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Biogeomorphic interactions in the Turtmann glacier forefield, Switzerland

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ABSTRACT

Glacier forefields are dynamic environments dominated by active paraglacial processes and simultaneous vegetation succession, triggered by glacier retreat since the Little Ice Age. While these dynamics are accelerating in the last decades owing to climate change, interactions between vegetation and geomorphic processes and components and the resulting patterns are only partly understood. Using a biomorphic approach based on preexisting geomorphic and glaciological data, geomorphic activity was classified and mapped in the Turtmann glacier forefield, Switzerland. Vegetation and environmental parameters were sampled. Vegetation analysis was subsequently carried out with vegetation classification and ordination for identifying relationships to environmental parameters. A paraglacial impact on vegetation succession could be shown and differentiated according to geomorphic activity on constant terrain age. Biogeomorphic concepts were then applied to explain these patterns. Three biogeomorphic succession phases were identified and related to degrees of activity, species composition, and strength of interactions. Integrating our results into the paraglacial concept, we show how the paraglacial adjustment of a glacier forefield is significantly affected by biogeomorphic interactions.

1. Introduction

Since the late nineteenth century, glacier forefields have been a key research interest for geomorphologists, ecologists, and biologists (Coaz, 1887; Poser, 1932). Their continuous ecological and geomorphological change is conditioned by the ongoing stepwise glacier retreat since the end of the Little Ice Age (LIA) and its recent acceleration in the last decades (Paul et al., 2004). Dynamics of glacier retreat steadily expand the space for active geomorphic processes as well as vegetation colonization and succession.

1.1. Paraglacial glacier forefield systems

As unvegetated valley-floor deposits are exposed to erosion, they undergo paraglacial modification by mass movements, frost sorting, and wind and water transport (Ballantyne, 2005). Lateral moraines are especially prone to paraglacial sediment reworking, e.g., through slope failure, surface wash, and debris flows, which are considered to be the dominant agents (Ballantyne, 2002a). Occurring glaciofluvial processes within the glaciofluvial subsystem also contribute strongly to sediment reworking (Irvine-Fynn et al., 2011). This accelerated geomorphic activity declines as soon as the metastable paraglacial system stabilizes caused by the exhaustion of paraglacial sediment storages or vegetation colonization (Ballantyne, 2002b).

1.2. Vegetation colonization and primary succession in glacier forefields

Vegetation colonization starts with pioneer species. These are adapted to the dominance of abiotic processes by their dispersal mechanisms (Chapin et al., 1994), their seed sizes and growth rates (Stöcklin and Bäumler, 1996), as well as by their physiognomy (Schröter et al., 1926).

Colonization by pioneers proceeds to primary succession that can be defined as ‘species change on substrates with little or no biological legacy’ over time (Walker and del Moral, 2003, p. 7). This process is controlled by abiotic and biotic factors, which change with increasing terrain age, as described in the geoecological succession model (Matthews, 1992). At the beginning of primary succession, abiotic impacts are the most important influences (Raab et al., 2012). In glacier forefields, they include sediment characteristics and active geomorphic processes (‘terrain age factor complex’) as well as topographic and hydrological controls such as snow melt, exposure, slope aspect, and moisture (‘microtopography factor complex’) (Matthews and Whittaker, 1987; Whittaker, 1987; Raffl et al., 2006). With proceeding vegetation succession, biotic processes – such as competition (Clements, 1928), facilitation, tolerance, and inhibition (Connell and Slatyer, 1977) – receive increasing importance (Matthews, 1992; Walker and del Moral, 2003; Raab et al., 2012).

These temporal abiotic–biotic dynamics result in gradients in species composition, which can be interpreted as specific successional pathways, phases, and succession trends (Matthews, 1992). They include increasing vegetation cover, biomass, and vegetation stratification with increasing terrain age (Walker and del Moral, 2003) and a

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peak in species numbers between 40 and 80 years after deglaciation (Matthews, 1992).

1.3. Relationships between vegetation and geomorphic components and processes in glacier forefields

Research specifically considering geomorphology and vegetation in glacier forefields has often been confined within the respective disciplinary frontiers. Geomorphic processes in glacier forefields are seen as disturbances in ecology (Matthews, 1999; Walker and del Moral, 2003), while vegetation development was often generally seen as dependent on geomorphic processes for short timescales (Schumm and Lichty, 1965). Approaches regarding physical and biological interactions were often unidirectional, with some exceptions (Matthews, 1992; Richter, 1994; Matthews et al., 1998).

Several studies showed that vegetation succession is regularly disturbed by geomorphic processes (Oliver et al., 1985; Richter, 1994; Matthews, 1999). These often paraglacial processes slow the succession rate, rapidly reverse the succession to earlier stages, and thus result in the persistence of pioneer species on older terrain (Matthews, 1999). This shows in spatial vegetation discontinuities and heterogeneities (Moreau et al., 2004). These patterns are well-known in glaciofluvial environments with pioneer vegetation in active proglacial channels on older terrain (Moreau et al., 2008; Nagl and Erschbamer, 2010). The impact of geomorphic processes on vegetation seems to decline with increasing terrain age and the occurrence of late successional vegetation such as shrubs and trees (Richter, 1994).

