km^2 ± 1.3%. This glacier reduction results in both the exposure of outcropping rocks and nunataks (1.30 km^2), in the expansion of glacier forelands (14.67 km^2), and in the formation of glacial lakes and water ponds (0.17 km^2).

We focused our attention on the glacier forelands by analysing on the most recent orthophotos (2007 flight) their features and in particular applying a manual classification of such areas to underline if they show bare rock or unconsolidated sediments and if glacial lakes and water ponds are occurring in the areas recently abandoned by ice. In this way, 143 parcels were detected at the snout of the 41 analysed glaciers. Sixty-one (61) parcels, totally 2.65 km^2 wide, resulted made by bare rock exposures and eighty-two (82) parcels, altogether 12.02 km^2 wide, were found made by unconsolidated sediment, thus underling that the 82% of the newly exposed areas are subjected to runoff and meltwater actions and gravitative processes and represent unstable and potentially fast changing environments (Table 5).

The one hundred and forty-three (143) parcels feature a wide range of size variability: the smallest ones were found 0.0009 km^2 and 0.0031 km^2 wide, for bare rock and unconsolidated sediment (i.e.,: till deposits), respectively; the largest ones result 1.1843 km^2 and 1.2225 km^2 wide, for bare rock and unconsolidated sediment, respectively.

The size of the newly exposed areas resulted linearly related with glacier area and the widest rock and debris exposures occur at the snout of the biggest glaciers (Figure 2).

Moreover we also detected 18 water bodies varying their size from the maximum value of 0.052 km^2 (found analysing the lake in the proglacial area of Scerscen Inferiore glacier, see geolocation in Table 1) to the minimum of 0.0003 km^2 (featured by the Lake in the foreland of Pizzo Varuna Glacier, see geolocation in Table 1). The mean lake size is found equal to 0.015 km^2 and altogether the 18 lakes cover an area of 0.17 km^2.

As regards the temporal evolution of such phenomena, from Figure 4. it can be noticed that the widest enlargement of the proglacial areas occurred in the time frame 1981–2003 (more than 50% of the total

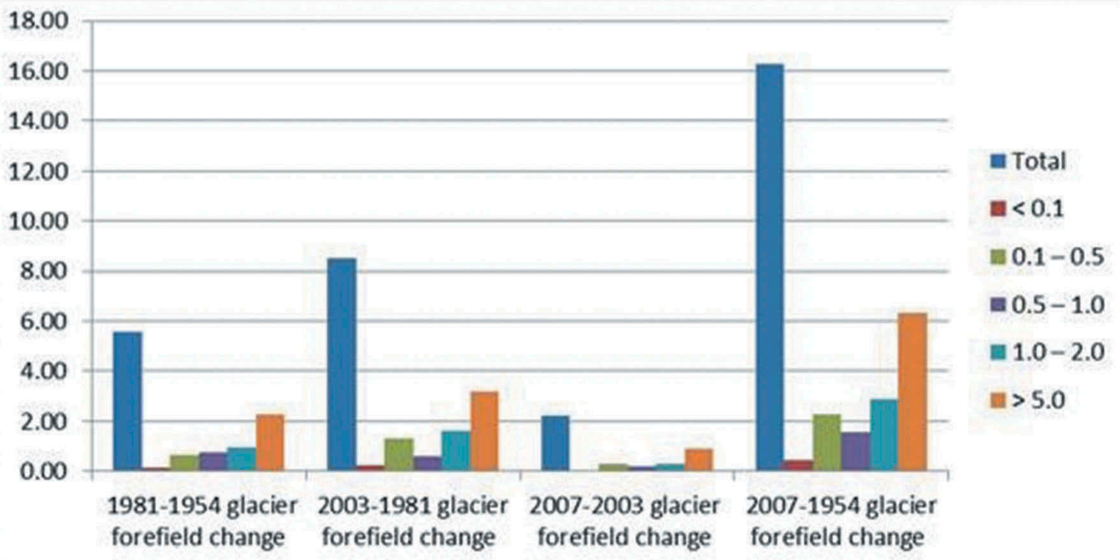

Figure 4. Diagram showing the area abandoned by glaciers and then acquired by forelands in the time windows we analysed (1954–1981, 1981–2003, and 2003–2007). The purple bars indicate enlargement of areas abandoned by glaciers smaller than 1 km^2, the green bars indicate increases of zones abandoned by glaciers in the range 0.1–0.5 km^2, the violet bars indicate areas free from glaciers ranging from 0.5–1.0 km^2, the light blue bars indicate areas deglaciated from glaciers 1.0–2.0 km^2 wide and the brown bars indicate areas deriving from retreating glaciers wider than 5.0 km^2.

