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BIOGEOMORPHIC DYNAMICS IN THE TURTMANN GLACIER FOREFIELD, SWITZERLAND

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According to hierarchy theory, phenomena in a focal level, such as this thesis, cannot be understood without considering their higher level constraints and lower level components and explanations.

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CONTENTS

CONTENTS

SUMMARY

Worldwide, glacier retreat enlarges glacier foreland areas. These environments are characterized by pronounced geomorphic and ecologic dynamics. Large amounts of glacial sediments are transported by geomorphic processes in the glaciofluvial floodplain and at steep lateral moraine slopes during paraglacial adjustment. At the same time, plants colonize the new habitat during vegetation succession and thereby stabilize glacial sediments. However, so far it is not understood under which conditions plants can establish on active lateral moraine slopes, how they stabilize glacial sediments and how resulting interactions between plants and geomorphic processes shape the glacier foreland landscape. This understanding is essential to deal with changing glacier foreland landscapes under the influence of climate change. Sediment availability and sediment transport are currently increasing in glacier forelands. Resulting sediment input into reservoirs of hydropower stations limits their effectiveness, while geomorphic processes originating at steep lateral moraine slopes additionally pose natural hazards. The aim of this thesis is to enhance the understanding of feedbacks between geomorphic processes and plants in glacier forelands, especially on lateral moraine slopes, by employing a biogeomorphic approach. Biogeomorphology is a discipline at the interface of geomorphology and ecology and investigates feedbacks between geomorphic processes, landforms and ecologic and evolutionary processes. Previous biogeomorphic research at rivers and coasts demonstrated that certain species, called ecosystem engineers, strongly influence geomorphic processes and landform development. These feedbacks link geomorphic and ecologic dynamics in a biogeomorphic succession and characterize fluvial and coastal environments as biogeomorphic ecosystems.

This thesis investigates if similar biogeomorphic feedbacks occur on lateral moraine slopes and in glacier forelands, based on geomorphic and ecologic data from Turtmann glacier foreland (Switzerland). For this purpose, a hierarchical, scale-based approach is employed, which considers biogeomorphic feedbacks on different spatiotemporal scales and finally links them in a panarchy approach.

On a small scale, the dwarf shrub *Dryas octopetala* L. was identified as ecosystem engineer. Through its adapted root- and above ground biomass traits, it changes mechanical, thermal, hydrological and chemical material and surface properties. Thereby, it influences occurring geomorphic processes, facilitates species establishment and advances soil development.

SUMMARY

On an intermediate scale, ecosystem engineer establishment and impact depend on the relationship between geomorphic process frequency and magnitude and plant species resilience (regrowth after disturbances) and resistance (against disturbances). Processes with a high magnitude or frequency only allow the establishment of quickly re-growing pioneer species. Once process frequency decreases, or time between large magnitude processes is sufficient, ecosystem engineers can establish (establishment threshold). These grow more slowly than pioneers but are highly resistant. Once they reach a certain cover (engineering threshold), they start to limit water soil erosional processes and promote bound solifluction in a biogeomorphic feedback window. Biogeomorphic feedbacks cease when more competitive later successional species replace ecosystem engineers (competition threshold).

Ecosystem engineering by *D. octopetala* can produce turf-banked solifluction lobes (TBLs) as biogeomorphic structures. This process is described in a conceptual biogeomorphic model of TBL development. Engineer roots decrease slope movement and initiate risers. Behind them, fine, frost-susceptible material accumulates, amplified by sediment trapping in the dense *D. octopetala* mat structure. A lobe tread develops which is characterized by needle ice and diurnal frost creep. Once *D. octopetala* colonizes the tread, its thick organic mat reduces near-surface frost creep and promotes deeper gelifluction. Large TBLs can develop, which represent an important component of paraglacial adjustment and provide variable habitats for other species through their lobe elements.

On a long timescale, paraglacial adjustment and vegetation succession interact during biogeomorphic succession. In the geomorphic phase, dead ice melt and mass movement processes create the initial material and geomorphic setting and inhibit vegetation colonization. In the pioneer phase, gullying processes dominate and control the establishment of pioneer species with suitable response traits. Through their effect traits, ecosystem engineer species change the process regime from water soil erosional to bound solifluction processes in the biogeomorphic phase. Through feedback traits, ecosystem engineers are adapted to solifluction movement. Turf-banked solifluction lobes as biogeomorphic structures can develop, soil development advances and the establishment of later successional species is facilitated. Through competition, these exclude ecosystem engineers in the ecologic phase. Biotic interactions dominate, paraglacial adjustment is completed. On a large spatial scale, lateral moraine slopes are characterized by a mosaic of linked geomorphic and vegetation patches. Biogeomorphic succession proceeds within these patches. Large magnitude geomorphic processes and ecosystem engineering change this patch mosaic by creating new patches. Geomorphic processes from adjacent valley slopes keep these biogeomorphic patch dynamics running, even on high terrain age.

Based on these scale-related biogeomorphic feedbacks, lateral moraine slopes are identified as biogeomorphic ecosystems. Scale interactions in a panarchy of biogeomorphic feedback adaptive cycles create their structure and function.

In summary, this thesis demonstrates how scale-related biogeomorphic feedbacks control lateral moraine and glacier foreland landscape development and highlights the applicability and importance of hierarchical, scale-based approaches for biogeomorphic research.

ZUSAMMENFASSUNG

Durch den zunehmenden Rückzug von Gletschern weltweit entstehen immer größere Gletschervorfelder. Diese sehr dynamischen Umwelten werden sowohl durch geomorphologische, als auch durch ökologische Prozesse geformt und geprägt. Geomorphologische Prozesse transportieren große Mengen glazialer Sedimente im glazifluvialen Gerinne und an steilen Moränenhängen. Zeitgleich mit dieser paraglazialen Anpassung besiedeln Pflanzen den neuen Lebensraum und können dadurch Sedimente und Hänge stabilisieren. Jedoch ist bislang noch unklar, wann Pflanzen Moränenhänge besiedeln können, wodurch sie stabilisierend wirken und welche Rolle Wechselwirkungen zwischen geomorphologischen Prozessen und Formen und Vegetationsdynamik für die Landschaftsentwicklung von Gletschervorfeldern spielen. Angesichts des Klimawandels wird dieses Verständnis jedoch benötigt, um zukünftige Veränderungen der Gletschervorfeld-Landschaft abschätzen zu können. Diese können sowohl Wasserkraftwerke und -speicher, als auch Tourismus in Gletschervorfeldern beeinflussen. Zunehmend verfüllen glaziale Sedimente Stauseen, während geomorphologische Prozesse, wie Murgänge von steilen Moränenhängen, Naturgefahren darstellen.

Ziel dieser Arbeit ist es, das Verständnis von Rückkopplungen zwischen geomorphologischen Prozessen und Pflanzen in Gletschervorfeldern, insbesondere aber auf Seitenmoränen, zu verbessern. Dazu wird ein biogeomorphologischer Ansatz im Turtmanngletschervorfeld (Wallis, Schweiz) angewandt. Biogeomorphologie ist eine neue Disziplin, welche an der Schnittstelle zwischen Geomorphologie und Ökologie angesiedelt ist. Sie untersucht Rückkopplungen zwischen geomorphologischen Prozessen und Formen und ökologischen und evolutionären Prozessen. Bisherige biogeomorphologische Forschung in Flüssen und an Küsten konnte zeigen, dass bestimmte Pflanzenarten, sogenannte Ökosystemingenieure, geomorphologischen Prozesse stark beeinflussen und dadurch bestimmte geomorphologische Formen schaffen können. Diese Rückkopplungen verknüpfen ökologische und geomorphologische Landschaftsentwicklung in einer biogeomorphologischen Sukzession und kennzeichnen Flüsse und Küsten als biogeomorphologische Ökosysteme.

Die Existenz von vergleichbaren biogeomorphologischen Rückkopplungen in Gletschervorfeldern, insbesondere auf Seitenmoränen, wurde in dieser Arbeit basierend auf ökologischen und geomorphologischen Daten aus dem Turtmanngletschervorfeld überprüft. Dazu wurde ein hierarchischer, skalenbasierter Ansatz verwendet, welcher biogeomorphologische

Rückkopplungen auf verschiedenen Raum-Zeit-Skalen betrachtet und sie zum Schluss in einem skalenübergreifenden Panarchie-Ansatz zusammenführt.

Auf kleiner Raum- und kurzer Zeitskale zeigt diese Arbeit, dass auch in Gletschervorfeldern Ökosystemingenieure vorkommen und geomorphologische Prozesse wesentlich beeinflussen. Die Zwergstrauch-Art *Dryas octopetala* L. wurde als Ökosystemingenieur identifiziert, welcher durch seine angepassten Wurzel-, Blatt-, Zweig- und Stammeigenschaften mechanische, thermale, hydrologische und chemische Material- und Oberflächeneigenschaften verändert und damit die vorkommenden geomorphologischen Prozesse, die Ansiedlung von weiteren Arten und die Bodenentwicklung beeinflusst.

Die Ansiedlung und die Einwirkung von Ökosystemingenieuren wird auf einer mittleren Raum- und Zeitskale von der Beziehung zwischen Frequenz und Magnitude von geomorphologischen Prozessen und Resilienz (Wiederbesiedlungsgeschwindigkeit nach Störungen) sowie Resistenz (Widerstand gegen Störungen) der vorkommenden Arten bestimmt. Prozesse mit hoher Magnitude, wie Schneelawinen oder Murgänge, oder Prozesse mit hoher Frequenz, wie hangaquatische Prozesse, lassen lediglich die Ansiedlung schnell nachwachsender Pionierarten zu. Nimmt die Prozessfrequenz ab, oder ist der Abstand zwischen Prozessen mit hoher Magnitude ausreichend groß, können sich Ökosystemingenieurarten ansiedeln (Ansiedlungsschwellenwert). Diese brauchen länger zum Wachsen, sind aber sehr resistent gegenüber geomorphologischen Prozessen. Erreichen sie eine bestimmte Größe oder Bedeckungsgrad (Ingenieurtätigkeitsschwellenwert), limitieren sie das Auftreten von hangaquatischen Prozessen und fördern gebundene Solifluktion in einem biogeomorphologischen Rückkopplungsfenster („biogeomorphic feedback window“). Biogeomorphologische Rückkopplungen erlahmen wenn Ökosystemingenieure durch konkurrenzstärkere Strauch- und Baumarten verdrängt werden (Konkurrenzschwellenwert).

Wie Ökosystemingenieure zur Entstehung von gebundenen Solifluktionsloben beitragen, wird in einem konzeptionellen biogeomorphologischen Modell der Solifluktionslobenentwicklung beschrieben. *D. octopetalas* Wurzeln erhöhen lokal die Hangstabilität, die Hangbewegung verlangsamt sich und eine initiale Lobenkante („riser“) kann entstehen. Hinter dieser wird weiteres Material durch Hangprozesse abgelagert und formt den Lobenkörper („tread”). Dies wird gefördert durch die dichte *Dryas*-Matte, in welcher sich frostempfindliches Feinsediment ansammelt, während auf dem vegetationsfreien Lobenkörper Kammeis- und Frostkriechprozesse dominieren. Wenn im Laufe der Zeit der Lobenkörper komplett von *D. octopetala* bedeckt wird,

verändert ihre mächtige organische Matte die thermalen Untergrundeigenschaften und begünstigt dadurch die Entstehung von Eislinsen. Gelifluktion mit hohen Porenwasserdrücken tritt vermehrt auf, große Solifluktionsloben entstehen. Diese stellen eine wichtige Form der paraglazialen Anpassung dar und bieten mit ihren Formelementen Lobenkante, Lobenkörper und einem Lobenrücken anderen Pflanzenarten ein abwechslungsreiches Habitat. Deshalb sind gebundene Solifluktionsloben biogeomorphologische Strukturen.

Auf einer langen Zeitskala interagieren paraglaziale Anpassung und Vegetationssukzession in einer biogeomorphologischen Sukzession. Nach Gletscherrückzug dominieren das Ausschmelzen von Toteis und die damit verbundenen geomorphologischen Prozesse, wie Schuttrutschungen und Murgänge, in einer geomorphologischen Phase und verhindern die Besiedlung durch Pflanzen. Nach Ausschmelzen des Toteises können sich Pionierarten, meist Kräuter ansiedeln, welche an die in dieser Pionier-Phase auftretenden Murgänge und hangaquatischen Prozesse („Gullying“) durch Respons-Eigenschaften („response traits”) angepasst sind. Mit der Ansiedlung und dem Einwirken von Ökosystemingenieurarten durch ihre Effekt-Eigenschaften („effect traits”) beginnen gebundene Solifluktionsprozesse in der biogeomorphologischen Phase zu dominieren, gebundene Solifluktionsloben entstehen. Durch Rückkopplungseigenschaften („feedback traits”), wie flexibles Wurzelwachstum, sind Ökosystemingenieure an diese Prozesse angepasst. Mit zunehmender Hangstabilisierung und Bodenentwicklung, gefördert durch die Ökosystemingenieure, können sich Spätbesiedler wie Strauch- und Baumarten ansiedeln. In der ökologischen Phase können diese Ökosystemingenieure verdrängen. Biotische Interaktionen dominieren, geomorphologische Prozesse treten nicht mehr auf und die paraglaziale Anpassung ist abgeschlossen.

In einer großen Raumskala zeigt der Seitenmoränenhang ein gekoppeltes geomorphologisches und Vegetationsmosaik, welches nahezu unabhängig vom Geländealter ist. Dieses Mosaik setzt sich aus sogenannten Flecken („patches”) zusammen, in welchen die beschriebene biogeomorphologische Sukzession abläuft. Veränderungen des Mosaiks entstehen durch geomorphologische Prozesse wie Murgänge und Schneelawinen, welche neue Flecken schaffen, oder durch die flächenhafte Ausbreitung von Ökosystemingenieurarten. Diese biogeomorphologische Fleckendynamik („biogeomorphic patch dynamics“) hängt besonders von Hangtoposequenzposition der Flecken sowie vom Moränentyp ab. Biogeomorphologische Sukzession und Fleckendynamik bestimmen sowohl Ökosystementwicklung als auch paraglaziale Anpassung von Seitenmoränen.

Biogeomorphologische Rückkopplungen auf verschiedenen Skalen folgen adaptiven Zyklen, welche in einem Panarchie-Ansatz verbunden werden können. Interaktionen zwischen den Skalen bestimmen die Struktur und Funktion des biogeomorphologischen Ökosystems („biogeomorphic ecosystem“) Seitenmoräne.

Diese Arbeit zeigt auf, wie skalenbezogene biogeomorphologische Rückkopplungen die Landschaftsentwicklung in Gletschervorfeldern, insbesondere auf Seitenmoränen, beeinflussen können und hebt die Bedeutung von hierarchischen, skalenbasierten Ansätzen für die biogeomorphologische Forschung hervor.

