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Original Research Article

Debris-covered glaciers as habitat for plant and arthropod species: Environmental framework and colonization patterns

Duccio Tampucci[a,*,1], Roberto Sergio Azzoni[b], Patrizia Boracchi[c], Clara Citterio[a], Chiara Compostella[d], Guglielmina Diolaiuti[b], Marco Isaia[e], Giuseppe Marano[c], Claudio Smiraglia[d], Mauro Gobbi[f,1], Marco Caccianiga[a,1]

[a] Dipartimento di Bioscienze, Università degli Studi di Milano, Via Celoria 26, 20133 Milano, Italy
[b] Dipartimento di Scienze e Politiche Ambientali (DESP), Università degli Studi di Milano, Via Celoria 2, 20133 Milano, Italy
[c] Dipartimento di Scienze Cliniche e di Comunità, Università degli Studi di Milano, via Venezian 1, 20133 Milano, Italy
[d] Dipartimento di Scienze della Terra "A. Desio", Università degli Studi di Milano, Via Mangiagalli 34, 20133 Milano, Italy
[e] Dipartimento di Scienze della Vita e Biologia dei Sistemi, Università degli Studi di Torino, Via Accademia Albertina 13, 10123 Torino, Italy
[f] Sezione di Zoologia degli Invertebrati e Idrobiologia, MUSE—Museo delle Scienze, Corso del Lavoro e della Scienza 3, 38122 Trento, Italy

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ABSTRACT

Debris-covered glaciers are glaciers with the largest part of the ablation zone covered by a debris layer. Recent papers showed that debris-covered glaciers are able to support plant and arthropod life, advancing the hypothesis that such landforms could act as warm-stage refugia for cold-adapted species due to their microclimate features and thermal inertia. However, integrated research comparing debris-covered glaciers with surrounding landforms to outline their ecological peculiarities are currently lacking. We analyze some abiotic (glacier surface velocity, ice melting rate and supraglacial debris thickness; ground temperature and humidity; substrate physical and chemical parameters) and biotic features (vascular plant and arthropod communities) of an Alpine debris-covered glacier (Belvedere, Western Alps, Italy), and compare them with those of the surrounding iceless landforms as reference sites (stable slope and iceless moraine). Our data show remarkable differences between stable slopes and unstable landforms as a whole (iceless moraine and supraglacial debris). The iceless moraine and the supraglacial debris show similar substrate features, but different ground temperature (lower on supraglacial debris) and different occurrence of cold-adapted species (more frequent/abundant on supraglacial debris). Such differences could be attributed to the thermal effect of underlying ice. Our data support the hypothesis advanced by previous studies: the thermal contrast with the surrounding landforms and the ability to descend below the climatic treeline give debris-covered glaciers the ecological requirements to be considered potential warm-stage refugia for cold-adapted species. However, our data highlighted that biotic colonization of such landforms could be prevented by some glaciological features, like the mechanical disturbance due to the ordinary ice dynamics (e.g. high glacier surface velocity) and time since the last extraordinary ice dynamic (e.g. surge-type movements). The combined effect of such features is currently preventing colonization by low-dispersal taxa as some cold-adapted ground beetles.

1. Introduction

The increasing rock debris cover on glacier surfaces is one of the most relevant effects of the current climate change on many mountain regions of the world, with noteworthy implications both by the glaciological (Diolaiuti et al., 2003; Mihalcea et al., 2006, 2008a; Azzoni et al., 2016) and biological viewpoints (Fickert et al., 2007; Pelfini et al., 2007, 2012; Gobbi et al., 2011; Caccianiga et al., 2011; Azzoni et al., 2015). The phenomenon can be explained by the progressive exposure of englacial debris with ice melting, and by the increasing occurrence of rock-falls from the slopes freed by glacier thinning and thus exposed to macro-gelivation processes (Kirkbride and Warren, 1999; Mattson, 2000; Diolaiuti et al., 2003,

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* Corresponding author.
E-mail address: duccio.tampucci@gmail.com (D. Tampucci).

