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Moss flora of two Alpine glacial and periglacial sites on crystalline and carbonatic bedrock

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Abstract - Mosses are important pioneer organisms in cold and wet habitats, such as glacial and periglacial habitats of the European Alps. These habitats include glaciers and rock glaciers, respectively, and are of increasing interest for being directly threatened by climate change and for hosting a specialized and often rare and endemic biodiversity (EU Habitats Directive, habitat code 8340, Natura 2000 network). However, the moss flora of rock glaciers was never studied, and, in general, few studies were performed specifically on mosses of ice-related landforms in the European Alps. The aim of this work is to give a first comparative checklist from two Alpine sites, the rock glacier of Lazaunkar (Bolzano, Italy) and the debris-cover glacier and rock glacier of Cima Uomo (Trento, Italy), with different bedrock compositions. Threatened species (according to the International Union for Conservation of Nature red lists) and extremely specialized high-elevation species were found in both sites, but mostly on crystalline bedrock in Lazaunkar. This biodiversity is the most threatened by climate change. These findings highlight how these habitats still need to be studied and monitored in the future.

Key words: biodiversity, checklist, cold-loving organism, permafrost, threatened habitats.

Riassunto - Flora muscinale di due siti glaciali e periglaciali alpini, su basamento cristallino e carbonatico.

I muschi sono importanti organismi pionieri in ambienti freddi e umidi. Gli ambienti glaciali e periglaciali delle Alpi, come ghiacciai e i rock glacier, sono di interesse sempre crescente per essere fortemente minacciati dal cambiamento climatico e per ospitare una biodiversità estremamente specializzata e spesso rara ed endemica (UE Direttiva Habitats, codice habitat 8340, network Natura 2000). Tuttavia, la flora muscinale dei rock glacier non è mai stata studiata e, in generale, pochi lavori sono stati condotti sulle Alpi specificamente sui muschi degli ambienti legati al ghiaccio. L'obiettivo di questo lavoro è fornire una prima checklist comparativa di due siti Alpini, il rock glacier del Lazaunkar (Provincia di Bolzano), nonché il ghiacciaio nero e il rock glacier di Cima Uomo (Provincia di Trento), caratterizzati da diversa litologia. Sono state trovate specie minacciate (in accordo con le liste rosse dell'*International Union for Conservation of Nature*) e specie adattate all'alta quota in entrambi i siti, ma soprattutto su substrato cristallino, presso il Lazaunkar. Questa biodiversità è la più minacciata dal cambiamento climatico. Questi risultati sottolineano quanto questi ambienti debbano ancora essere studiati per poter essere monitorati in futuro.

Parole chiave: biodiversità, checklist, habitat minacciati, organismi frigofili, permafrost.

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INTRODUCTION

Mosses are widely distributed organisms strictly linked to freely available water in the form of precipitation or cloud moisture, with only a few species adapted to survive in dryland areas (Geffert *et al*., 2013). They have an important role in facilitating habitat formation (Grims, 1982; Wheeler *et al*., 2011; Lett *et al*., 2017) and in microhabitat construction (e.g., Rusek, 2001), especially in glacial habitats (Jonsdottir, 2005; Coulson & Midgley, 2012). They also support multiple ecosystem services – mainly linked to soil carbon and nutrient cycles – especially in low-productive ecosystems where vascular plant cover is low (Eldridge *et al*., 2023). Ice-related landforms like glacial and periglacial (i.e., associated with permafrost) sites are extreme habitats of increasing interest for being directly threatened by climate change and for hosting specialized and often rare and endemic biodiversity (Cauvy-Fraunié & Dangles, 2019; Gobbi *et al*., 2021; Valle *et al*., 2022); for this reason, they are included in the Natura 2000 network as "Permanent Glaciers" (code 8340; Council of the European Communities, 1992). There is evidence of the role of mosses as pioneer organisms in glacial habitats (e.g., Gärtner, 2010; Hågvar *et al*., 2020, Crosta *et al*., 2024, Valle *et al*., 2025), even on the ice surface (Fickert *et al*., 2007; Belkina & Vilnet, 2015). However, to our knowledge, no studies are available that describe the moss flora of periglacial habitats, and only a few works specifically describe the moss flora of ice-related landforms, often reporting only their overall presence without identification at the species level or limiting identification to dominant species (e.g., Grims, 1982; Hyvönen & Hyvönen, 1985; Fickert *et al*., 2007; Gärtner, 2010).