LIST OF PUBLICATIONS

1. **Eichel, J.** (minor revisions): Vegetation succession and biogeomorphic interactions in glacier forelands. In: Heckmann, T. & D. Morche (eds): Geomorphology of proglacial systems - Landform and sediment dynamics in recently deglaciated alpine landscapes. [Section 2.4]
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5. **Eichel, J.**, Krautblatter, M., Schmidtlein, S.and R. Dikau (2013): Biogeomorphic interactions in the Turtmann glacier forefield, Switzerland. In: Geomorphology 201, p. 98 - 110. doi:10.1016/j.geomorph.2013.06.012 [Chapter 7]

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Term	**Explanation**	**Reference(s)**
Adaptive cycle	Model of internal cyclic dynamics of a system with four phases (exploitation, conservation, release, reorganization)	Holling, 1973; Holling and Gunderson, 2002
Biogeomorphic ecosystem	Ecosystems in which interactions between biota and geomorphology determine ecosystem structure and functioning	Balke, 2013; Corenblit et al., 2015
Biogeomorphic ecosystem engineering	Ecosystem engineering which affects geomorphic processes and landforms	Phillips, 2016
Biogeomorphic feedback window	Conditions in which biogeomorphic feedbacks can occur on lateral moraine slopes, depending on the relationship between process magnitude and frequency and plant species resilience and resistance	Eichel et al., 2016
Biogeomorphic structure/unit	Landform created by ecosystem engineering with abiotic, residual and/or functional components for engineer/non-engineer species	Corenblit et al., 2010, 2016
Biogeomorphic succession	Dominance of physical (geomorphic) and biotic (vegetation) processes and their interactions changes during four phases within a successional timescale	Corenblit et al. 2007, 2009
Biogeomorphic transient form ratio	Conditions for the occurrence of biogeomorphic structures, depending on the relationship between organism adaptations to geomorphic disturbances, disturbance level and sediment supply	Corenblit et al., 2011; Phillips, 1999
Biogeomorphology	Studies on linkages between ecology and geomorphology; compare 'feedback biogeomorphology' for usage in this study	Viles, 2003
Complexity	Property of a system resulting from a high number of system elements and their feedbacks and interactions. Complexity is increasing with increasing numbers of elements and interactions/feedbacks.	Elverfeldt, 2012
Debris flow	Mixture of fines, larger sediment and water moving downslope in a Bingham flow, triggered by intensive rainfall or rapid snowmelt	Dikau, 2003; Hungr, 2005; Iverson, 2005
Disturbance	Destructive events that disrupt ecosystem, community or population structure, irrespective of if they are normal for the system or not	Pickett and White, 1987
Disturbance regime	Temporal and spatial disturbance dynamics over a longer time period	Turner et al., 2001
Ecosystem	System comprising populations, communities, physical environment and their interactions	Odum, 1953; Tansley, 1935

Ecosystem engineer	Organisms that directly or indirectly change the physical state of biotic or abiotic materials, thereby modulate the availability of resources to other species and modify, maintain and create habitats	Jones et al., 1994
Ecosystem engineering	Process of environmental modification and creation or maintenance of habitats by organisms	Jones et al., 1994; Jones, 2012
Ecosystem function	Collective life activities of organisms and their interactions with environmental conditions in ecological systems, sustained by overall system processes	Jax, 2005
Ecosystem structure	Network of ecosystem components and their interactions	Golley, 2000
Effect trait	Any trait by which a plant can influence environmental conditions, e.g. the occurrence of geomorphic processes, community or ecosystem properties	Corenblit et al., 2015; Violle et al., 2007
Emergence	Emergence is the development of new structures and patterns at higher scales, which cannot be explained by principles or knowledge from smaller scales	Dikau, 2006; Harrison, 2001
Feedback biogeomorphology	The study of feedbacks between Earth surface processes and landforms, and organisms and ecological and evolutionary processes	Corenblit et al., 2011, this thesis
Feedback trait	Any trait that can responds to changes the engineer induced in the environment	Corenblit et al., 2015
Geomorphic system	System consisting of landforms and landform properties, processes and process properties, material and material properties and functional relationships between these components	Ahnert, 1998; Chorley and Kennedy, 1971
Geomorphometry	Science of topographic quantification, term 'geomorphometric' used in this thesis used to denote the sum of topographic properties (height, area, slope gradient, curvature, aspect) of a landform	Pike et al., 2009; Schmidt and Dikau, 1999
Glacier foreland	Proglacial area in front of a glacier, which has been exposed since the Little Ice Age and comprises the glaciofluvial and lateral and terminal moraines subsystems, synonymous with glacier forefield	Kinzl, 1929; Matthews, 1992
Gullying	Combination of debris flow and soil erosional processes producing gully landforms on lateral moraine slopes	Curry et al., 2006; Jäger and Winkler, 2012
Hierarchy theory	Considers three scale-related levels with their holons and relationships in a hierarchy to deal with complex systems	O’Neill et al., 1986
Holon	System viewed in its scale context	O’Neill et al., 1986

Hysteresis	A single value of an independent variable (e.g. discharge) can be associated with two or more values of an independent variable (e.g. sediment transport)	Phillips, 2003
Landform	Feature related to geomorphic process or process complex, characterized by specific geomorphometry and made of by landform elements	Pike et al. 2009
Landsliding	Downward movement of slope material resulting from a failure along a well-defined shear plane	Dikau, 2003
Lateral moraine	Glacial landform produced by sediment deposition or deformation along the lateral margins of a glacier	Knight, 2003; Small, 1983
Level	Rank within hierarchy	O'Neill et al., 1986
Mass movement processes	Downward and outward movement of slope material under the influence of gravity	Dikau, 2003
Niche construction	Environmental modification of abiotic and biotic properties by organisms	Odling-Smee et al., 2003, 2013
Non-linearity	System output is not proportional to input, e.g. due to thresholds, positive feedbacks, hysteresis	Phillips, 2003
Panarchy	Conceptual framework that describes a hierarchical system of adaptive cycles and their interactions	Holling, 2001; Holling et al., 2002
Paraglacial	Processes, sediment accumulations, landforms, landsystems and landscapes conditioned by glaciation and deglaciation	Ballantyne, 2002; Church and Ryder, 1972
Patch	Surface area that differs from its surroundings in structure and function, e.g. species composition and habitat properties	Lovett et al., 2007; Watt, 1947
Patch dynamics	Changes of the patch mosaic in time due to disturbance and internal patch succession	Pickett & White, 1987; Pickett et al., 1999
Path dependency	Time-dependent development of systems configuration along trajectories that can strongly depend on initial conditions	Dikau, 2006; Verleysdonk et al., 2011
Periglacial processes	Cold non-glacial processes , often associated with freeze-thaw activity	French, 2007
Plant functional trait	Any morphological, physiological or phenological feature of the plant individual, which determines its fitness by affecting its growth, reproduction and survival	Violle et al., 2007

Resilience	Reaction of a system towards a disturbance; either (i) the resistance of the system to disturbance and speed to return to equilibrium after disturbance (engineering resilience; applicable for equilibrium systems) or (ii) the capacity of the system to absorb or withstand disturbance while maintaining state of system in terms of structural and functional integrity (in non-equilibrium systems)	Holling, 1973, Gunderson and Holling, 2002
Response trait	Any trait whose value varies in response to environmental conditions, e.g. occurring geomorphic processes, and thereby enhances dispersal, establishment and survival	Corenblit et al., 2015, Violle et al., 2007
Scale	Physical spatial or temporal dimension of an object or process, characterized by both extent (total dimensions) and grain/resolution (subintervals)	Turner et al., 2001; Wu, 1999
Self-organization	Formation of patterns or structures from internal system dynamics, independent of external impact	Phillips, 2003
Solifluction	Slow downslope movement of soil mass resulting from freeze-thaw processes (needle-ice creep, diurnal and annual frost creep and gelifluction)	Matsuoka 2001
Threshold	The point at which the behaviour of a system changes	Phillips, 2003
Toposequence (Slope)	Arrangement of hillslope units (upper slope, midslope, lower slope) within the hillslope	Dikau et al., 2003
Vegetation succession	Gradual, directional change in the species composition and structure of ecosystems over a longer period of time	Dierschke, 1994; Matthews, 1992
Water soil erosional processes	Processes eroding slope material by running water, including slope wash, sheet erosion, interrill erosion, rill erosion and gully erosion, excluding fluvial processes	Fullen and Catt, 2003
Windows of Opportunity	Time windows in which pioneers can colonize active environments, depending on the relation between pioneer dispersal, growth and disturbance occurrence.	Balke et al. 2013, 2014

1 INTRODUCTION AND MOTIVATION

> *'The key factor mediating landscape response to climate change is variability in biological and physical processes' (Reinhardt et al., 2010, p. 88)*

Retreating glaciers expose new terrain, characterized by bare, unstable sediments, at their fronts. These glacier foreland areas are highly dynamic, as their geomorphic and ecologic systems are in disequilibrium with the new, non-glacial conditions (Ballantyne, 2002a; Haeberli et al., 2016; Matthews, 1992). Intensive geomorphic processes rework the new sediments during a period of paraglacial adjustment (Ballantyne, 2002a), with highest geomorphic activity in the glaciofluvial floodplain and at steep lateral moraine slopes (Carrivick et al., 2013; Irvine-Fynn et al., 2011). At the same time, plants colonizes the bare sediments with changing species compositions during vegetation succession (Erschbamer et al., 2008; Matthews, 1992). A new ecosystem develops (Milner et al., 2007; Schaaf et al., 2011).

Glacier foreland areas are currently strongly expanding. Due to globally rising temperatures, glaciers are retreating worldwide and could completely and permanently disappear within the coming decades or centuries (Ganopolski et al., 2016; Radić et al., 2013; Stokes et al., 2013; Zemp et al., 2006). Resulting extended glacier foreland areas offer a high potential for human utilization, e.g. through hydropower stations, often benefitting from natural glacier bed overdeepenings (Haeberli et al., 2016; Linsbauer et al., 2012). Their reservoirs are also important means to mitigate water problems in lowland regions that result from decreasing glacial water storage (Farinotti et al., 2016; Viviroli et al., 2011). However, increasing sediment export from the deglaciating terrain limits hydropower station effectiveness and reservoir capacity (Lane et al., 2016; Micheletti and Lane, 2016; Raymond Pralong et al., 2011). In addition, geomorphic processes originating at instable lateral moraine slopes, such as debris flows, increasingly pose a natural hazard in foreland areas (Deline et al., 2015; Haeberli and Whiteman, 2015; Kääb et al., 2005).

To deal with these problems, we need to understand how glacier foreland landscapes develop in future. This development strongly depends on coupled geomorphic and ecologic dynamics (Haeberli et al., 2016; Reinhardt et al., 2010). Yet, despite a long history of geomorphic and ecologic research in glacier forelands, feedbacks between geomorphic and vegetation dynamics are not well understood. It has been suggested that plant colonization stabilizes glacier foreland sediments (Ballantyne, 2002a; Matthews et al., 1998). However, it is not known under which conditions plants can establish, especially on highly active lateral moraine slopes (Curry et al., 2006), and if some plant species are more effective in stabilizing sediments than others. In addition, how paraglacial adjustment and vegetation succession interact in space and time, and thereby affect sediment dynamics and ecosystem development in glacier forelands, is unknown.

These knowledge gaps can be attributed to the unidirectional nature of many previous geomorphic and ecologic studies. While geomorphologists often neglected the role of plants and their dynamics for geomorphic processes, ecologists often disregarded that the terrain colonized by plants is dynamic due to occurring geomorphic processes (but see Haugland, 2006; Matthews, 1999 and Moreau et al., 2008 for notable exceptions).

New biogeomorphic approaches can overcome these unidirectional views and enable a holistic landscape understanding. Biogeomorphology is a discipline at the interface of geomorphology and ecology that investigates feedbacks between geomorphic processes and landforms and ecologic and evolutionary processes (Viles, 2004; Corenblit et al, 2011). The importance of biogeomorphic feedbacks for landscape development was recently demonstrated in fluvial and coastal environments (Balke et al., 2014; Corenblit et al., 2015; Gurnell et al., 2012; Stallins, 2005). Biogeomorphic research found that certain plants, called ecosystem engineers, actively change geomorphic processes and resulting landforms (Balke et al., 2012; Corenblit et al., 2016; Gurnell, 2014). These small scale biogeomorphic feedbacks are linked to larger scale geomorphic and vegetation patterns by strong scale interactions (Gurnell, 2014; Stallins, 2006). In time, geomorphic and ecologic dynamics are closely linked during biogeomorphic succession (Balke, 2013; Corenblit et al., 2007; Kim, 2012). As biogeomorphic feedbacks create ecosystem structure and function in many fluvial and coastal environments, these environments have been identified as biogeomorphic ecosystems (BEs) (Balke 2013; Corenblit et al., 2015). Prior to this thesis, no previous study had explicitly investigated biogeomorphic feedbacks in glacier forelands. Yet, it is very likely that strong biogeomorphic feedbacks exist here, as unfavourable climatic conditions and geomorphically active terrain will require plants to adapt and enhance their survival by affecting their environment (Corenblit et al., 2015; Viles, 2004). Thus, biogeomorphic research in glacier forelands is very rewarding, as it can not only improve the understanding of future landscape dynamics but also advance the comprehension of biogeomorphic feedbacks in general.

This thesis represents a first biogeomorphic approach to glacier forelands, with a focus on lateral moraine slopes in the Turtmann glacier foreland (Switzerland). It combines geomorphic and ecologic knowledge and approaches from previous glacier foreland research with new biogeomorphic concepts in a hierarchical, scale-based approach. Thereby, biogeomorphic feedbacks can be assessed on different scales and subsequently linked to improve the overall understanding of biogeomorphic dynamics on lateral moraine slopes and in glacier forelands.

A state-of-the-art overview on biogeomorphology and geomorphic and ecologic dynamics in glacier forelands follows this introduction in Chapter 2, providing the most relevant background information for ecologist, geomorphologists and biogeomorphologist alike. The chapter starts with a general overview on biogeomorphology and its historical evolution and trajectory (Section 2.1), followed by a presentation of key biogeomorphic concepts (Section 2.2). Scale concepts and approaches from geomorphology, ecology and biogeomorphology are subsequently summarized (Section 2.3) and an overview on geomorphic and vegetation dynamics in glacier forelands is provided (Sections 2.4, 2.5). Based on these previous sections, research gaps concerning biogeomorphic dynamics in glacier forelands are identified in Section 2.6. How these research gaps are addressed using a hierarchical, scale-based approach is demonstrated in Chapter 3. Subsequent chapters 4 to 8 present thesis results according to their spatiotemporal scale, based on publication manuscripts (except Chapter 8). In Chapter 4, the dwarf shrub *Dryas octopetala* L. is identified as a small scale ecosystem engineer species. Conditions for biogeomorphic feedbacks on an intermediate scale are subsequently determined in a biogeomorphic feedback window concept. Chapter 5 presents results from a detailed biogeomorphic survey of a turf-banked solifluction lobe, which demonstrates how interactions between material, soil moisture and vegetation influence solifluction lobe development during paraglacial adjustment. How the ecosystem engineer *D. octopetala* can initiate and promote the development of turf-banked solifluction lobes as biogeomorphic structures is laid out in detail in Chapter 6. Chapter 7 provides an overview on biogeomorphic feedbacks in the entire glacier foreland on a large scale, demonstrating that paraglacial adjustment and vegetation succession can be decoupled from terrain age and follow a biogeomorphic succession. Chapter 8 provides a more detailed description of biogeomorphic succession on lateral moraine slopes by linking it to paraglacial adjustment and vegetation succession on a longer timescale. Spatial patterns of paraglacial adjustment and vegetation succession and their changes in time are subsequently addressed in the concept of biogeomorphic patch dynamics. Chapter 9 provides a synthetic reflection on the identified scale-related feedbacks (Section 9.1) and identifies lateral moraine slopes as biogeomorphic ecosystems (Section 9.2). Subsequently, it suggests how interactions between biogeomorphic feedback adaptive cycles in three scales can create lateral moraine BE structure and functioning (Section 9.3). Limitations and shortcomings of this thesis are discussed in Section

9.4. Chapter 10 concludes on the thesis objectives and summarizes key findings. In addition, it also provides an outlook on future biogeomorphic research.

To facilitate the understanding of this thesis, a glossary explaining key terms from geomorphology, ecology, systems theory and biogeomorphology is provided prior to this introduction. The appendix includes a list of species occurring at the moraine slopes and large format geomorphic, material and vegetation maps.