[1] These authors equally contributed to this work.

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2009; Stokes et al., 2007). While a thin debris layer promotes further ablation through its thermal conductivity, a debris layer thicker than 3–5 cm (the "critical thickness", sensu Mattson et al., 1993) causes an ice melting rate decreasing logarithmically as a consequence of debris thermal insulation, allowing glaciers to reduce further mass loss in spite of the ongoing climate warming (Nakawo and Rana, 1999). Therefore, over a transition from a cold-climatic stage to a warm-climatic one, glacier systems are able to turn from a debris-free state to a debris-covered one, a new metastable equilibrium characterized by lower (in magnitude and rates) ablation, smaller amplitude of frontal fluctuations and tongue resting at lower altitudes (Kirkbride, 2000; Diolaiuti et al., 2003, 2009; Deline, 2005).

In some cases, debris-covered glaciers are able to support plant and arthropod life. Vegetation on these landforms was observed since the first decades of 20th century (e.g. Negri, 1935, 1942; Valbusa, 1937; Birks, 1980), but were only recently analyzed in depth by the ecological viewpoint. Vascular plants that most successfully colonize supraglacial debris are pioneer species with an extensive and shallow root system, even though shrubs and trees can frequently occur (Fickert et al., 2007; Pelfini et al., 2007, 2012; Caccianiga et al., 2011). Arthropod species can establish as well on supraglacial debris, especially predatory taxa (ground beetles and spiders) that probably take nutrition from incoming aeroplankton (aphids and springtails) and flying insects (flies) (Gobbi et al., 2006a, 2011, 2017). Plant and arthropod species assemblage and richness seems to be affected by ground stability as a function of glacier surface velocity and by ground temperature as a function of debris thickness (Caccianiga et al., 2011; Gobbi et al., 2011). Interestingly, debris-covered glaciers can host cold-adapted high alpine taxa below their normal altitudinal distribution (even below the treeline) probably as a consequence of the thermal effect of underlying ice (Fickert et al., 2007; Caccianiga et al., 2011; Gobbi et al., 2011).

The importance of geomorphological heterogeneity at landscape level to preserve biodiversity in spite of the climate changes is known, since specific landforms can locally maintain suitable ecological conditions for certain species even when the context became adverse for them (Birks and Willis, 2008; Stewart et al., 2010; Ashcroft et al., 2012; Scherrer and Körner, 2011; Keppel et al., 2015; Gentili et al., 2015). In the matter of that, the role of debris-covered glacier is still controversial. Fickert et al. (2007) proposed such landforms as refugia and dispersal pathways during the ice ages, calling into question the ice ages themselves as periods of biogeographical isolation. Other authors interpreted debris-covered glaciers as potential warm-stage refugia for cold-adapted plants (Caccianiga et al., 2011) and arthropods (Gobbi et al., 2011), as a consequence of the microclimate features due to the underlying ice and the thermal inertia due to the debris cover. Since supraglacial debris occurs during warm-climatic stages rather than cold-climatic ones, it may provide a new suitable habitat for cold-adapted species right when they are most threatened by the increasing temperature and the upshift of altitudinal belts (Theurillat and Guisan, 2001; Pauli et al., 2003; Thuiller et al., 2005; Dullinger et al., 2012; Pizzolotto et al., 2014).

In spite of the different biogeographical interpretations of debris-covered glaciers, all the Authors agreed on the crucial role of species dispersal ability in employing such landforms as habitat and refugia. Plants ability to colonize supraglacial debris depends on species dispersal ability and propagules availability in the surrounding landscape (Caccianiga et al., 2011), while their prospect to persist on supraglacial debris may depend on their ability to close the life cycle before calving off the glacier front and then to recolonize the upper zones to restart a new life cycle (Fickert et al., 2007). Dispersal ability is also supposed to drive arthropods response to the climate warming, since high-dispersal species may be able to follow the upshift of altitudinal belts while low-dispersal ones may be forced to search for closer refugia (Gobbi et al., 2011); so a critical topic is whether low-dispersal arthropods are able to colonize debris-covered glaciers.