Knowledge of this flora is fundamental for planning, monitoring, and conservation programs (e.g., Puglisi & Cataldo, 2019; Callaghan & Gadsdon, 2023). This work aims to contribute to the knowledge of mosses in periglacial and related habitats by providing a first comparative checklist of two Alpine sites, respectively differentiated by crystalline and carbonatic bedrock.

MATERIALS AND METHODS

Study areas

Sampling was performed at two Alpine sites located on different bedrocks in the central-eastern European Alps. Lazaunkar site ("LAZ": 46°44'48.0"N, 10°45'19.3"E; Val Senales, Trentino-Alto Adige, Bolzano Province, Italy. Figs. 1a and c) is characterized by the presence of an active rock glacier that extends for 0.12 km^2, covering the altitudinal range between 2700 m and 2480 m asl (Krainer *et al*., 2015: data from 2005). The bedrock is constituted by paragneiss and micaschists (Krainer *et al*., 2015). Cima Uomo site ("UO": 46°24'35" N, 11°48'25" E; Valle San Nicolò, Trentino-Alto Adige, Trento Province, Italy. Figs. 1b and d) hosts both a rock glacier (between 2430 and 2400 m asl) and, just uphill, a debris-covered glacier occupying an area of 0.10 km^2 between 2460-2700 m asl (Seppi *et al*., 2015). Cima Uomo is characterized by carbonate bedrock. In both sites, the substrate of the investigated landform is constituted by stony debris of different dimensions, including 1 m and above, on Lazaunkar and isles of fine debris (Fig. 2).

Sampling design

In each site, ice-related landforms, rock glaciers and debris-covered glaciers (only at Cima Uomo) were investigated (Fig. 1). To have a more complete overview of the moss flora of these habitats, also close ice-free landforms with similar substrates were investigated. In particular, a fossil rock glacier (i.e., rock glacier without ice core) and a scree slope were investigated at Lazaunkar, and the moraine of the Little Ice Age (LIA) glacier at Cima Uomo (Fig. 1).

On each landform, identified as a sampling unit ("mesohabitat"; Vanderpoorten *et al*., 2010), 2-6 random plots were identified. The number of plots was chosen according to the landform area (Fig. 1). Each plot consisted of a square of 50 m^2 where all morphological species, discriminated with the aid of a magnifier, were intensively collected. Each sample was stored and transported in a paper bag for dehydration. Samples are preserved in the collection of the Herbarium Universitatis Mediolanensis (University of Milan).