2 BIOGEOMORPHOLOGY: INTEGRATING GEOMORPHIC AND VEGETATION DYNAMICS IN GLACIER FORELANDS

‚It is almost a truism to point out that ecological and geomorphological systems interact’ (Stallins, 2006, p. 208)

This chapter provides a state-of-the-art review on biogeomorphology in general and on geomorphic and vegetation dynamics and biogeomorphic interactions in glacier forelands. In the first two sections (2.1, 2.2), it depicts the ‘trajectory of biogeomorphology’, summarizing the foundations of current biogeomorphic research based on previous geomorphic, ecologic and joint approaches. Thereby, a background for this thesis is provided and the thesis is positioned into current biogeomorphic research. Key biogeomorphic concepts, on which this thesis builds, are presented. In Section 2.3, the importance of scale approaches in both geomorphology and ecology is highlighted and key scale concepts are presented, which constitute the framework for this thesis. Subsequently, an overview on geomorphic dynamics in glacier forelands is given, which focuses on the paraglacial adjustment of lateral moraine slopes. The main approaches and mechanisms of vegetation succession in glacier forelands are discussed in Section 2.5, including a first case study overview on biogeomorphic interactions on lateral moraine slopes. The last section (2.6) summarizes main five research needs concerning biogeomorphic dynamics in glacier forelands and on lateral moraine slopes, which are targeted in this thesis.

2 BIOGEOMORPHOLOGY

2.1 The trajectory of biogeomorphology – where we come from

Generally speaking, biogeomorphology studies interactions between geomorphic and ecologic systems. Though biogeomorphology was formally defined and named as a discipline only in the 1980s, studies linking geomorphology and ecology – both implicitly and explicitly – date back as early as the 17th and 18th centuries, especially to the end of the 19th century. Their numbers were growing strongly in the last two decades. This history of biogeomorphology provides the foundation for this thesis and will be briefly outlined in this section, presenting the origins and early development of biogeomorphology, the ‚birth of biogeomorphology' in 1988 and recent developments in the 1990s and 2000s (Figure 2.1).

2.1.1 Joint foundations and early ideas

First ideas on relationships between vegetation and topography, earth processes and material were already proposed by Darwin (1769 – 1859) and Humboldt (1808 – 1882). However, in this time, and also later, climate was seen as the most important factor influencing vegetation (Marston, 2010). Early studies on landscape shape in geomorphology and interactions between organisms and environments in ecology were mainly descriptive. Often, they were disregarding either the biotic components of the Earth surface (geomorphic studies) or Earth surface dynamics (ecologic studies) (Marston, 2010; Renschler et al., 2007). Notable exceptions studying both plants and geomorphic processes and landforms in this time were Gilbert (1877) and Cowles (1899, 1901) (Figure 2.1). In his work in on landscape development in the Henry Mountains (USA), Gilbert (1877) already considered the role of vegetation for weathering, local hydrological cycle and the retardation of erosion by splash and overland flow. Cowles (1899, 1901) even went further in the first truly biogeomorphic studies, in which he jointly investigated vegetation and landforms dynamics at Lake Michigan and around Chicago (USA). He showed that feedback loops exist between vegetation dynamics and dune development, linked specific species compositions to specific landforms and suggested that vegetation and landform changes occur simultaneously. In the process, he proposed the concept of vegetation succession, as well as the concept of a successional order of landform development.

Although the disciplines did not overlap much in their content for the next decades following these pioneering biogeomorphic studies, the concepts proposed by Cowles were taken up by later ecologists and geomorphologists. A deterministic, time-dependent development of vegetation succession towards a climax was proposed by Clements (1916), while Davis (1899) described landform development in a 'geographical cycle' linked to fluvial erosion (Figure 2.1).

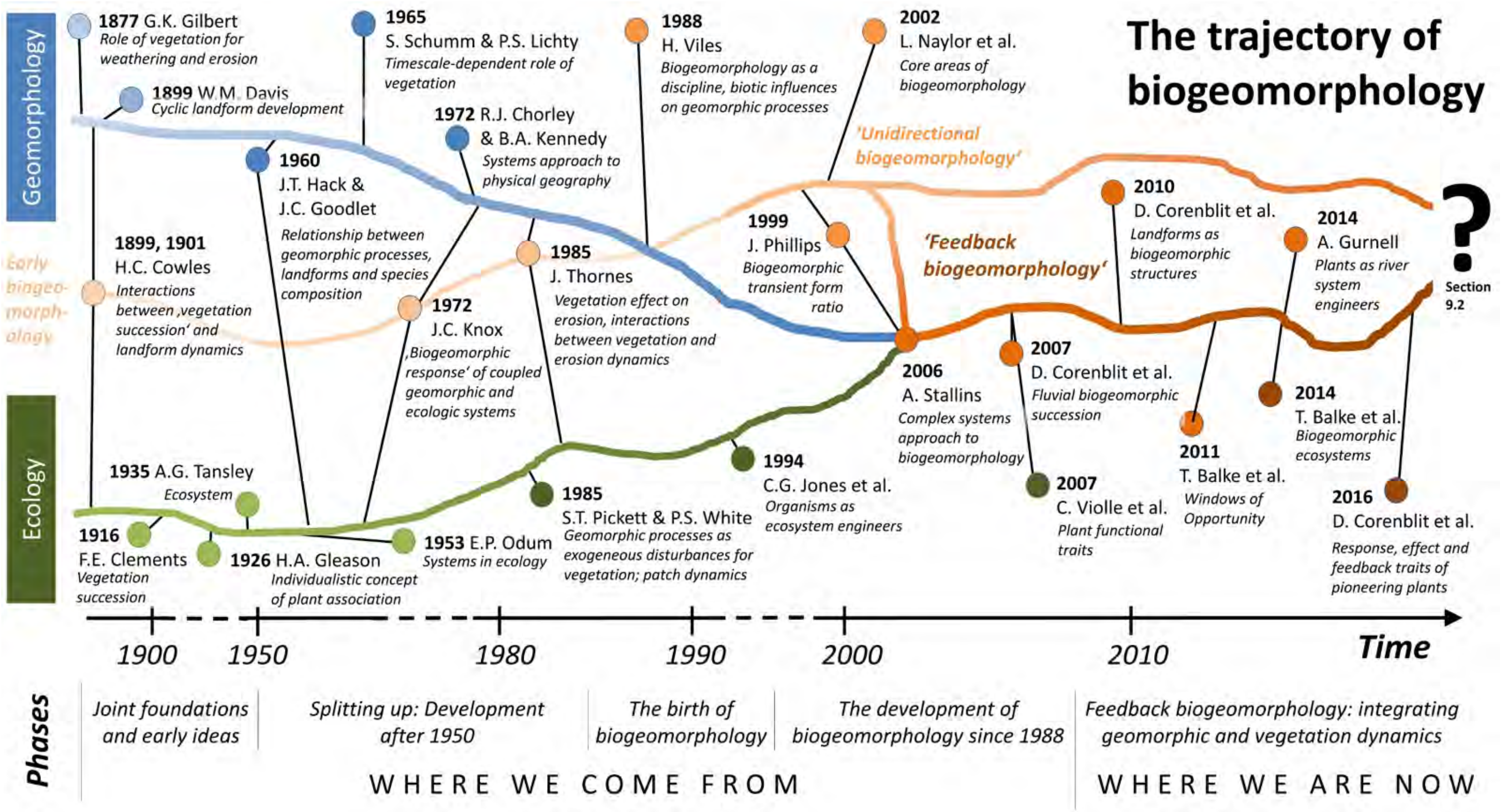

Figure 2.1: The trajectory of biogeomorphology, summarizing the development of biogeomorphology from early approaches to unidirectional and feedback ecology and highlighting the most important contributions. Sections 2.1 and 2.2 follow the indicated phases.

Both concepts were criticized later, e.g. by Penck (1924) and Gleason (1926). They pointed out the unlikeliness of an ‘endpoint’ (climax) of both landscape and vegetation development, as erosion and uplift occur simultaneously during landscape development (Penck, 1924), while the individual behaviour of plants limits re-occurring associations during vegetation development (Gleason, 1926).

In this time of unidirectional thinking, the development of the ecosystem concept by Tansley (1935) is also a noteworthy approach from a biogeomorphic viewpoint. In contrast to previous studies, this approach considers ,the whole system (in the sense of physics), including not only the organism-complex, but also the whole complex of physical factors forming what we call the environment of the biome’. Thus, Tansley’s ecosystem concept implicitly integrates geomorphic dynamics into the study of the biotic environment.

2.1.2 Splitting up: Development after 1950

In the mid 20th century, following the two world wars, discipline boundaries sharpened and very few studies were conducted across them (Hupp et al., 1995). As Osterkamp and Hupp (2010, p. 247) stated, ‘a gulf generally separated the substantive study of physical and biological systems’. From a geomorphic point of view, this can probably be attributed to the paradigm shift in geomorphology in this time towards quantification of processes and modelling (Marston, 2010; Renschler et al., 2007). In order to quantify geomorphic processes, studies needed to be simplified and additional factors complicating things, such as vegetation, were simply taken out (Osterkamp and Hupp, 2010). At the same time, ecology split up into a theoretical, community-based approach, which focusses on species in their communities, and into a process ecology approach, which focuses on the dynamics of ecosystems (Renschler et al., 2007). Although geomorphic dynamics necessarily form a part of ecosystem dynamics, geomorphologists were not contributing to an ecosystem understanding. In turn, ecology treated landforms as static. However, the development of system theory (Bertalanffy, 1950) in this time provided a common ground for both disciplines and was taken up into ecology by Odum (1953) for his ecosystem concept and by Chorley and Kennedy (1971) into physical geography and geomorphology for the classification of geomorphic systems (Figure 2.1).

Yet, the disciplinary gap was also bridged in this time by some atypical studies which considered the role of vegetation for landscape development (Schumm and Lichty, 1965), the role of geomorphic processes for vegetation dynamics (Pickett and White, 1987) or even geomorphic processes and landforms and vegetation jointly (Hack and Goodlett, 1960; Knox, 1972; Thornes, 1985) (Figure 2.1).

Schumm and Lichty (1965) evaluated how the role of factors influencing landscape development changes depending on the considered timescale. They found vegetation to be dependent on climate and lithology over geological (cyclic) timescales of thousands to millions of years, but to be independent in modern (graded; centuries to millennia) and present time (steady; one year or less). On this timescale, it influences the hydrology and erosion in a drainage basin.

In their conceptual patch dynamics approach to spatiotemporal vegetation dynamics and their drivers, Pickett and White (1985) identified geomorphic processes, such as landslides and periglacial processes as exogenous disturbances for vegetation. Linked with the magnitude-frequency concept in geomorphology (Wolman and Miller, 1960), they differentiated the impact of geomorphic processes on vegetation according to process specific frequency, intensity and severity.

On the way to link geomorphology and vegetation, the study by Hack & Goodlett (1960) on geomorphology and forest ecology in the Appalachian Mountains can be considered a ‚benchmark effort’ (Marston, 2010, p. 208). It shows that geomorphic processes, landforms, vegetation patterns and species composition are closely related on hillslopes. For example, they found that different groundwater flow paths, related to hillslope geomorphometry, correspond with different forest communities.

For the first time, the term ‘biogeomorphic’ was utilized in a study by Knox (1972), who investigated the relationship between vegetation, run off and fluvial processes in a watershed. He developed a conceptual model of ‚biogeomorphic response’ of the coupled geomorphic and vegetation system to abrupt changes in climate regimes. This model describes how relative vegetation cover, relative hillslope potential for erosion and relative geomorphic work (e.g. sediment yield) are linked and depend on climate.

A further main foundation of biogeomorphology was laid by Thornes (1985). In his monograph ‘The ecology of erosion’, he did not only summarize previous unidirectional approaches to vegetation effects on soil erosion, but already highlighted their limitations and provided a first approach on vegetation and erosion interactions and dynamics.

2.1.3 The birth of biogeomorphology

The term and discipline ‘biogeomorphology’ was born in 1988 when Heather Viles published the edited volume ‘Biogeomorphology’ (Figure 2.1). In her introduction, she defines biogeomorphology as an ‚approach to geomorphology, which considers the role of organisms’, (Viles, 1988, p. 1). The subsequent chapters summarize previous unidirectional approaches on the role of organisms for geomorphology in a variety of environments. Interestingly, this approach was not well received in the beginning. Cox (1989) criticized that biogeomorphology was making ‚mountains out of molehills’ (referring to the the often small scale focus of several chapters, e.g. on earthworms) and declared that although ‚much of biogeomorphology is obviously fun, it is not so obviously fundamental’. Nevertheless, research linking geomorphology and ecology gained foot under the new term in the next decades.

2.1.4 The development of biogeomorphology since 1988

An idea of the development of biogeomorphic research since 1988 can be attained by from the growing numbers of publications on biogeomorphology and its related term ecogeomorphology (see section below). First publications on biogeomorphology in ISI-indexed journals appeared in 1990 (Figure 2.2 A), and, in relation to all publications on geomorphology (Figure 2.2 B), they made up nearly ten percent. It has to be noted that although the total number of publications in this field strongly increased from 1990 (5 ‘biogeomorphic’, 0 ‘ecogeomorphic’) to today (35 ‘biogeomorphic’ and 9 ‘ecogeomorphic’ publications in 2015), its total share in all publications on geomorphology did not rise that much. As the number of publications on geomorphology also strongly increased since 2005 (Figure 2.2 B), the total share did not increase much since 2010 and is constantly around 4% for ‘biogeomorphic’ publications and 1.5 % for ‘ecogeomorphic’ publications (Figure 2.2 C). In addition, we have to be aware that a lot of biogeomorphic research is not necessary labelled as biogeomorphic (Naylor et al., 2002), and therefore not represented in Figure 2.2.

Inside the terminology jungle: what is biogeomorphology?