Table 5. Features of the glacier forelands analysed by visual inspection of the 2007 orthophotos.

Surface typology	Number of parcels	Total coverage (km^2)	Total coverage (%)	Min parcel size (km^2)	Max parcel size (km^2)	Ave parcel size (km^2)	St deviation (km^2)
Bare rock	61	2.65	18.06	0.0009	1.1843	0.0434	0.1505
Unconsolidated sediment	82	12.02	81.94	0.0031	1.2225	0.1466	0.2077
Total	**143**	**14.67**	**100.00**				

deglaciation) and the result is the same considering all the glacier size classes thus suggesting this period was the most important in offering new environments.

Field investigations performed on some selected glacier forefield areas by the authors of this contribution suggested that whenever present, debris and unconsolidated sediment at glacier forelands are generally thicker than 0.5 m and, in several cases, they reach 1 m of depth. Considering such depth values featured by the debris layer mantling the 12.02 km^2 of glacier forelands it gives a rock debris volume ranging from 0.006 to 0.012 km^3. This material is continuously reworked, transported and re-deposited by meltwater and runoff, by gravitative processes and makes highly dynamic and fast changing these pristine areas.

An example of the changes occurred at the glacier fore fields is appreciable in Figure 5(a–d) where close-up images are shown.

5. Discussion and conclusion

The above reported data describing the recent retreat of glaciers and the expansion of forefields in the Bernina group give clear evidence of the rapid and accelerating climate change impacts affecting the high mountain environment and its surrounding.

In fact, the analysis of Bernina glaciers here performed underlines a stronger reduction of glacier coverage over half a century as well as an increasing widening of proglacial areas.

The glacier area change between 2007 and 1954 was −16.2 ± 0.4 km^2 (−36.5% of the area coverage in 1954).

The glacier surface reduction is enhanced more recently; the area change during was −2.14 km^2 in the period 2003–2007 (4 years, average value −0.535 km^2/y), −8.51 km^2 in the time window 1981–2003 (22 years, average value −0.387 km^2/y), and −5.55 km^2 for the interval 1954–1981 (27 years, average value −0.206 km^2/y).

This glacier reduction results in both the exposure of outcropping rocks and nunataks (1.30 km^2) and in the expansion of glacier forelands (14.67 km^2) where proglacial lakes and water ponds are also present (0.17 km^2).

The 82% of the newly exposed areas were found made by unconsolidated till deposits thus making them subject to meltwater actions, runoff and gravitative processes thus representing unstable and potentially fast changing environments. The widest enlargement of the proglacial areas occurred in the time frame 1981–2003 (more than 50% of the total deglaciation, see Figure 4) and the result is the same considering all the glacier size classes thus suggesting this period was the most important in offering new environments.

Our results about glacier reduction are consistent with glacier retreat and warming trends highlighted in the last decades at mid-latitudes (Kaab et al., 2002; Citterio et al., 2007; D'Agata et al., 2014; Diolaiuti et al., 2012b, 2011; Knoll & Kerschner, 2009; Maragno et al., 2009; Paul et al., 2007, 2004). Results regarding glacier forefields widening are instead a novelty as commonly such changes are not estimated.

The results here support the idea that small glaciers with narrow altitudinal range are losing more of their area, also noted in other studies (Diolaiuti et al., 2012b, 2011; Kaser & Osmaston, 2002; Mark & Seltzer, 2005; Racoviteanu, Arnaud, Williams, & Ordonez, 2008). This may be explained by ascent of the year round ablation zone in response to raising of the ELA under climate warming conditions (Kaser & Osmaston, 2002). In contrast, larger glaciers have a wider altitudinal range, with ELAs well below the maximum elevation at the glacier head.

Moreover, analysing glacier size distribution, it can be noticed that in the Bernina group of the 31 glaciers (Table 2) with areas over 0.1 km^2 in 1954, only 17 remained in 2007. This is critical since it is the smaller glacier sizes that have lost area proportionally the most.

Extrapolations of developments documented by repeated glacier inventories (Kaab et al., 2002; Paul et al., 2004) and provided by numerical models (Oerlemans & Knap, 1998) both suggest that the disappearance of several mountain glaciers is quite likely a matter of few decades (Haeberli, 2008). Also Bernina glaciers could experience such ominous scenario if no meaningful changes will occur in the climate trend.