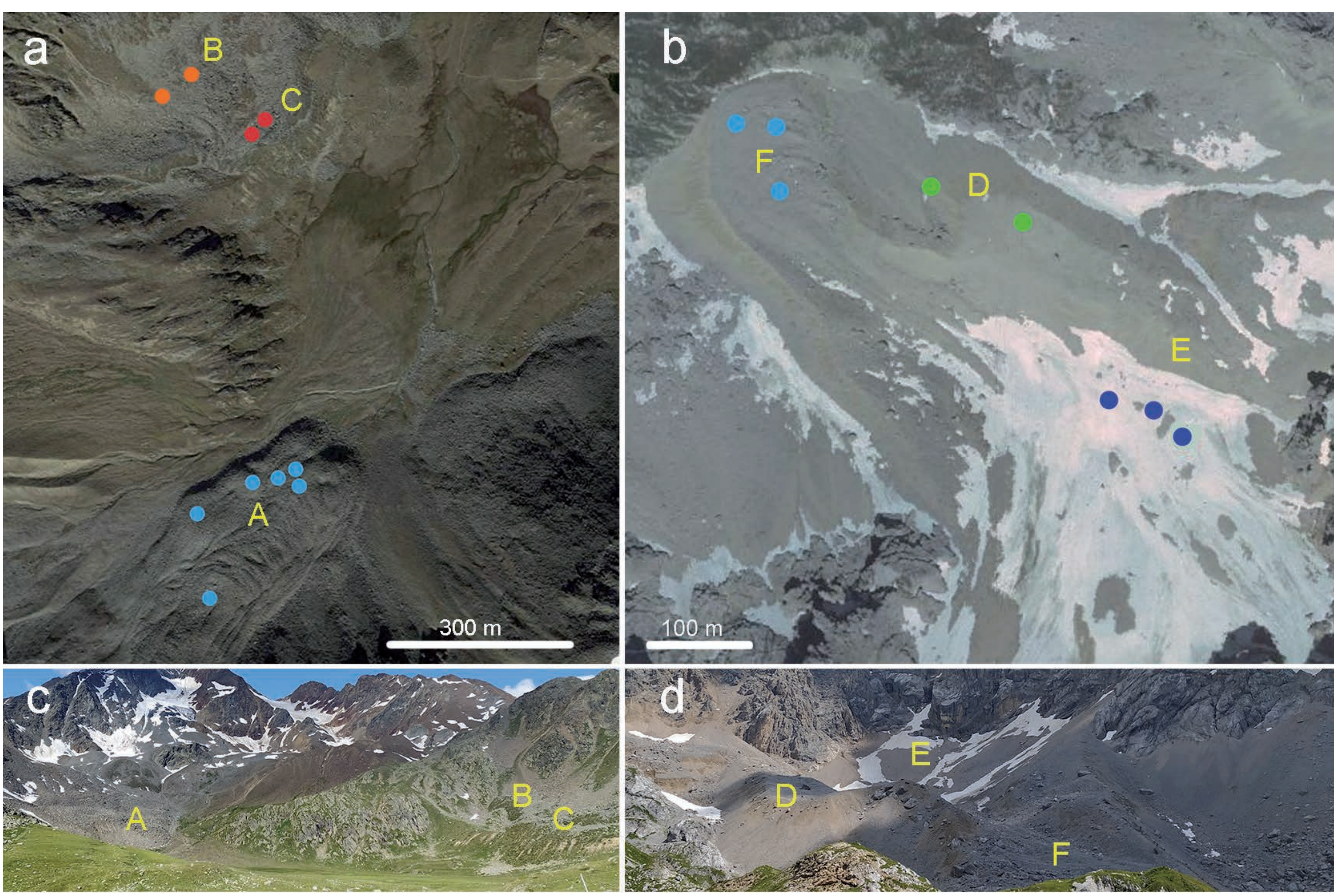

Fig. 1 – Sampling design on Lazaunkar (a) and Cima Uomo (b) and an overview of the two sites, (respectively c and d). Yellow letters indicate studied landforms: A and F) active rock glaciers (light blue dots); B) scree slope (orange dots); C) fossil rock glacier (red dots); D): moraine of the Little Ice Age (green dots); E) debris-covered glacier (blue dots). / Piano di campionamento al Lazaunkar (a) e a Cima Uomo (b) e una panoramica dei due siti (rispettivamente c e d). Le lettere gialle indicano le landform studiate: A e F) rock glacier attivi (punti azzurri); B) ghiaioni (punti arancioni); C) rock glacier relitto (punti rossi); D) morena della Piccola Età Glaciale (punti verdi); E) debris-covered glacier (punti blu).