With increasing biogeomorphic research, the discipline diversified and a kind of ‘terminological confusion’ developed, as more and more sub-disciplines or disciplines with a different focus were established (Haubold and Lehr, 2009; Naylor et al., 2002). These include the sub-disciplines zoogeomorphology and phytogeomorphology and the new discipline ecogeomorphology. While zoogeomorphology has established well as a sub-discipline of biogeomorphology dealing with the effects of animals on geomorphic processes (Butler, 1992, 1995), the term ‘phytogeomorphology’

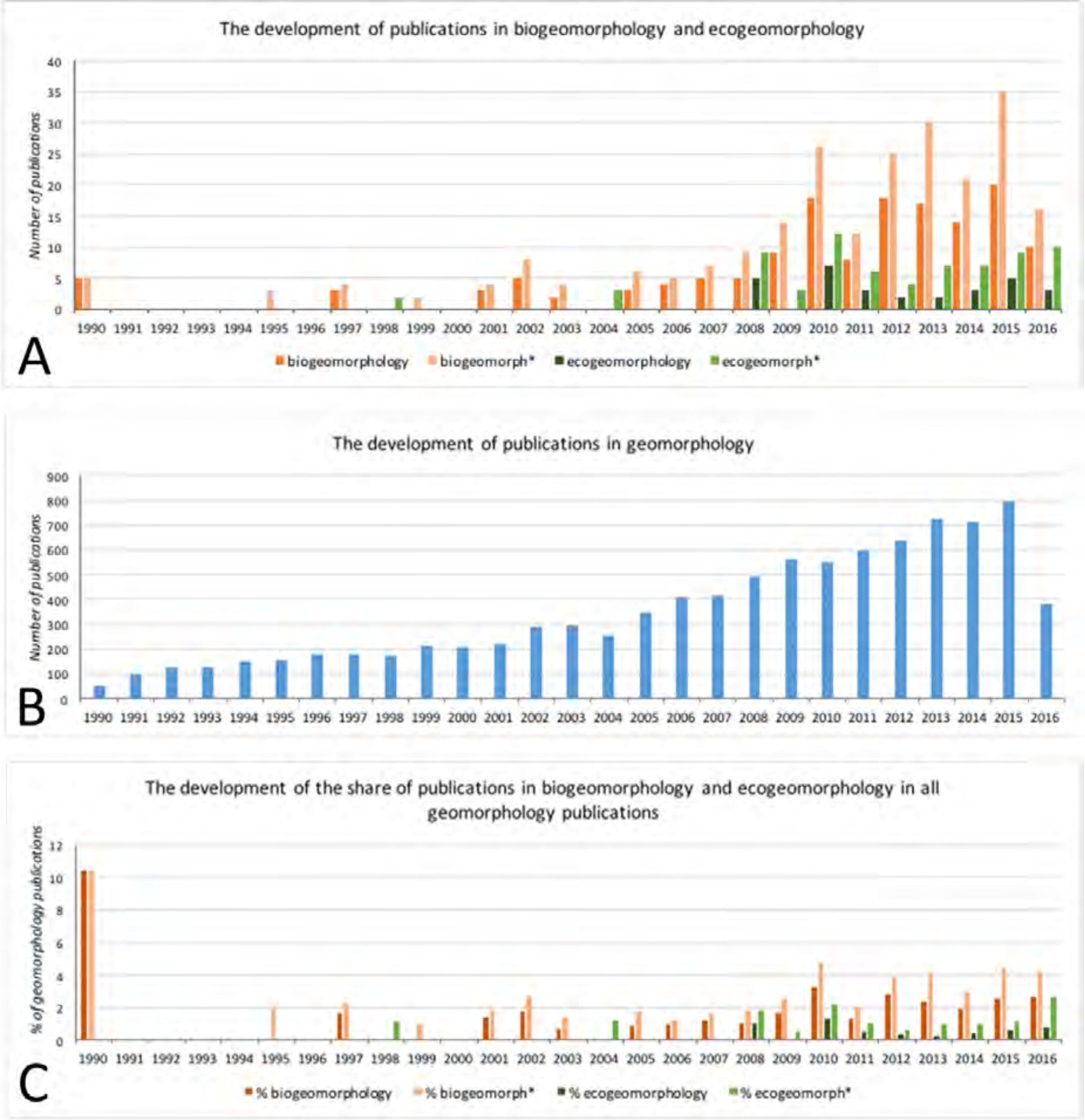

Figure 2.2: Development of publications in biogeomorphology, based on topic search in ISI Web of Knowledge using indicated search terms. **A** Increasing numbers of publications on ‚biogeomorphology' and ‚ecogeomorphology' from 1990 to 2016, including ‚biogeomorph'-ic and ‚ecogeomorph'-ic research. **B** Increasing number of publications per year on ‚geomorphology' from 1990 to 2016. **C** Share of ‚biogeomorphology', ‚ecogeomorphology', ‚biogeomorph'-ic and ‚ecogeomorph'-ic publications in all geomorphology publications from 1990 to 2016. Date: 15.07.2016.

is not unambiguously used. It can describe either the interrelationships between plants, landforms and geomorphological processes, first used in relation to remote sensing (Howard and Mitchell, 1985), or be seen as synonymous with ecogeomorphology (Wheaton et al., 2011). The term

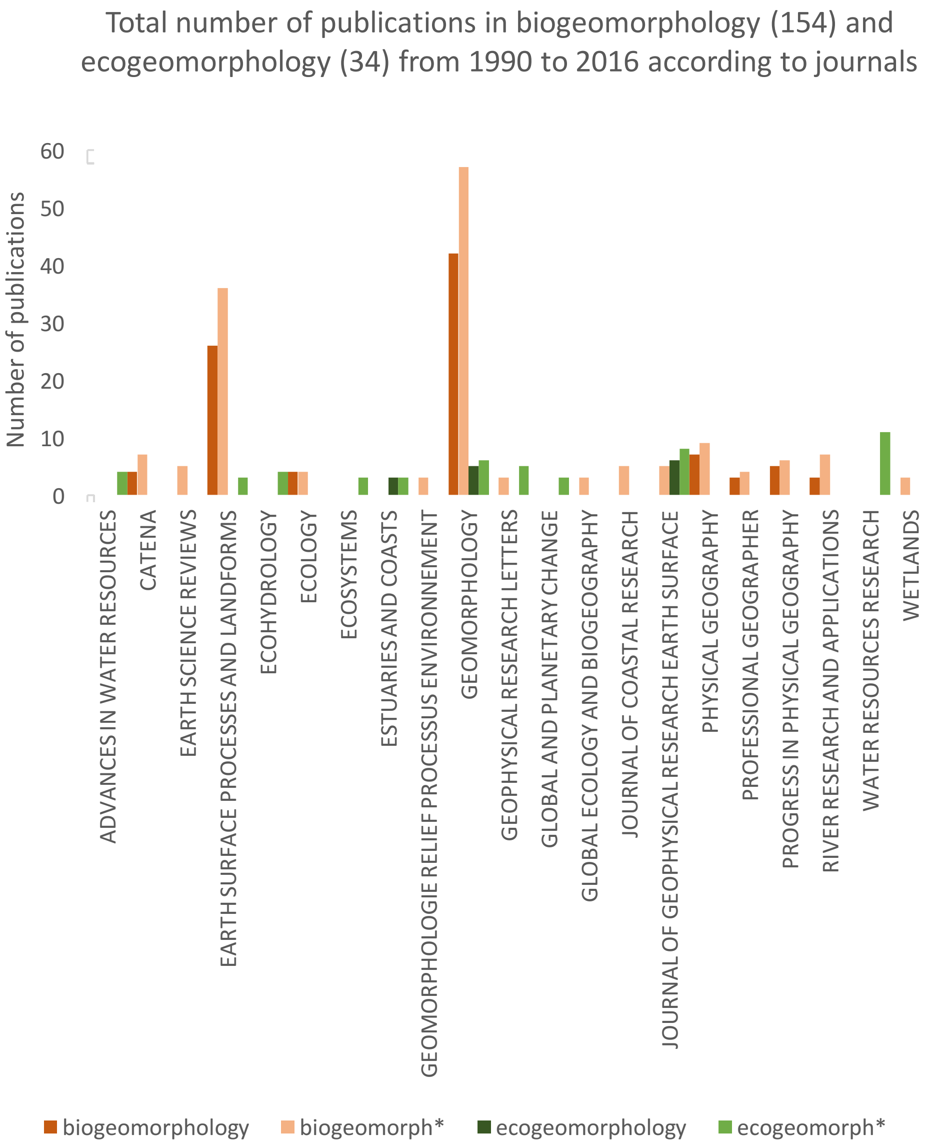

Figure 2.3: Total number of publications in biogeomorphology and ecogeomorphology from 1990 to 2016 according to journals, based on topic search for terms in ISI Web of Knowledge. At least three publications on the respective topic have to be published in a journal for the journal to be shown. Date: 15.07.2016

ecogeomorphology has been used first by Hupp et al. (1995) to name a sub-discipline of biogeomorphology with a focus on ecological aspects within biology. However, Thoms and Parsons (2002, p. 113) later used the term to describe an 'interdisciplinary approach to the study of river systems that integrates hydrology, fluvial geomorphology and ecology'. 'Functional ecogeomorphology' (Fisher et al., 2007) and 'biomorphodynamics' (Murray et al., 2008) are further terms to describe feedbacks between organisms, biological processes and physical processes and morphology, however, these terms they are not widely used.

In 2011, Wheaton et al. proposed to establish a separation between biogeomorphology, focusing on the modification of weathering by biota, and ecogeomorphology, focusing on the modification of erosion and deposition processes. Yet, it seems that 'biogeomorphology' has succeeded as a term to describe all studies on linkages between ecology and geomorphology (Viles, 2004), with much higher total numbers of publications (154) than ecogeomorphology (34) since 1990 (Figure 2.3) and a wide focus on all kinds of geomorphic processes. In the last ten years, biogeomorphic studies included both unidirectional studies based on early biogeomorphic research and more feedback-oriented modern biogeomorphic research (Figure 2.1, see Section 2.2). The preference of the term 'biogeomorphology' for geomorphic-ecologic linkages could be attributed to the fact that biogeomorphic research is still coming mainly from a geomorphic background, while ecogeomorphology seems to be more linked to hydrology and hydrologic processes, as defined by Thoms & Parsons (2002) (Figure 2.3). A summary of total publications on biogeomorphology and ecogeomorphology according to journals supports this reason, as biogeomorphic research is mainly published in the classical geomorphic journals Geomorphology and Earth Surface Processes and Landforms, while ecogeomorphic research is published in journals more related to hydrological topics, such as Advances in Water Resources, Ecohydrology and Water Resources Research. This thesis also employs the term 'biogeomorphology' with a focus on 'feedback biogeomorphology', which will be exemplified in Section 2.2.

Key concepts from 1990s and 2000s

In addition to a rising total number of publications, some key conferences and biogeomorphic concepts mark the development of biogeomorphology in the 1990s and 2000s. In 1995, the 26th Binghamton Symposium in Geomorphology took up the new topic and discussed about 'Biogeomorphology, terrestrial and freshwater systems' (Hupp et al., 1995). Concepts important for the further development of the discipline and for this thesis from this time come from Phillips (1999) and Naylor et al. (2002) (Figure 2.1).

In his monograph on complexity, order and scale in Earth Surface Systems, Phillips (1999) introduced the concept of a biogeomorphic transient form ratio, based on the transient form ratio from Brunsden and Thornes (1979) (see Section 2.3.2). This biogeomorphic concept was later taken up and exemplified by Corenblit et al. (2011) (Figure 2.4). The biogeomorphic transient form ratio defines the conditions under which biogeomorphic interactions can occur. These depend on

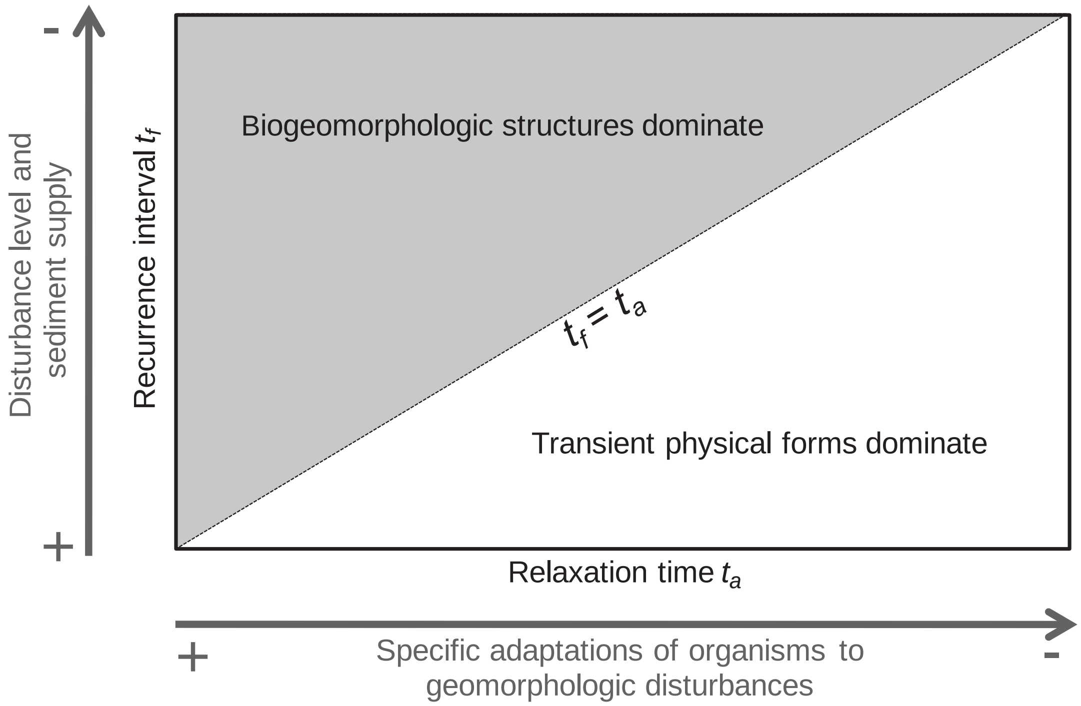

Figure 2.4: Biogeomorphic transient form ratio, showing the relationship between organism adaptations to geomorphic disturbances (x axis) and disturbance level and sediment supply (y axis). This relationship determines if transient physical forms or biogeomorphic structures dominate in the coupled geomorphic-ecologic system. Taken from Corenblit et al., 2011, p. 321.

the ratio between recurrence interval of geomorphic disturbances (frequency), associated with disturbance level (magnitude) and sediment supply, and the relaxation time of vegetation and its resilience to disturbances. The latter factors depend on the specific adaptations of organisms to geomorphic disturbances, thus, how quickly they can regrow after a disturbance and which magnitude of disturbances they can withstand. In case the recurrence interval of geomorphic processes is shorter than the relaxation time of the vegetation, transient forms dominate in the coupled geomorphic-ecologic system. If the recurrence interval is longer than the relaxation time of the vegetation, biogeomorphic interactions and structures become dominant.

In 2002, Naylor et al. summarized the progress in biogeomorphology up to this point and determined the core subject areas of biogeomorphology: bioerosion, biocontruction and bioprotection. Bioerosion describes the biological processes or agents which increase erosion themselves or by reducing protection. Bioconstruction is the process in which organisms produce sedimentary deposits, accretions or accumulations, while bioprotection occurs through the active or passive prevention or retardation of earth surface processes by organisms. In addition, Naylor et al. (2002) pointed out main shortcomings of previous biogeomorphic research, especially the unidirectional research on vegetation influences on geomorphic processes, neglecting reverse impacts of geomorphic processes on vegetation. This shortcoming also shows in the core subject areas of previous research that were identified in this study.

2.1.5 Wind of change: towards 'feedback biogeomorphology'

The critics on unidirectional approaches stated by Naylor et al. (2002) were taken up by others, who found that biogeomorphology often consists of 'a catalogue of unidirectional linkages' (Stallins, 2006, p. 214), produced by adding 'a bio-component to a geomorphological study' (Haussmann, 2011).

It is possible that these prevailing unidirectional approaches could result from problems integrating different disciplines, as stated by Pickett et al. (1994). Concerning the integration of geomorphology and ecology, these comprise especially the problems of (i) own view points and assumptions and (ii) own methodology and methods for each discipline, and (iii) a lack of common definitions and lexicons. Different viewpoints also exist in previous ecologic and geomorphic research. While the former usually assumes that the landscape is static, the latter often considers vegetation/biota as a static external variable (Thornes, 1990) or just in term of 'there' and 'not there' (Renschler et al., 2007). In addition, a theoretical overlap between geomorphology and ecology is missing or was buried with time (Figure 2.1), however, this needs to be established for a successful integration (Renschler et al., 2007; Stallins, 2006). Concerning the methodology and methods, Haussmann (2011) highlighted the existence of different research approaches as a main challenge to deal with in biogeomorphology. While geomorphic research wants to understand the mechanism underlying the process and prefers mathematical modelling approaches, ecology is less interested to understand how the mechanism works and therefore prefers statistical models and experiments. A further problem pointed out by Haussmann (2011) is that most biogeomorphic studies are conducted by geomorphologists and only very few ecologists practice biogeomorphology. She states that for a 'real biogeomorphology', both fields need to be integrated with their approaches, philosophies and principles and researchers from both fields need to cooperate.