The ongoing glacier shrinkage and the consequent proglacial area widening, are changing in a deep way the mountain landscape of Lombardy Alps (where the Italian side of Bernina Group is located), which are expected first to show features and landforms now visible within the Pyrenees (where the present glaciation is the relict of the previous one and is formed by small cirque glaciers, see González Trueba et al., 2008) and, in a second phase to resemble the Apennines (where only the Calderone Glacier can be found, actually classified as a debris covered glacieret together with small snow fields, see Branda et al., 2010; Pecci et al. 2008).

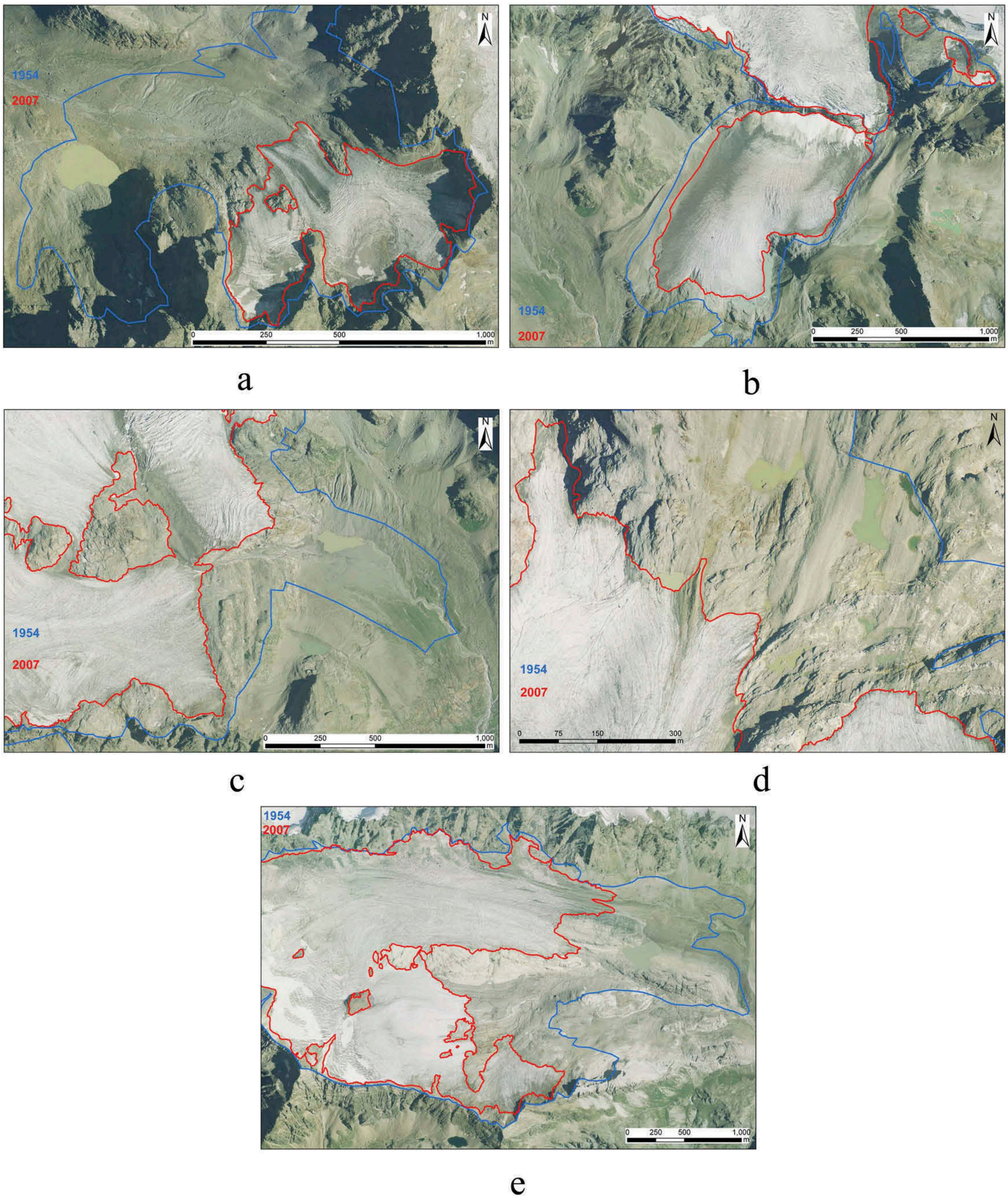

Figure 5. (a) Caspoggio glacier (570,507 E, 5,131,991 N): it is appreciable a newly formed lake in the glacier foreland, moreover unconsolidated sediment and a bare rock area (i.e., roche moutonée) are also visible in the flat area which is strongly re-worked by meltwater. (b) Fellaria est glacier (573,364 E, 5,135,156 N): a proglacial lake is visible on the left hydrographical side, this was in the past (i.e., 1954) an ice contact lake; moreover also unconsolidated sediment re-worked by meltwater is present. A rock exposure (i.e., roche montonée) is also visible. (c) Fellaria Ovest glacier (571,746 E, 5,133,777 N): a newly formed lake is present in the glacier foreland area. Unconsolidated sediment reworked by melting water is also visible together with a wide flat area featuring vegetation (shrubby and grass one) occurrence. (d) Pizzo Scalino glacier (575,946 E, 5,125,974 N): seven newly formed lakes are visible in the glacier foreland area. (e) Scerscen Inferiore glacier (565,177 E, 5,133,396 N): a newly formed lake is present, moreover also unconsolidated sediment and bare rock areas are visible.

Geodynamically wise it is now occurring the transition from the glacial system to the paraglacial one (Ballantyne & Benn, 1994, 1996; Curry and Ballantyne, 1999). The areas where in the recent past the main shaping and driving factors were glaciers are now subject to the action of melting water, adding its action to the runoff one, slope evolution and dynamics and periglacial processes. Morphological changes develop at different rates in relation with shape and features of the newly exposed areas. Bare rock exposures (e.g., roches moutonneé, smoothed surfaces, etc.…) accomplish meltwater runoff while unconsolidated till deposit are unstable and can be remobilized by running waters or by gravitative processes.