Morphological identification

For morphological identification, each sample was hydrated and analyzed under a stereo microscope (for general morphology) and with a light microscope for microscopic characters. In particular, the gametophyte (stem, leaf, rhizoids, and cells) and, when present, the sporophyte, were analyzed following the identification keys reported in Cortini Pedrotti (2001, 2005), and in Guerra *et al*. (2021) and Ignatova *et al*. (2009) for the genus *Schistidium*. Nomenclature refers to Hodgetts *et al*. (2020). For *Bryum* sp. 2 (UO), *Dicranella* sp. and *Schistidium* sp. (LAZ) it was not possible to identify samples at the species level because of the lack of material including diagnostic parts of the plant, such as the sporophyte.

Information on ecology and the altitudinal distribution in Italy was taken from Cortini Pedrotti (2001, 2005), while information on species presence in the Trentino-Alto Adige region was from Aleffi *et al*. (2023). The International Union for Conservation of Nature (IUCN) red list categories were taken from Puglisi *et al*. (2024) for Italy and Hodgetts *et al*. (2019) for Europe and refer to both geographical Europe ("EU" in Tab. 1) and the area of the 28 Member States of the European Union ("EU 28" in Tab. 1).

RESULTS

In total, 36 species were found: 19 at Lazaunkar, and 17 at Cima Uomo (Tab. 1). A total of 22 species were found on the two active rock glaciers, 8 on a fossil rock glacier, 11 on the scree slope and on the LIA moraine. No species were found on the debris-covered glacier of Cima Uomo. Only two species were found on both sites, *Encalytpa alpina* and *Pohlia cruda*.

According to IUCN red list (Tab. 1), at Italian scale the investigated sites host a critically endangered species (*Dicranum brevifolium*), two endangered species (*Hymelonoma compactum* and *Dicranum elongatum*) and two vulnerable species (*Ptychostomum funkii* and *Grimmia incurva*).

At the European scale, the most critical taxa are *Andreaea nivalis* (near threatened, according to "EU" red list), *Hymelonoma compactum* (Data Deficient according to both