A key publication to overcome these limitations and unidirectional approaches, to integrate the disciplines and to promote a change to a more feedback-oriented biogeomorphology comes from Stallins (2016) (Figure 2.1). He took the complex systems theory present in both discipline as a starting point for integration. Based on this, he stated that linked geomorphic and ecologic systems are complex, adaptive systems, which are characterized by (i) multiple causality, (ii) ecosystem engineers, (iii) ecological topology, and (iv) ecological memory. Multiple causality describes that there is no causal priority for one factor as interactions between geomorphic and ecologic system components are always recursive. In time, this recursivity has a sorting effect and produces linked geomorphic and vegetation patterns in landscapes. Ecosystem engineers are species that can influence geomorphic processes, e.g. by affecting material properties, and thereby modify geomorphic thresholds, thus, can change the occurrence of geomorphic. A full description of the ecosystem engineer concept, which is a main foundation for this thesis, is provided in Section 2.2.2. Ecological topology describes patterns in linked geomorphic-ecologic systems, which are made up by different assembly states and transient state. Each assembly state possesses a certain set of species and abiotic processes controlling structure and function. In time, a subset of abiotic and biotic components is selected and reproduced by interactions. This ecological memory becomes encoded in organisms and their environment and controls future patterns. These concepts coming from a complex system approach helped to smooth the way for integrating geomorphic and ecologic view points, methods, methodology and terminology in subsequent years.

2.2 The trajectory of biogeomorphology – where we are now

2.2.1 Feedback biogeomorphology: integrating geomorphic and vegetation dynamics

In the 2000s/2010s, a biogeomorphic branch of ‚feedback biogeomorphology' developed in response to critics on previous unidirectional biogeomorphic approaches (Figure 2.1). The term 'feedback biogeomorphology', introduced in this thesis, describes the current biogeomorphic research in the 2010s focussing on feedbacks between geomorphic and biotic components instead of unidirectional linkages. It is defined as the study of feedbacks between Earth surface processes and landforms, and organisms and ecological and evolutionary processes, following Corenblit et al. (2011). In feedback biogeomorphology, both geomorphic and biotic system components are seen as dynamic, with feedbacks between them driving the dynamics, structure and functioning of the coupled geomorphic-ecologic system. This integrative approach is promoted by defining biogeomorphology as a sub-discipline of Earth System Science, studying the interactions between the different Earth spheres, rather than considering it as a sub-discipline of geomorphology. Thereby, disciplinary boundaries inhibiting the integration are eliminated and the focus on investigation is neither geomorphic nor ecologic. Biogeomorphic progress in the 2010s has been marked by the integration of ecologic concepts into biogeomorphic research (see Table 2.1), which was previously dominated mainly by geomorphic concepts and approaches due to its origin. These include, among others, the concepts of ecosystem engineering, plant functional traits and vegetation succession (Figure 2.1; Table 2.1). Feedback biogeomorphic research focused mainly on fluvial (Corenblit et al., 2007, 2009; Gurnell et al., 2012), coastal (Balke, 2013; Bouma et al., 2013; Wang and Temmerman, 2013) and arid/dune environments (Baas and Nield, 2007; Saco et al., 2007; Stallins and Parker, 2003; Tobias, 2015) and lead to the development of new biogeomorphic concepts, which help to understand coupled dynamics.

2.2.2 Key biogeomorphic concepts

Key biogeomorphic concepts for this thesis, ordered according to their spatiotemporal scale, are (i) ecosystem engineering and plant functional traits (Corenblit et al., 2015; Jones et al., 1994; Phillips, 2016a; Violle et al., 2007), (ii) Windows of Opportunity (Balke et al., 2011, 2014), (iii) biogeomorphic structures (Corenblit et al., 2010a), (iv) (fluvial) biogeomorphic succession (Corenblit et al., 2007, 2009) and (v) biogeomorphic ecosystems (BEs; Balke et al., 2014; Corenblit et al., 2015) (see Table 2.1).

Table 2.1: Overview on key biogeomorphic concepts, ordered according to their spatiotemporal scale. Foundation concepts, main ideas and applications in different environments are shown

	Concept	Foundation concepts	Main idea	Application (environment)
Small scale	***Ecosystem engineering*** (Corenblit et al., 2010a; Jones et al., 1994; Jones, 2012)	Keystone and foundation species (Mills et al., 1993; Paine, 1966)	Environmental modification and creation or maintenance of habitats by organisms	Fluvial environments (Corenblit et al., 2014; Gurnell, 2014) Coastal environments (Gutiérrez et al., 2012) Lateral moraine (Eichel et al., 2013; see Chapter 4)
	Biogeomorphic ecosystem engineering (Phillips, 2016)	Ecosystem engineering (see above)	Ecosystem engineering which affects geomorphic processes and landforms	Karst environment (Phillips, 2016) Lateral moraine (see Chapter 6)
	Response, effect and feedback traits of pioneering plants (Corenblit et al., 2015)	Plant functional traits (Violle et al., 2007), Plant functional types (Box, 1981; Lavorel et al., 2007)	Pioneering species in BEs possess three types of traits, which control their interactions with geomorphic environment	Fluvial and coastal environments (Corenblit et al., 2015) Lateral moraine (see Chapter 6)
Intermediate scale	***Windows of opportunity*** (Balke et al., 2011; Balke, 2013; Balke et al., 2014)	Density threshold (Bouma et al., 2009) Alternative stable states (Holling, 1973; Lewontin, 1969)	Pioneer colonization occurs in time windows depending on the relation between pioneer dispersal, growth and disturbance occurrence.	Coastal environment (Balke, 2013; Balke et al., 2014) Lateral moraine (Eichel et al., 2016; see Chapter 4)
	Biogeomorphic structures/units (Corenblit et al., 2010a, 2016)	Niche construction (Odling-Smee et al., 2003)	Feedbacks between organisms and geomorphic processes create specific landforms with abiotic, residual and/or functional components	Fluvial environment (see Corenblit et al., 2016) Lateral moraine (see Chapter 6)
Large scale	***(Fluvial) Biogeomorphic succession*** (Corenblit et al., 2007, 2009)	Succession (Clements, 1916) Facilitation (Connell and Slatyer, 1977)	Dominance of physical (geomorphic) and biotic (vegetation) processes and their interactions changes during four phases within a successional timescale	Fluvial and coastal environments (Balke, 2013; Corenblit et al., 2010b; Kim, 2012) Glacier foreland (Eichel et al. 2013; see Chapter 7)
	Biogeomorphic ecosystem (BE) (Balke, 2013; Corenblit et al., 2015)	Ecosystem (Tansley, 1935)	Ecosystems in which interactions between biota and geomorphology determine ecosystem structure and functioning	Coastal and fluvial environments (Balke, 2013; Corenblit et al., 2015) Glacier foreland (see Chapter 9)

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(i) *Ecosystem engineering and plant functional traits*

The concept of ecosystem engineers was developed by Jones et al. (1994) and denotes 'organisms that directly or indirectly modulate the availability of resources to other species, by causing physical state changes in biotic or abiotic materials. In doing so they modify, maintain and create habitats' (p. 373). Ecosystem engineers can be differentiated into autogenic engineers, which change their environment through their own physical structures and allogenic engineers, which affect their environment by changing the physical state of living and non-living material. Environmental effects of ecosystem engineers include changes of geomorphic dynamics, such as sediment transport rates and topographic changes (Corenblit et al., 2011), and are therefore highly relevant for biogeomorphic research. The process in which plants affect and interact with their environment is called ecosystem engineering.

Ecosystem engineer plants affect geomorphic dynamics through their functional traits, which determine the engineering mechanism. A plant functional trait is any morphological, physiological or phenological feature of the plant individual, which determines its fitness by affecting its growth, reproduction and survival (Violle et al., 2007). Traits can relate to the whole plant (e.g. growth and life form), its leaves (e.g. leaf size and area), its stem and roots (e.g. root length and rooting depth) and regenerative mechanism and capacity (e.g. dispersal mode and seed mass) (Lavorel et al., 2007). Response and effect traits are distinguished based on the interaction of a plant individual with its environment, or, in a biogeomorphic context, on interactions with geomorphic processes, landforms and material properties (Figure 2.5).

A response trait is any trait whose value varies in response to environmental conditions (Violle et al., 2007). In a biogeomorphic context, response trait values are adapted to occurring geomorphic processes and thereby enable successful dispersal, recruitment, establishment and reproduction (Corenblit et al., 2015). Effect traits are traits by which a plant can influence environmental conditions, community or ecosystem properties (Violle et al., 2007). In a biogeomorphic context, they affect geomorphic processes, landforms and material conditions and are often morphological

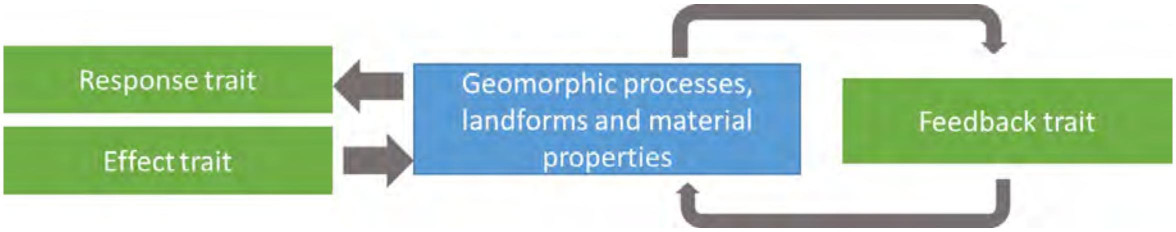

Figure 2.5: Illustration of response, effect and feedback plant functional traits in a biogeomorphic context. Based on Corenblit et al. (2015).

or biomechanical traits (Corenblit et al.,2015). In addition, feedback traits can exist, which can respond to changes they induced in geomorphic processes, landforms and material properties. Although only effect traits affect geomorphic properties, ecosystem engineers need all three types of traits, as response and feedback traits enable engineers to establish in dynamic geomorphic environments and to survive changes they induced in these.

For river and coastal systems, several engineer plant species have been identified, such as riparian willow (*Salix* spp.) and poplar (*Populus* spp.) species (Corenblit et al., 2014; Gurnell, 2014) and *Spartina anglica* (Balke et al., 2012). Summaries of plant influences as ecosystem engineers in river and coastal systems and their relevant traits are provided by Gurnell (2014) and Corenblit et al. (2015).

How ecosystem engineers change their environment in an ecosystem engineering process has been described by Gutiérrez and Jones (2008). Through their effect traits, ecosystem engineers can induce a *structural change* in their environment. Physical properties are modified, e.g. the mechanical resistance of the soil (Jones et al., 2010). An engineered structure is created, which possesses different abiotic properties than the structurally unmodified environment, e.g. a different soil texture. This structural and *abiotic change* in turn induce *biotic changes* in the environment, e.g. changes in species abundances and distributions, species interactions and primary productivity (Jones et al., 2010). All of these changes can feed back to the engineer if its activity or density is coupled to its structural, abiotic or biotic environment. Ecosystem engineering can be seen as one type of niche construction (Odling-Smee et al., 2003, 2013), which describes the process of environmental modification of abiotic and biotic properties by organisms

By changing their environment in the ecosystem engineering process, ecosystem engineers can control ecosystem structure (network of ecosystem components and their interactions; Golley, 2000) and functioning (collective life activities of organisms and their interactions with environmental conditions in ecological systems, sustained by overall system processes; Jax, 2005). When environmental changes are related to changes in geomorphic processes and landforms, this process is termed 'biogeomorphic ecosystem engineering' (Phillips, 2016).

(ii) Windows of Opportunity

The concept of 'Windows of Opportunity' (WoO) describes the necessary conditions for plant recruitment and establishment in ecosystems with alternative stable states, e.g. mangrove coasts. It derives from the previous concept of the 'recruitment box' (Mahoney and Rood, 1998) and has been empirically developed for mangrove (*Avicennia*) species in a flume experiment (Balke et al., 2011). If WoOs occur depends on the relationship between (i) magnitude and frequency of disturbances and initial habitat conditions (physical system properties) and (ii) plant species traits that determine how its diaspores are dispersed and how quickly it can establish. For successful seedling establishment, seeds need to be dispersed by a dispersal event (e.g. inundation) within a river or a coastal ecosystem (mangrove, salt marsh). Subsequently, the dispersal event needs to be followed by a sufficiently long disturbance free period during which the seeds can germinate and the plant establish. How long this disturbance-free period needs to be for successful establishment depends on the traits of the colonizing plant species (Balke et al., 2014). Following the establishment, biogeomorphic feedbacks can start when plant development exceeds a critical above and below-ground biomass, density or size threshold (Bouma et al., 2009; Corenblit et al., 2007). The window of opportunity is limited to the growing season (Balke et al., 2014) and also requires the proximity of a diaspore source. The concept of WoOs can explain sudden state shifts in disturbance driven BEs between bare and vegetated states, either due to WoO enabling seedling establishment and colonization or large magnitude, low frequency disturbances destroying established populations.

(iii) Biogeomorphic structures/units

Biogeomorphic structures or units are landforms created by ecosystem engineering, which differ from their environment through their geomorphometry and material properties. They usually consist of several landform components that can be identified in landform geomorphometry and can have different functions (abiotic, residual and functional) for the engineer or also non-engineer species. Abiotic landform components are strictly created by physical processes, with no inference of organisms. Residual landform components are created by ecosystem engineering, but do not benefit the engineer. Functional landform components directly benefit either (i) the engineer or (ii) non-engineer species. Examples for biogeomorphic structures are wooded point bars in fluvial and tussocks in coastal environments (Balke et al., 2012; Corenblit et al., 2016). Although engineer species in different regions possess different engineering traits, biogeomorphic structures are probably created by similar ecosystem engineering processes (Corenblit et al., 2015).

(iv) (Fluvial) Biogeomorphic succession

The concept of biogeomorphic succession describes how the dominance of physical (geomorphic) and biotic (vegetation) processes and their interactions changes during four phases within a successional timescale (Corenblit et al., 2007, 2009). Each phase, (i) *geomorphic*, (ii) *pioneer*, (iii)

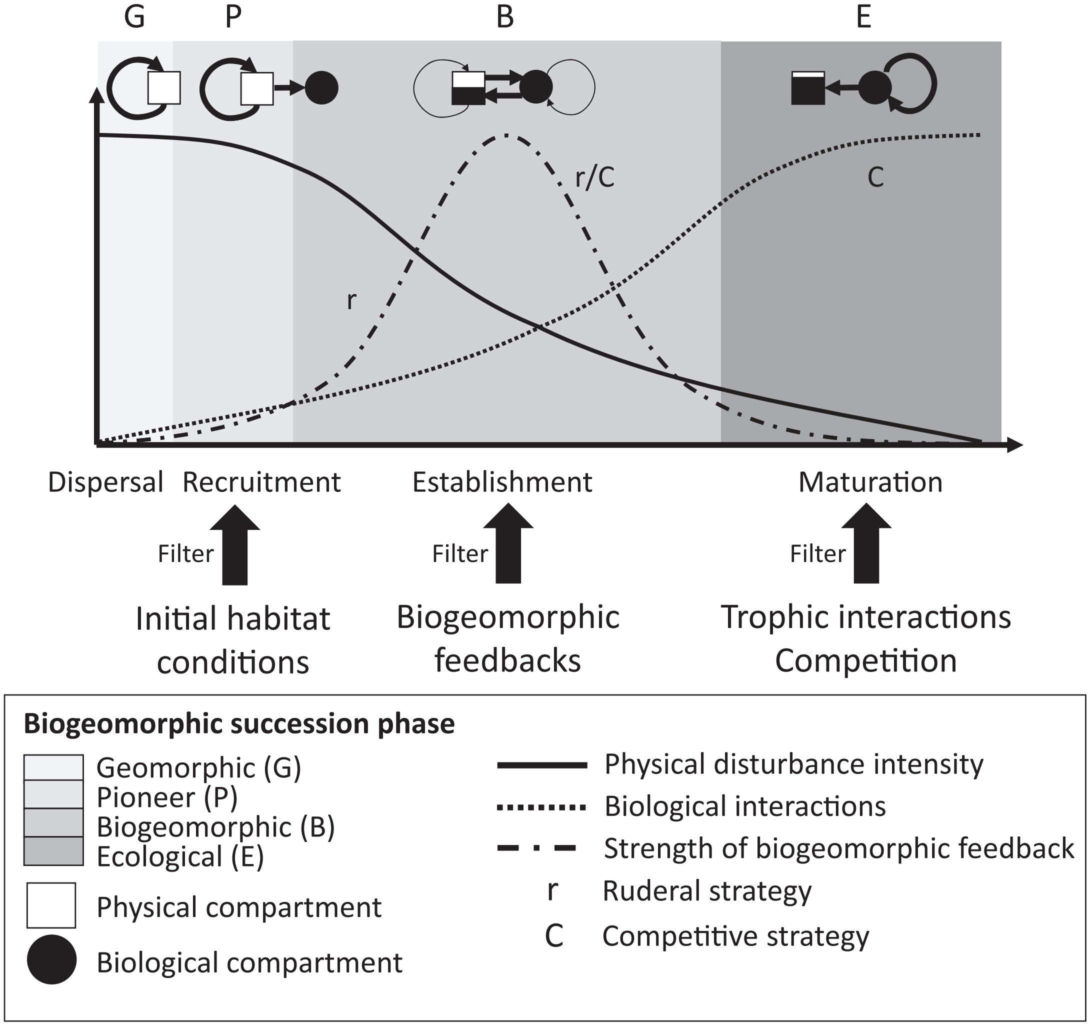

Figure 2.6: Conceptual model of biogeomorphic succession from Corenblit et al. (2015), showing changing intensities of physical disturbances, biological interactions and biogeomorphic feedbacks during the successional phases. Influences of ecosystem engineers in the physical compartment are indicated in black. Taken from Corenblit et al., 2015, p. 1365.