Studies about geomorphological (e.g. Diolaiuti et al., 2003, 2009; Deline, 2005), botanical (e.g. Fickert et al., 2007; Caccianiga et al., 2011) and zoological features (e.g. Gobbi et al., 2011, 2017; Franzetti et al., 2013; Turchetti et al., 2013; Azzoni et al., 2015) of debris-covered glaciers were already performed, but no studies integrated multidisciplinary data about climate, substrate, plants and arthropods at the same time following a functional approach. Furthermore, no studies compared debris-covered glaciers with the surrounding landforms as reference sites and clearly contextualized such landforms with respect to the altitudinal zonation of mountain ecosystems (e.g. with respect to the climatic treeline as lower limit of the alpine belt; Körner, 2003).

In the present paper we analyze some abiotic (glacier surface velocity, ice melting rate and supraglacial debris thickness; ground temperature and humidity; substrate physical and chemical parameters) and biotic features (vascular plant and arthropod communities) of an Alpine debris-covered glacier (Belvedere, Western Alps, Italy), and compare them with those of the surrounding iceless landforms as reference sites (stable slope and iceless moraine). A functional approach was followed to identify cold-adapted and high-dispersal species. Our hypotheses are: 1) the debris-covered glacier differs from the surrounding landforms by (a) ground temperature/humidity and (b) substrate physical/chemical parameters; 2) the debris-covered glacier differs from the surrounding landforms by (a) plant/arthropod species richness/abundance, (b) plant/arthropod cold-adapted species and (c) plant/arthropod high-dispersal species; 3) glaciological variables drive the distribution of plant/arthropod species richness/abundance/assemblage on the debris-covered glacier. In the light of the obtained results, we finally aimed to assess the role of debris-covered glaciers as potential warm-stage refugia for cold-adapted species.

2. Study area

The present study was performed on the Belvedere glacier (Wester Italian Alps, Monte Rosa Massif in Marazzi, 2005, 45° 57.685 N, 7° 54.925 E) (Fig. 1), one of the most well-known debris-covered glaciers of the Alps (e.g. Monterin, 1923). Its fame is partially due to its interesting and hazardous dynamics, like the several outburst floods recorded from 1868 to 1979 and the surge-type movement occurred between the summers 2001 and 2002 (Haeberli et al., 2002; Mortara and Tamburini, 2009). The glacier is c. 5.8 km long and 0.7 km wide, covering a total surface of c. 4.5 km^2 (Smiraglia et al., 2015). It takes origin from the confluence of four main tongues descending from the large east face of Monte Rosa (4633 m a.s.l.) and reaches 1785 and 1820 m a.s.l. with two divergent frontal lobes; such altitudes make Belvedere the glacier reaching the lowermost altitude of the Italian Alps after the Miage glacier (1730 m a.s.l.) (Mortara and Tamburini, 2009; Smiraglia et al., 2015). The Belvedere glacier surface is almost completely covered by a debris layer whose thickness ranges from c. 5 cm in the upper tongue to 20–30 cm in the frontal lobes, with peak levels of c. 80 cm in depressions (Diolaiuti et al., 2003). Two main moraine systems border the glacier: an external one deposed in the Little Ice Age (at present consolidated and fully covered by vegetation) and an internal more recent one (still unconsolidated and with lower vegetation cover) (Mortara and Tamburini, 2009). The area is characterized by a substrate of gneiss and schists (Mattirolo et al., 1951) and a sub-oceanic climate regime (Mortara and Tamburini, 2009; Tampucci et al., 2016). The climatic treeline resulted to be located at c. 2215 m a.s.l., c. 430 m above the glacier