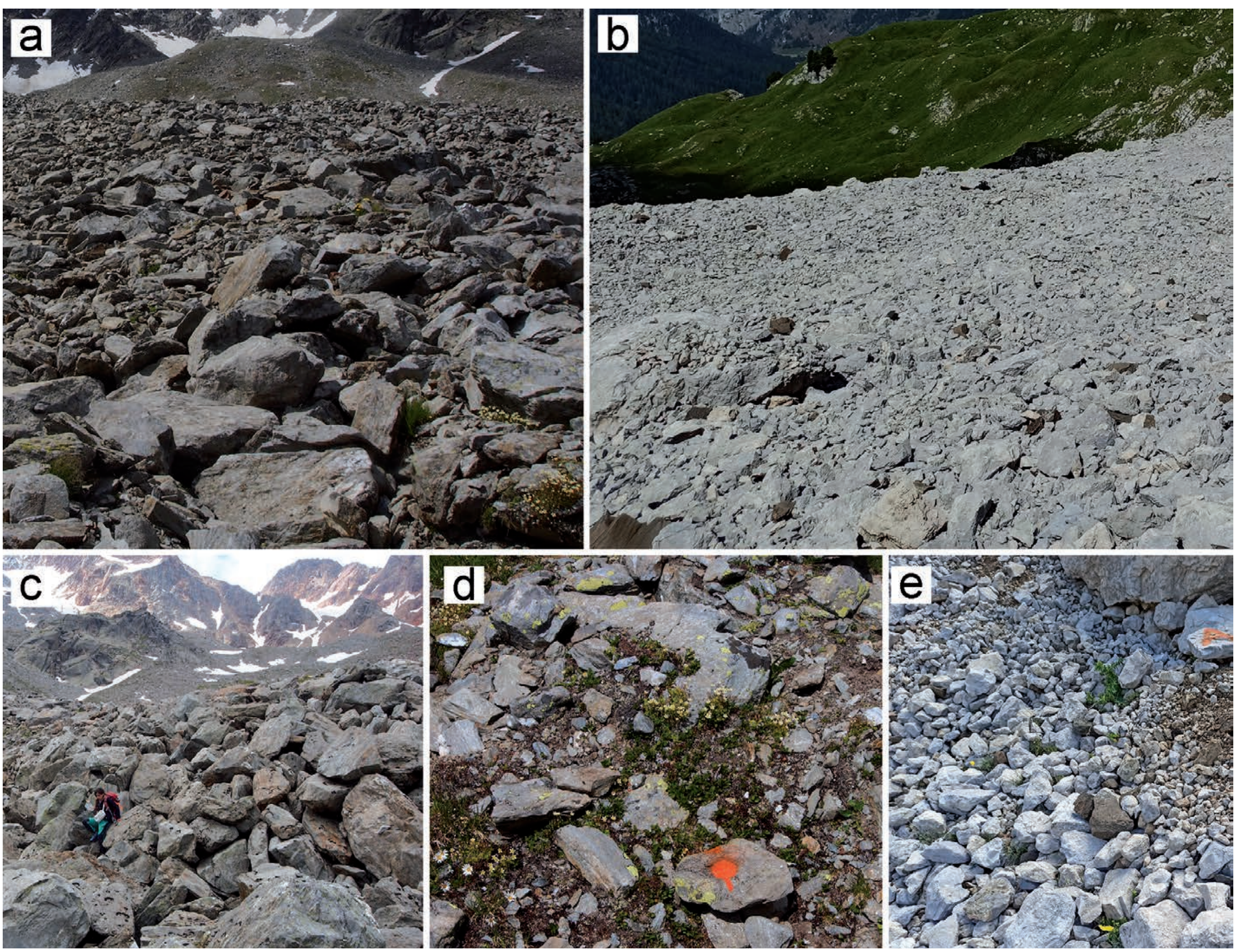

Fig. 2 – Details of the surface of the sampled sites at Lazaunkar in a general view of the active rock glacier (a), of cyclopic rocks (with a person as a comparison) (c) and fine debris island (d) and at Cima Uomo in a general view of the active rock glacier (b) and detail on its debris surface (e). / Dettaglio della superficie dei siti campionati del Lazaunkar, con una visione del rock glacier attivo (a), dei massi ciclopici (con una persona come confronto) (c), e le isole di detrito fine (d) e di Cima Uomo, con una visione del rock glacier attivo (b) e un dettaglio della sua superficie (e).

Tab. 1 – Species found at the two sites, with indication of the landform where they were found. No species were found on the debris-covered glacier, which is not reported in the table. / Specie trovate nei due siti, con indicazioni sulle geoforme dove sono stati rinvenuti. Nessuna specie è stata trovata sul ghiacciaio nero, per questo non è riportato in tabella.