biogeomorphic and (iv) *ecologic phase*, possesses a specific ecosystem structure and functioning and a specific set of interactions and feedbacks (Figure 2.6; Corenblit et al., 2015). In the (i) *geomorphic phase*, geomorphic processes of the physical compartment dominate and control, together with material properties, properties and stability of landforms (Corenblit et al., 2015), but also the physical disturbance intensity and species dispersal. In the (ii) *pioneer phase*, the physical compartment exerts a main influence on the biotic compartment, as geomorphic processes, landforms and material properties determine initial habitat conditions and disturbance regime. Disturbance regime and species traits determine the occurrence of WoOs by controlling species dispersal and enabling species recruitment (germination, seedling survival and growth).

Occurring pioneer engineer species are r-strategists with response traits adapted to dispersal by geomorphic processes, e.g. hydrochorous dispersal with high seed production. Pioneer response traits, such as clonal establishment or morphological plasticity, are important for species recruitment in the unstable conditions of the pioneer phase. With successful engineer establishment, biogeomorphic feedbacks and biotic interactions increase. In the (iii) *biogeomorphic phase*, interactions between physical and biological compartment occur and the physical compartment starts to be partly biologically controlled. Biogeomorphic feedbacks are strongest and filter species establishment by creating patterns, e.g. protected areas dominated by sediment accretion, which are surrounded by areas with erosion dominating as an offsite effect. Response traits important for successful establishment and growth in the biogeomorphic phase are a high phenotyphic plasticity and traits that support resistance to mechanical constraints, e.g. biomechanical traits. Both r and C strategists occur in this phase. In the (iv) *ecologic phase*, the physical compartment is strongly influenced by biotic processes and the intensity of biogeomorphic feedbacks decreases due to decreasing physical disturbance intensity. Biological interactions are most intense, with trophic interactions and competition determining the maturation of occurring species, which are mostly C strategists.

The biogeomorphic succession process can be interpreted as an adaptive cycle *sensu* Holling (1973) (see Section 2.3.3). Succession processes (exploitation, conservation) are combined with processes of destruction and reorganization (Corenblit et al., 2009; Gunderson, 2001), which are triggered by larger magnitude disturbances of the system, e.g. a strong flood (cf. Corenblit et al., 2009, 2007). The biogeomorphic succession concept has been successfully applied for fluvial systems (Corenblit et al., 2010b) and for mangroves and salt marshes (Balke, 2013; Kim, 2012).

(v) Biogeomorphic ecosystems

The term biogeomorphic ecosystems (BEs) describes ecosystems in which interactions between biota and geomorphology determine ecosystem structure and functioning, especially in terms of geomorphic system configuration (process, landforms, material properties) and dynamics (Balke et al., 2014; Corenblit et al., 2015). These ecosystems are geomorphically dynamic and therefore unstable and subject to frequent and regular disturbances (Corenblit et al., 2015). Their disturbance regime is characterized by the regular occurrence of low to medium magnitude disturbances and episodic medium to high magnitude disturbances (extreme events). Habitat properties, species assemblage, matter and energy fluxes, as well as geomorphic dynamics, are emergent properties of plant-geomorphic feedbacks in these systems. BEs are functionally similar in terms of the occurrence and mechanisms of biogeomorphic feedbacks and can be defined using a trait-based approach (Corenblit et al., 2015). In BEs, plants must have developed response traits to geomorphic environment and disturbance regime, they must possess effect trait to control the geomorphic environment and also possess feedback traits as the result of occurring biogeomorphic feedbacks. However, the number and intensity of feedbacks in BEs differs due to (i) different taxa and floristic assemblages, (ii) divergent trajectories and path dependency in system development, (iii) different disturbance regimes, which control duration and spatial extent of the biogeomorphic successional phases and (iv) individual feedback loops that depend on disturbance regime and plant characteristics. It has been suggested that similar disturbance regimes and environmental constraints in different environments lead to convergent plant strategies (Corenblit et al., 2015).

The BE concept can be seen as a main step towards an integration of geomorphology and ecology. In comparison to previous approaches, this concept considers geomorphic and ecologic components not as parts of different systems (geomorphic system and ecosystem) which interact (cf. Viles et al. 2008), but as equally important parts of a single system, which is defined by interactions between geomorphic and ecologic components. In reference to Stallins (2006), this complex system approach is well suited to understand biogeomorphic dynamics. It accounts for complexity and non-linearity of geomorphic systems and ecosystems, which show in their hierarchical structure and phenomena such as thresholds, emergence, self-organization, hysteresis and path dependency (Currie, 2011; Dikau, 2006; Levin, 1998; Phillips, 2003; Wu and Loucks, 1995).

2.3 Scales in biogeomorphology

The term 'scale' describes the physical spatial or temporal dimension of an object or process and is characterized by both extent (total dimension) and grain/resolution (subintervals) (Wu, 1999). Scale approaches are not only common, but necessary for the investigation of complex systems in both geomorphology and ecology. Complexity in ecologic and geomorphic systems arises from (i) the diversity of geomorphic and ecologic processes and patterns, (ii) non-linearity and (iii) heterogeneity (Phillips, 2003; Wu, 1999). As complexity frequently takes the form of a hierarchy (Wu, 1999), no single correct scale can be found to describe and investigate an ecosystem (Levin, 1992) or geomorphic system (de Boer, 1992). Instead, multiple scales need to be investigated to understand which causes and mechanisms are important at which scale and how the different scales are linked in complex ecological and geomorphic systems (Levin, 1992; O'Neill et al., 1986; Stallins, 2006; Turner et al., 1989; Wu, 1999).

Consequently, the investigation of complex biogeomorphic ecosystems also necessitates a scale approach, which can represent a valuable tool to integrate the disciplines, as it represents a further conceptual overlap between them (Renschler et al., 2007). This section illustrates traditional approaches to space, time and scale in geomorphology and ecology, highlights two key scale concepts, hierarchy theory and panarchy, and describes their usage in ecology and geomorphology Finally, previous scale approaches and linkages in biogeomorphology are summarized.

2.3.1 Traditional approaches to time, space and scale in geomorphology and ecology

Traditional approaches to scale in geomorphology and ecology are mostly related to the role of time and space for geomorphic processes and landforms, landscape development, biotic components and ecologic processes.

In geomorphology, scale was often seen as a problem that limits the development of an overarching geomorphic theory (Church, 1996; Kennedy, 1977). However, as Kennedy (1977) and Church (1996) point out, a scale approach can rather help to combine different research approaches and therefore represents a ‚fundamental skeleton of the discipline' (Kennedy, 1977, p. 156). The importance of time and space was considered in terms of system equilibrium (cf. Chorley et al., 1984), causality (cf. Schumm and Lichty, 1965; section 2.1.2) and landscape change, which is linked to the magnitude and frequency of geomorphic processes. Process frequency (statistical return period of a specific process event) addresses the time component of geomorphic processes, which was found to be related to process magnitude (process intensity) and controls the effectiveness of geomorphic processes (moved material multiplied by landform change) and therefore landscape change. In fluvial systems, Wolman and Miller (1960) found that geomorphic processes with intermediate magnitude and frequency are most effective in modifying the fluvial landscape. Brunsden and Thornes (1979) further examined the role of time for landscape change and developed a transient form ratio to determine the sensitivity of landforms to internal and external changes. Using the ratio between relaxation time of landforms (the time which is needed to return to the characteristic form in steady state condition, e.g. specific river planform or hillslope gradient and curvature) and mean recurrence time of disrupting events (e.g. floods, debris flows), it shows that stable landforms can only form if the mean recurrence time of disruptions is longer than their relaxation time. Furthermore, the role of time for landscape change has been highlighted in terms of path dependency, which describes the time-dependent development of systems configuration along trajectories that can strongly depend on initial conditions (Dikau, 2006; Verleysdonk et al., 2011).

Linkages between time, related to geomorphic processes, and space, related to landforms, were further developed with a rising interest in landform modelling and mapping and terrain analysis in the 1980s and 1990s. Following Ahnert (1988), Dikau (1989) related time and space in a landform classification based on the duration of existence of a landform and its size. This concept was adapted into a well-known figure by Brunsden (1996), which also includes the time to completion of landforms (Figure 2.7 A). It is important to note that processes on different scales result in a palimpsest in the landscape (Chorley et al., 1984; Dikau 2006).

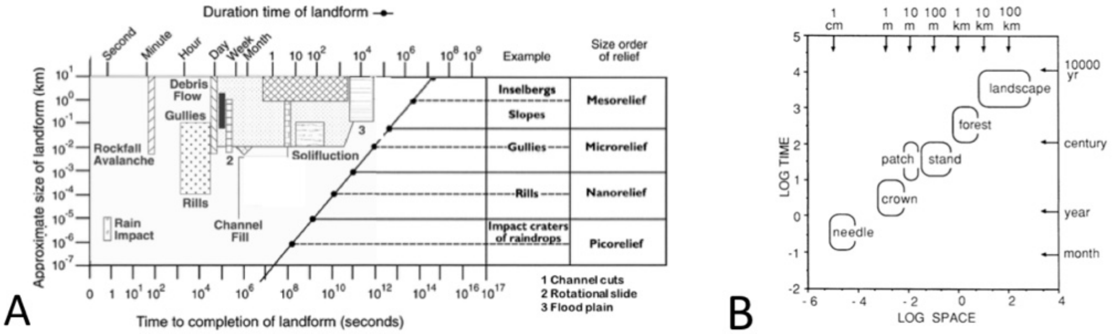

Figure 2.7: Similarity of geomorphic and ecologic approaches to space and time. **A** Geomorphic processes and landforms according to the time to completion of the landform, size and duration time. Taken from Brunsden, 1996, p. 285. **B** Time and space scales (logarithmic) of landscape elements and ecosystems in a boreal forest, ranging from a single needle to the entire landscape. Taken from Holling, 1992, p. 452.

Similar approaches to space and time are common in ecology. Typically, space and time in ecological systems have been addressed by sorting their components, individual, population, community, ecosystem, landscape, biome, according to their spatiotemporal scale (Wu, 1999). One example of this structure was presented for a boreal forest ecosystem by Holling (1992), who sorted the different landscape elements and ecosystems according to their spatial and temporal scale, ranging from a single needle to the entire landscape (Figure 2.7 B). In addition, the ecologic disturbance concept also deals with process occurrence in time and space, similar to the magnitude-frequency concept in geomorphology. Components of disturbances also include process magnitude (magnitude intensity) and frequency, further components are disturbance distribution, size of disturbed area, return interval (as inverse of frequency), timing and disturbance severity (Pickett and White, 1987; Turner et al., 2001).

2.3.2 Hierarchy theory

Hierarchy theory is an approach to deal with the hierarchical order of components on different scales showing both in geomorphic and ecologic traditional approaches (Figure 2.7). It tries to make complex systems understandable (Müller, 1992) by considering several scales and their linkages at the same time. A hierarchical approach focusses one ‚holon' (system in its scale context) in one space-time scale (Figure 2.8), which is determined by the level of the phenomenon of interest (Müller, 1992; O'Neill et al., 1986; Parsons and Thoms, 2007). A holon always consists of holons at lower levels of the hierarchy and is a component of a holon at higher levels (Figure 2.8). Each holon is governed by a fixed set of rules that determines its structure and functioning and interacts with higher or lower holons by exchanging information, matter and energy (de Boer, 1992; O'Neill et al., 1986).

Generally, three levels with their holons are investigated in hierarchical approaches (O'Neill et al., 1986; Wu, 1999). The focal level of research (level 0) is embedded between a higher level (level 1) and a lower level (level -1). The higher level is characterized by slow and long dynamics and acts as a constraint on the focal level, while the lower level is characterized by quick and short dynamics. Components of the lower level explain the mechanisms operating at the focal level. Within one level, interactions are generally more intense than interactions between the levels. One main statement of hierarchy theory is that it is not possible to transfer principles from one level to another (Gunderson and Holling, 2002; O'Neill et al., 1986; Wu, 1999) due to filters (Figure 2.8) and emergence (O'Neill et al, 1986).

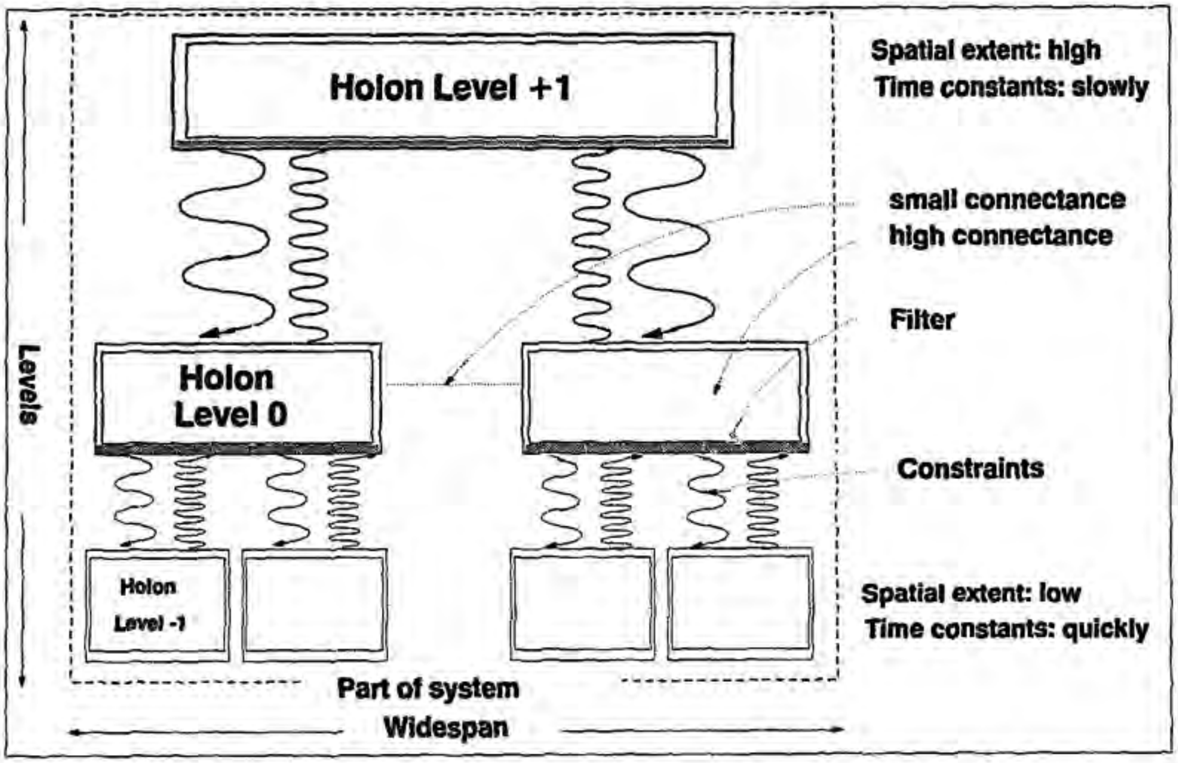

Figure 2.8: Illustration of a hierarchical approach, showing different levels with holons, their properties and interactions. Taken from Müller 1992, p. 224.