This decreasing impact of geomorphic processes on vegetation succession can be related to the stabilizing effect of vegetation on glacial sediment (Ballantyne, 2002b), which depends on the development stage of the ecosystem (Raab et al., 2012). A stabilization effect could not be shown for glacier forefield gully moraines (Curry et al., 2006) and sediment-mantled slopes (Mercier et al., 2009) with high geomorphic activity. When these landforms start to stabilize, initial ecosystem development starts with interactions between vegetation and geomorphic components and processes. This is leading to surface stabilization (Raab et al., 2012).

In periglacial forefield systems, vegetation colonization is seen as cause as well as effect of patterned ground formation (Matthews et al., 1998; Haugland, 2006). Influences of vegetation on cryogene processes here occur, e.g., through biomass and vegetation cover (Hjort and Luoto, 2009). When these feedbacks result in the crossing of a threshold toward enhanced stability, vegetation development beyond pioneer stages becomes possible (Haugland and Beatty, 2005).

These close linkages between geomorphic and vegetation development were also shown for glaciofluvial systems (Gurnell et al., 2000). They develop similar to fluvial systems with interactions between glaciofluvial processes and floodplain vegetation resulting in a mutual development of geomorphic system and vegetation (cf. Corenblit et al., 2007). This is caused by feedbacks, e.g., between plant roots and bank stability or biomass and flow velocity (Gurnell et al., 2000).

1.4. Biogeomorphic framework

The acceleration of glacier retreat from climate change in the last decades has boosted the importance of understanding these geomorphic and ecological glacier forefield dynamics, also in terms of sediment delivery and natural hazards (Haeberli and Beniston, 1998; Cannone et al., 2008; Moore et al., 2009; Heckmann et al., 2012). The actively developing discipline of biogeomorphology (cf. Wheaton et al., 2011) offers a large potential to enhance this understanding by jointly investigating vegetation and geomorphic dynamics in glacier forefields.

The term 'biogeomorphology' was coined by Viles (1988, p. 1) as 'approach to geomorphology which considers the role of organisms.' These more unidirectional approaches in the early stages of this new scientific field are now developing into a two-way approach (Marston, 2010). This considers the interactions between Earth surface processes, landforms, and ecological and evolutionary processes using new concepts and theories derived from ecology and evolutionary biology (Corenblit et al., 2011). The core of these approaches is based on a close systemic interaction between the geomorphic and biologic components and processes. They are integrating ideas from complex systems theory, e.g., path-dependency, non-linearity, complexity, and emergence (Levin, 1998; Phillips, 1999; Stallins, 2006). Recently developed concepts within this new biogeomorphic approach include biogeomorphic succession (Corenblit et al., 2007), geomorphic-engineer species (Corenblit et al., 2010), and a biogeomorphic transient form ratio (Phillips, 1999; Corenblit et al., 2011). These concepts will be illustrated in the discussion (see Section 4.5).

1.5. Research gaps and aims of this study

Current biogeomorphic research is focussed on coastal, slope, and fluvial systems (cf. Spencer and Viles, 2002; Marston, 2010; Osterkamp and Hupp, 2010). However, biogeomorphic research should be advanced in environments particularly affected by climate change (Marston, 2010; Reinhardt et al., 2010), such as glacier forefields. Because of their inherent characteristics, they offer important advantages for biogeomorphic studies: differing timescales of geomorphic and vegetation development do not pose problems (cf. Reinhardt et al., 2010), as primary succession and paraglacial adjustment in glacier forefields operate on similar time scales of some decades to a few centuries (Matthews, 1992; Ballantyne, 2002b). Because of the extreme physical conditions (Lazzaro et al., 2010), geomorphic and biotic processes probably are closely linked (Viles, 2003).

The application of biogeomorphic concepts in glacier forefields offers huge potentials to enhance the understanding of ecological and geomorphic glacier forefield dynamics. While relationships between vegetation and geomorphic components and processes were already detected in glacier forefields and related to a time-dependent development, a holistic understanding of these relationships is missing. This especially applies for the underlying interactions, mechanisms, influencing factors and their relation to the resulting pattern, also in terms of scale linkages. Regarding paraglacial geomorphic influences on vegetation succession in the glacier forefield, a differentiation of this influence according to process type or degree of activity (magnitude and frequency of processes) is in demand (Matthews, 1999). This could also improve the understanding of stabilization by vegetation, as boundary conditions and process thresholds (cf. Reinhardt et al., 2010) could be defined here within which this effect is operative.

The aims of this contribution are:

(i) to assess the paraglacial impact on vegetation succession in the forefield of Turtmann glacier, Valais, Switzerland;
(ii) to identify relationships and feedbacks between geomorphic activity and vegetation patterns; and
(iii) to apply the biogeomorphic concepts developed by Corenblit et al. (2007, 2011) for the interpretation of biogeomorphic interactions and resulting patterns in a glacier forefield.

2. Study site and methods

The approach of this study combines methods from ecology and geomorphology adapted to a biogeomorphic aim (see Fig. 1). It was applied to a glacier forefield that is already well-studied.

In a first step, existing geomorphic and glacier history data was used as a base for geomorphic activity mapping and vegetation sampling. In a second step, this data was integrated with sampled and mapped data into data sets for multivariate analysis of vegetation patterns and their relationship to environmental parameters. Results