	Site	IUCN category Italy (Puglisi *et al.*, 2024)	IUCN category Europe (Hodgetts *et al.*, 2019)	Micro habitat	Altitudinal belt	Active rock glacier	Fossil rock glacier	Scree slope	LIA moraine
Andreaea nivalis Hook.	LAZ	LC	**NT** (EU) LC (EU28)	RV**W**+	*			X	
Bartramia ithyphylla Brid.	LAZ	LC	LC	R+	**	X			
Brachythecium albicans (Hedw.) Schimp.	LAZ	LC	LC	G+	***	X			
Dicranella sp	LAZ	-	-			X			
Dicranum brevifolium (Lindb.) Lindb.	LAZ	**CR**	LC	R-	*	X			
Dicranum elongatum Schleich. Ex Schwägr.	LAZ	**EN**	LC	RH**W**	**		X		
Grimmia incurva Schwägr.	LAZ	**VU**	LC	RS+	*		X	X	
Grimmia montana Bruch & Schimp	LAZ	LC	LC	RD+	**	X		X	
Heterocladiella dimorpha (Brid.) Ignatov & Fedosov	LAZ	LC	LC	R**W**S+	***	X			
Hymenoloma compactum (Schleich. ex Schwägr.) Ochyra	LAZ	**EN**	**DD**	R+	*	X	X		
Kiaeria starkei (F. Weber & D. Mohr) I. Hagen	LAZ	LC	LC	RGV**W**	*	X	X	X	
Paraleucobryum enerve (Thed.) Loeske	LAZ	LC	LC	RG**W**	*		X	X	
Pohlia nutans (Hedw.) Lindb.	LAZ	LC	LC	RG+	***	X		X	
Politrychastrum sexangulare (Brid.) G.L.Sm	LAZ	LC	**NT** (EU) **VU** (EU28)	RV**W**	*			X	
Polytrichum piliferum Hedw.	LAZ	LC	LC	GD	***	X	X	X	
Ptychostomum imbricatulum (Müll.Hal.) Holyoak & N. Pedersen	LAZ	LC	LC	RG	***	X	X	X	
Schistidium sp.	LAZ	-	-					X	
Encalytpa alpina Sm.	LAZ, UO	LC	LC	HR-	**	X			
Pohlia cruda (Hedw.) Lindb.	LAZ, UO	LC	LC	HRS+	**	X	X	X	
Blindia acuta (Hedw.) Bruch & Schimp.	UO	LC	LC	R**W**	*	X			X
Brachytecium trachypodium (Brid.) Ignatov & Huttunen	UO	LC	LC	R-	**	X			
Campylophyllum halleri (Hedw.) M. Fleisch.	UO	LC	LC	R-	***				X
Distichium capillaceum (Hedw.) Bruch & Schimp.	UO	LC	LC	RS-	***	X			X
Encalypta vulgaris Hedw.	UO	LC	LC	HR-	***				X
Mnium thomsonii Schimp.	UO	LC	LC	HR**W-**	**	X			
Orthothecium intricatum (Hartm.) Schimp.	UO	LC	LC	HR**W**S-	***	X			
Bryum sp. 2	UO	-	-						
Ptychostomum elegans (Nees) D. Bell & Holyoak	UO	LC	LC	R**W-**	***	X			X

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Table 1 –Continued from previous page.

	Site	IUCN category Italy (Puglisi *et al.*, 2024)	IUCN category Europe (Hodgetts *et al.*, 2019)	Micro habitat	Altitudinal belt	Active rock glacier	Fossil rock glacier	Scree slope	LIA moraine
Ptychostomum funkii (Schwägr.) J.R. Spence	UO	**VU**	**VU** (EU) **EN** (EU28)	RG-	***				X
Sanionia uncinata (Hedw.) Loeske	UO	LC	LC	HR**W**	***				X
Schistidium apocarpum (Hedw.) Bruch & Schimp.	UO	LC	LC	R+	***	X			X
Stereodon hamulosus (Schimp.) Lindb.	UO	LC	LC	RG**W-**	**	X			
Syntrichia norvegica F.Weber	UO	LC	LC	R-	**				X
Tortella tortuosa (Hedw.) Limpr.	UO	LC	LC	RG-	***	X			X

LAZ, Lazaunkar; UO, Cima Uomo; microhabitat preferences: R, rocks; G, sand, gravel; H, humus; V, snowbed; W, high humidity; D, aridity; S, shadow; +, acidic soil reaction; -, alkaline soil reaction; altitudinal belt: *from alpine to nival belt; **from mountain to nival belt; ***from plain to nival belt. The International Union for Conservation of Nature (IUCN) categories for Europe consider both geographical Europe ("EU") and the political Europe of the 28 Member States of the European Union ("EU 28") (Hodgetts *et al*., 2019); where not specified, the category is the same for the two cases. / LAZ, Lazaunkar; UO, Cima Uomo; preferenze in termini di microhabitat: R, rocce; G, sabia, ghiaia; H, humus; V, vallette nivali; W, elevata umidità; D, aridità; S, ombra; +, substrato acido; -, substrato alcalino; fascia altitudinale: *dalla fascia alpina a quella nivale; **dalla fascia montana a quella nivale; ***dalla fascia planiziale a quella nivale. Categorie dell'*International Union for Conservation of Nature* (IUCN) per l'Europa considerando sia l'Europa geografica ("EU") che l'Europa Politica dei 28 Stati membri dell'Unione Europea ("EU 28") (Hodgetts *et al*., 2019); dove non specificato, la categoria è la stessa in entrambi i casi.