Emergence is the development of new structures and patterns at higher scales, which cannot be explained by principles or knowledge from smaller scales (Dikau, 2006; Harrison, 2001) This strongly limits reductionist aggregation or upscaling approaches in complex systems (Harrison, 2001; O'Neill, 1989).

Hierarchy theory in geomorphology

One of the first applications of hierarchy theory to geomorphology comes from Dikau (1989, 1990), who used a hierarchical approach to landform classification. He showed that landforms are made up of nested components in a spatial hierarchy from form facets at the smallest scale, over form elements at an intermediate scale to relief form association at the largest scale. De Boer (1992) took up hierarchy theory in a geomorphic systems context and stated that every geomorphic system consists of lower level systems and is part of a higher level system, therefore, geomorphic systems possess a nested, hierarchic structure. By applying hierarchy theory, he demonstrated the role of time and space for geomorphic systems and pointed out that the considered scale determines system evolution, causality, controlling factors and the occurrence of 'catastrophes'. Scale interactions depend on process frequency and magnitude.

A hierarchical approach to a geomorphic system was put in practice by Cammeraat (2002) to understand linked degradation and geomorphic development. He showed that geomorphic and ecosystem components can be ordered according to scale and highlighted the importance of small and intermediate scale geomorphic and ecologic processes for large scale landscape development as an emergent property. A further hierarchical approach to understand sediment budgets was made by Slaymaker (2006), while Phillips (2016b) recently tried to understand scale linkages and decoupling by using graph and network theory (cf. Neumann, 2015). He found that it becomes difficult to transfer information and relationships across more than three scale levels, which supports O'Neill et al. (1996)'s approach of three relevant levels for investigation.

Hierarchy theory in ecology: hierarchical patch dynamics

One example for the application of hierarchy theory in ecology is the hierarchical patch dynamics approach (Wu, 1999), which serves to explain the behaviour, spatial structure and dynamics of ecological systems. A patch is an area that differs from its surroundings in structure and function, e.g. in floristic composition, age of dominant species and habitat properties (Lovett et al., 2007; Watt, 1947). Several patches with different properties make up a spatial patch mosaic, which is characterized by patch composition (patch type and relative abundance) and spatial configuration (patch size, shape, juxtaposition, contrast, boundary conditions) (Watt, 1947; Wu and Loucks, 1995). The concept of patch dynamics describes the changes of the patch mosaic in time (Pickett et al., 1999). A major cause for patch change is disturbance, however, patches can also change due to patch internal vegetation succession (Wu and Loucks, 1995).

In the hierarchical patch dynamics approach, ecological systems are seen as spatially nested hierarchical mosaic of patches that differ in size, shape and successional stage (Wu, 1999; Wu and

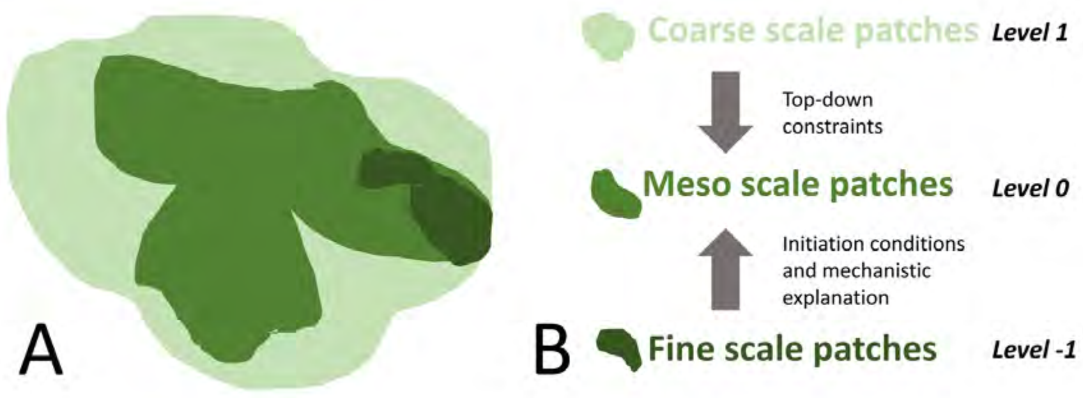

Figure 2.9: Illustration of the hierarchical patch dynamics concept according to Wu (1999). **A** Spatially nested patch hierarchy. **B** Linkages between patches from different levels.

Levin, 1997). Patches at higher levels impose top down constraints on lower level patches e.g. in terms of species pool, while lower level patches provide initiating conditions and mechanistic explanations for properties of higher level patches, e.g. for species composition (Wu and Loucks, 1995). Patch processes are related to specific scales. Non-equilibrium patch processes at lower scales can create a meta-stability in higher scales (Wu, 1999).

2.3.3 Panarchy

The concept of panarchy can be seen as an advancement of hierarchy theory which integrates internal system dynamics in terms of adaptive cycles into an hierarchical concept and describes how nested adaptive cycles in different hierarchical levels interact (Holling et al., 2002). Thus it represents an alternative to the ‚rigid top-down' view of hierarchy (Holling, 2001).

Adaptive cycle

An adaptive cycles describes the internal cyclic dynamics of a system based on four phases (Holling, 2001; Holling and Gunderson, 2002). In addition to the phases of (i) exploitation and (ii) conservation described in the classic successional concept (see Section 2.4), the adaptive cycle adds two more phases of ecosystem development: (iii) release or ‚creative destruction' due to over-connectedness of biomass and nutrients, and subsequent (iv) reorganization of nutrients (Holling, 1992, 2001; Figure 2.10). Thereby, the concept emphasizes the importance of cyclic dynamics in ecosystems with destabilization and destruction as inherent features, e.g. in forest ecosystems characterized by regularly occurring wildland fires.

In the (i) exploitation phase (r-Phase), pioneer species with ruderal behaviour (r-strategists) dominate (Holling, 1992; Holling et al., 2008). The ecosystem is characterized by rapid growth and resource acquisition. Interactions between system processes build up structure and organization within the system. Consequently, connectedness between system elements and stored capital (e.g. biomass) in the system, which are initially low, increase in this phase and the system reaches the (ii) conservation phase (K-Phase). In this phase, the developed system organization starts to control and direct interactions in the system. K-strategists dominate, the system aims at resource conservation and develops towards a climax-like state. However, increased connectedness and stored capital can make the system vulnerable to internal fluctuation and external impacts, such as fire, storms or pest. Once the system loses its stability due to internal or external disturbances,

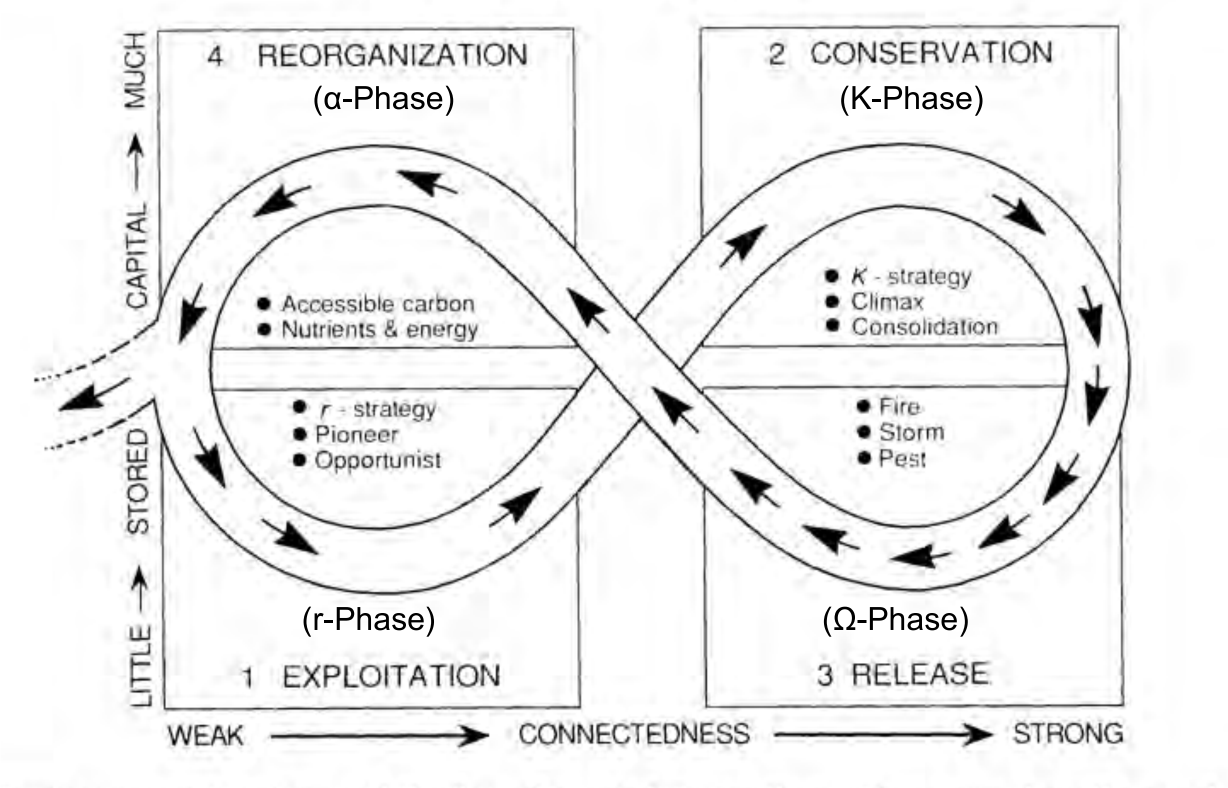

Figure 2.10: Adaptive cycle with four phases. Arrow distance indicates speed of ecosystem cycle. Connectedness between ecosystem variables is shown on the x-axis, stored capital in terms of nutrients and carbon on the y-axis. The system can exit the cycle change to another regime during the reorganization phase (exit to the left). Adapted from Holling, 1992, p. 481.

it enters the (iii) release phase (Ω-Phase) in which it collapses. Stored capital and energy are released, the system loses its connectedness and the system structure becomes disorganized. Opportunities for reorganization are created, however, subsequent development in the (iv) reorganization phase (α-Phase) becomes unpredictable and uncertain (Holling, 2001). The system can either reorganize to the same state and regime as before, with accessible carbon, nutrients and energy as important factors determining system reorganization. However, the system can also be invaded from structures and processes from neighbouring systems and a new regime can develop, for example with a different successional trajectory (Allen et al., 2014). Accessible carbon and nutrients and energy are important factors determining system reorganization.

During the adaptive cycle, time is uneven: While the system slowly processes from exploitation to conservation (forward loop), the change to release and reorganization (backward loop) is very quick (Figure 2.10) and determines system resilience and recovery. Resilience describes the reaction of an ecosystem towards a disturbance (Gunderson, 2000; Holling, 1973) and can either be measured as (i) the resistance of the system to disturbance and speed to return to equilibrium after disturbance (engineering resilience; applicable for equilibrium systems) or (ii) the capacity of the system to absorb or withstand disturbance while maintaining state of system in terms of structural and functional integrity (in non-equilibrium systems; Gunderson and Holling, 2002). In the adaptive cycle, the resilience in terms of capacity to absorb or withstand disturbance decreases from exploitation to conservation phase, and expands again during release and reorganization phase. It can be added as a third dimension to the adaptive cycle.

For geomorphic systems, the adaptive cycle model can be compared with Bak et al.'s (1987, 1988) sandpile model, in which sand is added and structure builds up due to self-organization (forward loop). However, once criticality is reached, release the stored energy is released by sand avalanches and the system reorganizes (backward loop) (Holling and Gunderson, 2002).

Scale linkages between adaptive cycles: panarchy

Scale linkages between adaptive cycles are described in the panarchy concept. The term panarchy derives from the combination of the name of Greek God Pan, from whose name the word panic derives, with the term hierarchy to express destabilizing dynamics in a hierarchical system (Holling et al., 2002). A nested set of adaptive cycles controls the behaviour of a panarchical system, which can be both creative and conserving (Holling, 1992; Figure 2.11). How many levels need to be considered in a panarchical approach depends on the scales of interest, similar to the hierarchical approach. Usually, three levels are addressed, of which the highest level is characterized by a large dimension and slow dynamics, while the lowest level is characterized by a small dimension and fast dynamics. At every level, self-organization and collapse occurs during the respective adaptive cycle, however, stability and instabilities in adaptive cycles can also result from processes and structures from upper or lower scales (Dikau, 2006). Thus, in comparison to a hierarchy, interactions between scales can occur both upward and downward and are related to within scale system position within adaptive cycles (Allen et al., 2014). Upward interactions ('revolt') can occur when the lower adaptive cycle reaches the release phase (Ω-Phase). Change occurring in the lower scale system in this phase can cascade into the higher scale system, especially when the latter is in its conservation phase (K-Phase) with a low resilience making it vulnerable to disturbances. An example for a revolt-interaction is fire in a forest ecosystem, which can start very locally (small scale system), but affect the entire large scale system if enough flammable biomass is stored there. Downward interactions, called 'remember', occur when changes of a higher level system during the release phase (Ω-Phase) influence the reorganization of lower level during the α-Phase,

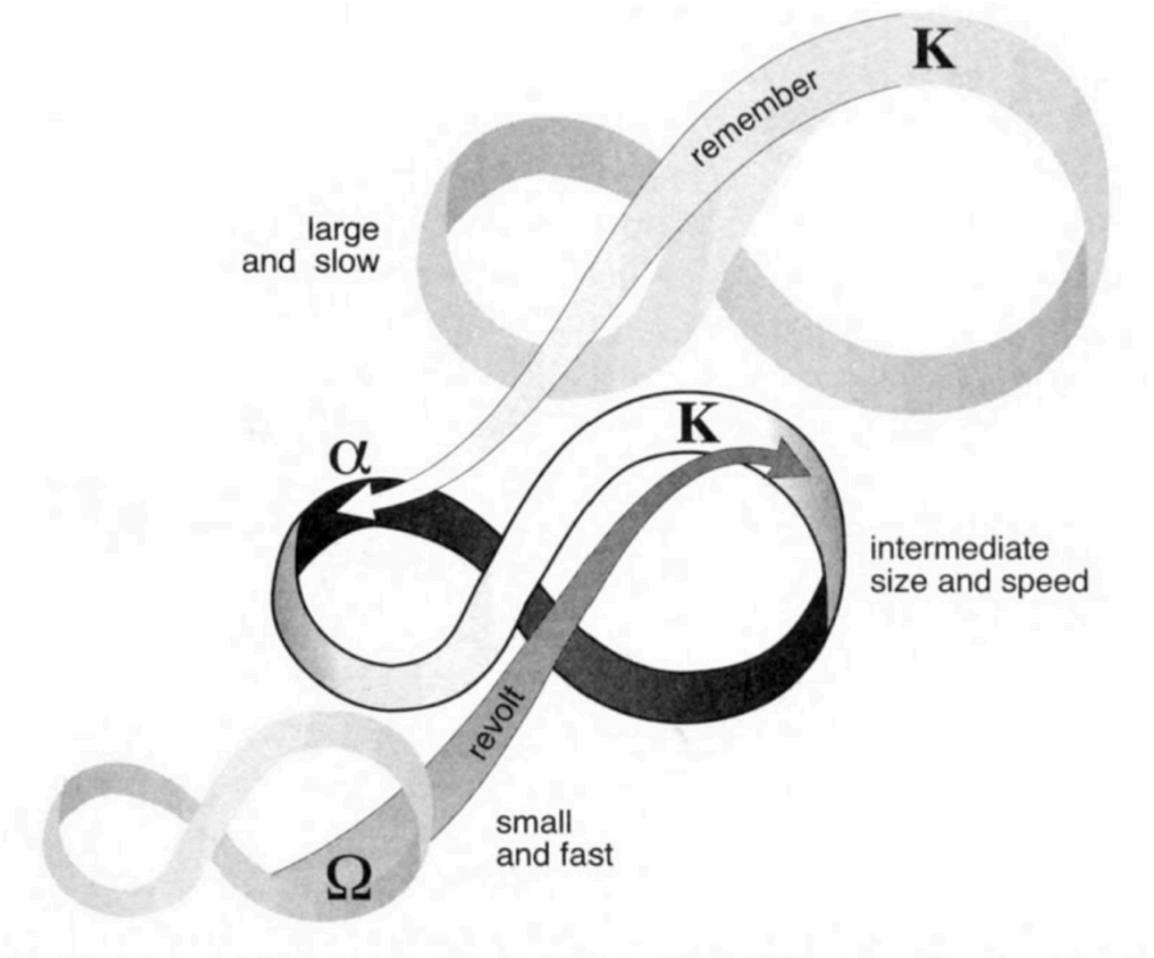

Figure 2.11: Panarchy with three adaptive cycles in different hierarchical levels. Adaptive cycles from different levels interact by 'revolt' and 'remember'. Taken from Holling et al., 2002, p. 75.

e.g. by providing a certain species pool. Thus, the larger system sets the memory for the smaller scale system and makes system reorganization to the same regime more likely (Allen et al. 2014).