Under such changing environmental features, the new territories are available for plant and trees colonization as observed in the Ortles-Cevedale Group (Garavaglia et al., 2010), and at the Forni glacier forefield where in the last years saples are germinating just very few years after the glacier margin retreat (Pelfini, unpublished data).

The melting of glaciers not only has obvious impacts on the surrounding ecosystems, but it also has adverse consequences upon the value of the sites where they are located, in the context of natural and geo heritage. Heritage is an irreplaceable source of life and inspiration, it is humankind's legacy from the past, with which we live in the present and pass on to future generations (UNESCO, 2007).

Also the GEO-Heritage (Bosson & Reynard, 2012) properties could be exposed to the unfavourable effects of changing climate and this is particularly the case of mountain glaciers, among the most fascinating elements of the high elevation environment.

In fact, the consequences of glacier shrinkage on the Alpine natural and cultural heritage have not been deepened at all and only few studies have been carried out (among the others, UNESCO, 2007; Haeberli, 2008; Diolaiuti & Smiraglia, 2010; Garavaglia et al., 2010; Bollati, Smiraglia, & Pelfini, 2013; Bollati, Pellegrini, Reynard, & Pelfini, 2017; Pelfini & Bollati, 2014).

In this context, our study can contribute to evaluate the impacts of glacier decrease on a fragile glacierized areas, as the Bernina group, in term of impact on landscape features and related shaping processes (Bollati et al., 2017) and on geoheritage and geodiversity (sensu Bollati, Leonelli, Vezzola, & Pelfini, 2015; Eberhard, 1997; Gray, 2004; Zwolinski, 2004; Piacente, 2005; Reynard & Coratza, 2007; Serrano & Ruiz-Flaňo, 2007) or better geomorphodiversity. Further researches need to more focus on glacier foreland changes (especially sediment budget, depositional landforms evolution, etc.) as the transition from glacial to paraglacial environments implies huge changes in terms of slope connectivity, sediment transport, erosion rate, etc. (e.g., Slaymaker, 2011; Wilson, 2017). Moreover a focus on human perception of climate changes (Garavaglia, Diolaiuti, Smiraglia, Pasquale, & Pelfini, 2012) and related implication for glacier (Diolaiuti et al., 2006) and glacial forelands fruition are important as a first approach to risk education. Finally a careful dissemination of knowledge related to such fragile environments both to a general public as well as in geo-education (Garavaglia & Pelfini, 2011) is crucial in helping people to get awareness for what concern environmental changes under changing climatic conditions.

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