European red lists), *Politrychastrum sexangulare* (near threatened, according to "EU", and vulnerable, according to "EU 28") and *Ptychostomum funkii* (vulnerable, according to "EU", and near threatened, according to "EU 28").

Ecologically, all the species are linked to rocky, gravelly, and sandy habitats, even if some of them also colonize more organic soils (7 species, 21% of the total number of species; in Tab. 1, species with "H" microhabitat preference). A total of 12 species (36%, Tab. 1) need high levels of humidity and can be associated with water streams, while only three species (9%) are associated with dry conditions and 5 species (15%) are linked to shaded places.

Excluding generalist species, mosses found on Lazaunkar are usually linked to acidic soils, apart from *Dicranum brevifolium* and *Encalypta alpina* which are usually linked to more alkaline soils. Species from Cima Uomo are usually linked to alkaline soils, except for *Pohlia cruda*.

Concerning the altitudinal distribution of species found, the Lazaunkar site shows a higher percentage of species strictly related to high-altitude environments, while in the Cima Uomo site, only one high-altitude species was found (Fig. 3).

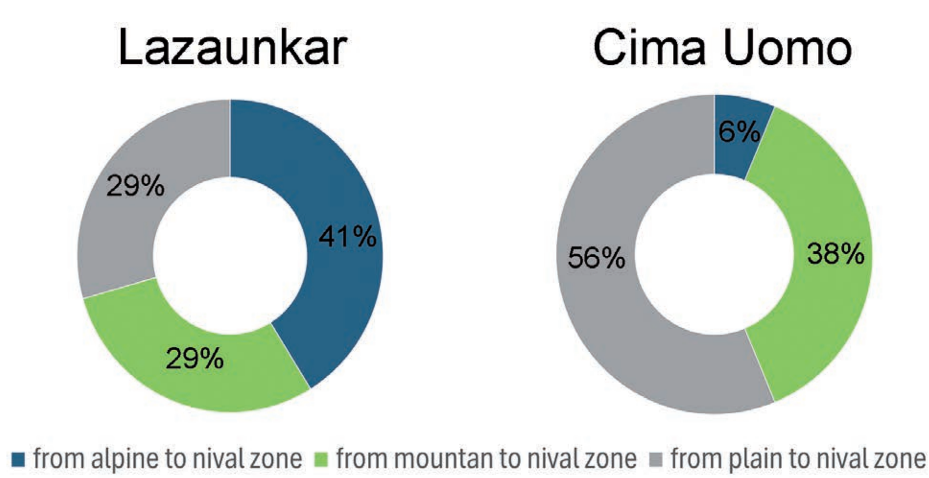

Fig. 3 – Altitudinal distribution of species found in the two sites. / Distribuzione altitudinale delle specie trovate per i due siti.

DISCUSSION AND CONCLUSIONS

Our data indicate that the moss diversity of the investigated landforms is not high (e.g., comparing it with that of urban environments; Fojcik & Stabel, 2014) but includes several taxa that are critical from a conservation perspective. *Dicranum brevifolium* has been recorded in Italy since 1968 (Aleffi *et al*., 2023) only for the Trentino-Alto Adige region, where we have confirmed its presence in the Lazaunkar site. *Dicranum brevifolium* is considered critically endangered at the national level because of its ecology, being threatened by habitat shifting and alteration (Puglisi *et al*., 2024). Habitat shifting and alteration is a common threat for all the other taxa the conservation of which is critical at the national level: the two endangered species, *Dicranum elongatum* and *Hymenoloma compactum*, and the two vulnerable species, *Grimmia incurva* and *Ptychostomum funkii*. Other impending threats are mining, quarrying, recreational activities and the exposure to extreme drought events (Puglisi *et al*., 2024). *Ptychostomum funkii* is showing a decrease in its European range confirming its endangered status at the European scale (Hodgetts *et al*., 2019).

Andreaea nivalis is a circumpolar species with a relict distribution at lower latitudes on high mountains of central and southern Europe (Jenīík, 1997) and is linked to melting snow or ice (Schultze-Motel, 1970; Murray, 1988). Because of its likely high sensitivity to climate change by virtue of its ecology and its fragmented distribution, the present record from Lazaunkar is remarkable and should be considered for future monitoring. Even if this species is not considered a priority for conservation at a national scale (least concern; Puglisi *et al* 2024), it is classified as near threatened at the European scale (Hodgetts *et al*., 2019). The same applies to *Politrychastrum sexangulare* (near threaten/vulnerable; Hodgetts *et al*., 2019), a typical snowbed species, currently threatened in a global warming scenario (Carbognani *et al*., 2012).

The great majority of these taxa of conservation concern were found on crystalline bedrock in the Lazaunkar site. Indeed, the observed biodiversity on crystalline bedrock appeared very specialized, including many exclusive high-elevation, cold-loving species. For example, *Polytrichastrum sexangulare*, *Dicranum elongatum* and *Andreaea nivalis* found in Lazaunkar are considered glacial relicts of subarctic species in the Alps (Fudali & Kučera, 2002). The majority of species found on both sites are typical of rocky habitats because of the dominance in all the investigated landforms of coarse stony debris. However, on the moraine originated during the last phase of glacier advance of the Little Ice Age, c. 200 years B.P., also species more exigent in terms of humus presence can grow, like *Sanionia uncinata*, already reported by Hyvönen and Hyvönen (1985) on Aletsch Glacier (Switzerland) as a typical species of recent moraines where a thin layer of humus occurs.

The sampled environments host both species of dry and exposed, and moist and shadowy habitats, highlighting microhabitat heterogeneity, which could be enhanced by the presence of ice influencing snow persistence and soil humidity at the surface. For example, *Andreaea nivalis* and *Grimmia incurva* prefer wet and rocky habitats of high elevations (Cortini Pedrotti, 2001), while *Politrychum piliferum* is typical of dry glacial mineral soils (Hyvönen & Hyvönen, 1985; Gärtner, 2010) but also occurs at low elevations (Cortini Pedrotti, 2001). The heterogeneous grain size distribution allows for the occurrence of species reported to be linked to vertical cliffs, like *Blindia acuta* (Hyvönen & Hyvönen, 1985). The importance of the bedrock as an ecological factor in these landforms is highlighted by the almost complete divergence between the floristic composition of the two sites, with species typical of alkaline soil, such as *Distichum capillaceum*, occurring in the Cima Uomo site.

It is noteworthy that, at least in our two sites, rock glaciers host a markedly different moss flora than that of proglacial habitats such as recently-deglaciated forelands, as dominant species reported to be highly frequent at these sites such as *Pohlia filum* and *Racomitrium canescens* are absent (Burga, 1999; Hyvönen & Hyvönen, 1985; Gärtner, 2010; Hågvar & Pedersen, 2015). No species were found on the debris-covered glacier, probably because of its high dynamicity and slope, and the frequent rockfall from the surrounding cliffs. However, further investigation is necessary to know the still understudied supraglacial moss biodiversity on the Alps, since an Arctic supraglacial moss richness would suggest a habitat suitability for hygrophilic mosses (Belkina & Vilnet, 2015).

As suggested for other taxa (Brighenti *et al*., 2021; Gobbi *et al*., 2021), it is possible that, in the future, in a global warming scenario, many threatened, cold-loving and hygrophilic species will retreat to periglacial refugia: Although preliminary, our findings suggest that this could also occur for mosses.

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