Both revolt and remember interactions cause episodic system behaviour and establish key features of ecosystems (Holling et al., 2002). As the panarchy concepts derives from ecology and socio-ecology, it has been frequently applied in ecologic and socio-ecologic studies (Garmestani and Benson, 2013; Holling, 2001; Walker et al., 2004). However, its applicability for geomorphic systems still needs to be tested (Dikau, 2006; Slaymaker, 2006).

2.3.4 Scales in biogeomorphology

As described earlier, scale approaches are a valuable tool for integrating disciplines, such as ecology and geomorphology for biogeomorphology (O'Neill et al., 1986). However, for a successful linkage of different disciplines, the scales of their components must be coherent. For example, state variables from one discipline must also be state variables in the other discipline and processes must occur on a similar timescale to enable interactions between them (O'Neill, 1989; Parsons and Thoms, 2007). The biogeomorphic transient form ratio proposed by Phillips (1999) provides a helpful tool to test this condition and identify the suitable scale(s) for biogeomorphic investigations.

Previous biogeomorphic research indicated that strong scale linkages exist between small scale biogeomorphic interactions and larger scale geomorphic and vegetation patterns (Gurnell, 2014). It has been suggested that small scale biogeomorphic interactions, often mediated by ecosystem engineers, control patch scale species composition and geomorphic processes and landforms (Corenblit et al., 2011, 2015; Gurnell, 2014; Parsons and Thoms, 2007). Consequently, patch properties and landscape patch mosaic can be seen as emergent properties resulting from lower scale feedbacks (Bouma et al., 2013; Stallins, 2006). However, despite the recognition of scale linkages in BEs, their mechanisms and functioning are so far insufficiently understood in biogeomorphology (Gurnell, 2014; Stallins, 2006). Yet, this understanding is needed for the successful restoration and management of BEs (Wu, 1999).

2.4 Geomorphic dynamics in glacier forelands

The terms ' ,glacier foreland’ denotes the proglacial area in front of a glacier with the glaciofluvial and lateral and terminal moraines subsystems (Figure 2.12 A), which has been exposed since the Little Ice Age (Kinzl, 1929; Matthews, 1992). In this thesis, it is used synonymously with ‘glacier forefield’. In terms of sediment transport, the glacier foreland area is one of the most active in high mountains regions (Barsch and Caine, 1984). It is characterized by a high variety of environmental phenomena including the geomorphic, hydrologic, biologic, climatic and pedogenic components of the foreland system (Matthews, 1992), which all are conditioned by the retreating glacier.

2.4.1 Paraglacial adjustment of glacier forelands

The impact of glacier retreat on geomorphic dynamics is described in the paraglacial concept. Originally, the term ‘paraglacial’ was defined as ,non-glacial processes that are directly conditioned by deglaciation’ (Church and Ryder, 1972, p. 3059). Ballantyne (2002b) complemented this definition with the paraglacial components sediment accumulations, landforms, landsystems and landscapes, which can also be conditioned by glaciation. Due to glaciation and deglaciation, paraglacial systems are ,out of balance’, thus, not in an equilibrium with contemporary conditions (Slaymaker, 2011). The process in which the system returns to its equilibrium was termed paraglacial adjustment (Ballantyne, 2002a). It ends when either the regional ,geological norm’ of primary denudation is reached (Church and Ryder, 1972) or when 99% of available sediment depleted or stabilized, e.g. by vegetation (Ballantyne, 2002a, 2002b). In comparison with other paraglacial landsystems, such as rock slopes or lacustrine and coastal environments, the paraglacial adjustment of glacier forelands is rather quick and assumed to be completed within some decades (Ballantyne, 2002b). However, it has been pointed out that it is very difficult to determine the end of paraglacial adjustment, as it is hard to determine the ‘normal’ sediment yield (Orwin and Smart, 2004) and paraglacial adjustment can be restarted by external impacts, e.g. large storms (Ballantyne, 2002a).

The glaciofluvial floodplain and lateral moraines are the most dynamic subsystems of glacier forelands (Carrivick et al., 2013; Geilhausen et al., 2012). In the glaciofluvial floodplain, sediments are reworked by meltwater and thawing ice processes with high sediment transport rates (Baewert et al., 2014; Benn and Evans, 2010). With on-gong paraglacial adjustment, floodplain channel pattern changes, which can be controlled by vegetation (Gurnell et al., 2000; see section

2.4.8). The focus of this thesis is set on lateral moraine slopes, for which the relevant geomorphic dynamics will be summarized in the next section.

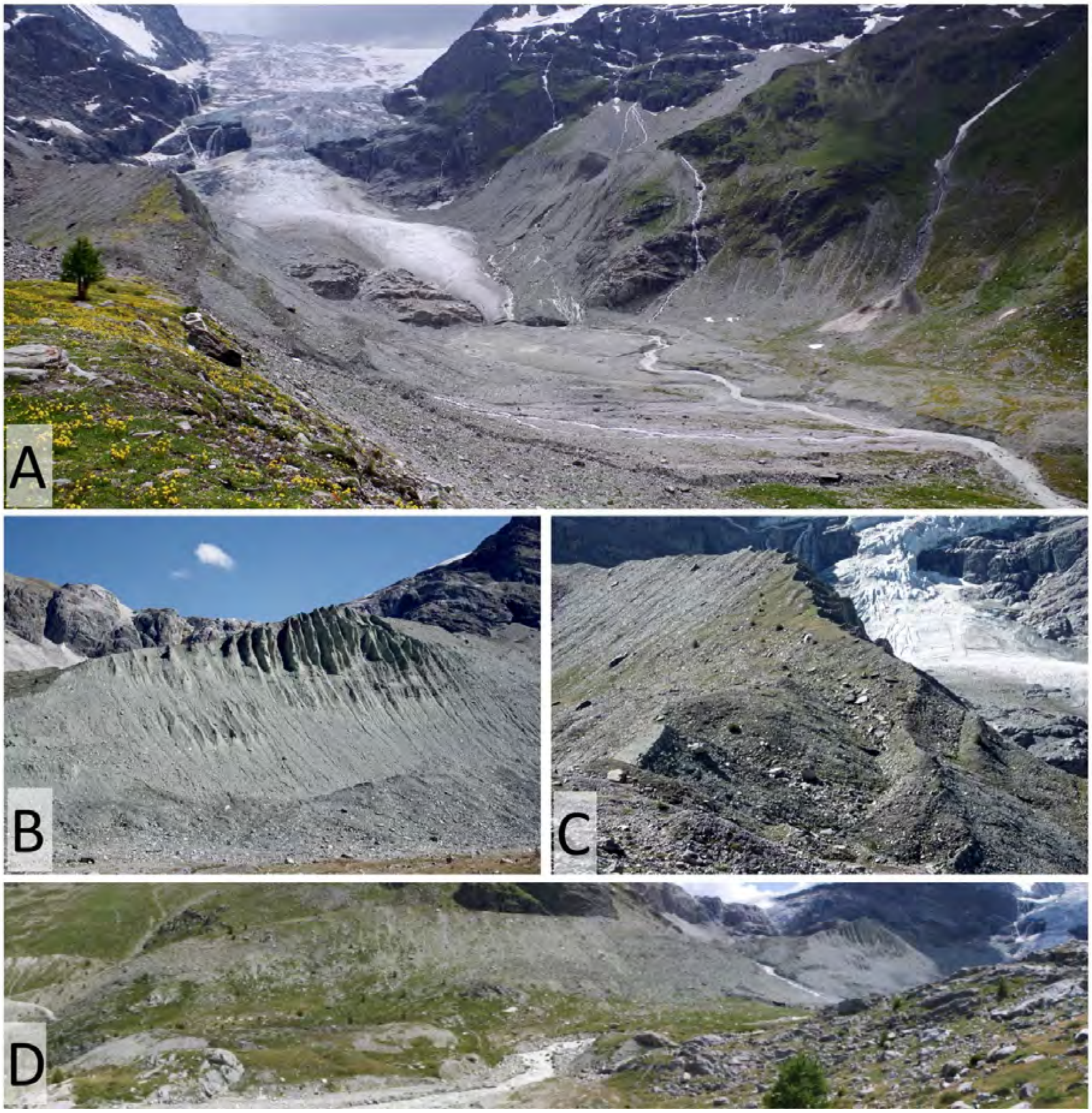

Figure 2.12: Illustration of geomorphic dynamics in glacier forelands. **A** Turtmann glacier foreland with lateral moraine subsystem on the left and upper center, glaciofluvial floodplain in the lower center. **B** Proximal steep lateral moraine slope characterized by dense gullies. **C** Gentler distal lateral moraine slope in the back with nested moraine ridges in the right front. **D** Eastern lateral moraine system of the Turtmann glacier forefield showing paraglacial process and landform and vegetation succession.

2.4.2 Paraglacial processes on lateral moraine slopes

Lateral moraines are glacial landform produced by sediment deposition or deformation along the lateral margins of a glacier (Knight, 2003; Small, 1983). Sediments from the glacier surface, often derived from up-freezing or shearing of en- and subglacial sediments, are deposited by debris flows and shallow sheet flows along the glacier margin (Lukas et al., 2012). Glacier ice or dead ice can be incorporated during this process into the lateral moraine as an ice core, mostly at its lower slopes. In addition, nested moraine ridges can form during stationary phases or smaller advances (Ballantyne and Benn, 1994; Small, 1983). High lateral moraines were often formed during the Little Ice Age in alpine settings (Ballantyne, 2002b; Small, 1983). Lateral moraine slopes differ between steep proximal and gentler distal slopes on the far side of the glacier (Ballantyne, 2005; Lukas et al., 2012) (Figure 2.12 B, C). It has been suggested that proximal slopes can be steeper than the angle of repose of the material due to (i) clasts dipping towards the distal slope and thereby increasing friction (Curry et al., 2009), (ii) overconsolidation of the sediments by glaciotectonisation and incremental till accretion (Lukas et al., 2012) or (iii) the ‚cementation’ of larger clasts by fines (Jäger and Winkler, 2012). Process activity is higher on these slopes, while distal slopes are often less active and vegetated more quickly (Curry et al., 2006; Jäger and Winkler, 2012). In the paraglacial concept, lateral moraines correspond to the ‚sediment-mantled slope system’ described by Ballantyne (2002b).

Paraglacial processes reworking sediment on lateral moraine slopes are associated with running water (soil erosion by water), freeze-thaw cycles (periglacial processes), wind (aeolian processes) and gravitation (mass movements) and depend on (i) sediment texture of the moraines, defined by the glacial deposition mechanism (Jäger and Winkler, 2012), (ii) slope gradient, (iii) moraine and moraine ridge height (Curry et al., 2006), (iv) climate (Heckmann et al., 2005), (v) available moisture (Feuillet and Mercier, 2012; Teysseire, 2006) and (vi) potential ice cores (Lukas et al., 2012).

Water soil erosional processes include rainsplash, sheet wash, interrill erosion, rill erosion and gully erosion, which wash out mainly fine grained material during rainfall events (Ballantyne, 2002b; Curry et al., 2006; Mercier et al., 2009; Rose, 1991). In addition, fines are translocated into the subsurface by eluviation processes mainly in the first years following deglaciation (Ballantyne, 2002b; Boulton and Dent, 1974). Streams from cliffs or slopes above the lateral moraine can also play a role for sediment transport on lateral moraine slopes (Ballantyne, 2005; Curry et al., 2006) and thermally erode dead ice (Ballantyne, 2002b; Curry et al., 2006; Mercier et al., 2009).

Periglacial processes include solifluction, cryoturbation and frost sorting, ploughing boulders and frost weathering (Ballantyne, 2002b; Deline et al., 2015; Matthews et al., 1998). Solifluction encompasses needle ice creep, diurnal and annual frost creep, gelifluction and plug-like flow above an underlying (permafrost) ice body and is of widespread importance for sediment transport on low to moderately inclined slopes (Ballantyne, 2002b; Matsuoka, 2001).

Aeolian processes include wind erosion and aeolian deflation, during which fines are blown out, exposing larger clasts to erosion (Boulton and Dent, 1974; Curry et al., 2006; Jäger and Winkler, 2012).

Mass movement processes under the influence of gravitation include translational debris sliding, rotational slides (slumps), fall or slide of individual clasts and debris flows (Ballantyne, 2002b; Ballantyne and Benn, 1994; Deline et al., 2015). Debris sliding describes the failure of unconsolidated material, often along near planar slip surfaces of dead ice, due to dead ice melt or rainfall (Deline et al., 2015; Small, 1983). Rotational slides occur along circular or spoon-shaped shear surfaces mainly due to dead ice melt or glacier thinning (Ballantyne, 2005; Kjær and Krüger, 2001). They often result in a lowering of the moraine crest or the entire moraine and significantly rework ice-cored moraines (Ballantyne, 2002b; Deline et al., 2015). Fall or slide of individual clasts is often triggered by the removal or finer material around the clasts by water erosional processes and often results in the further erosion of fines along the clast track (Ballantyne and Benn, 1994; Jäger and Winkler, 2012; Small, 1983). Debris flows have been widely identified as the dominant agent of sediment reworking on lateral moraine slopes (Ballantyne and Benn, 1994; Curry et al., 2006). In combination with water erosional processes, they can produce gully landforms by 'gullying' processes in medium sized to fine material, which consist of a gully channel and inter-gully walls (arrêtes) (Curry et al., 2006; Jäger and Winkler, 2012; Mercier et al., 2009). Debris flows often initiate at gully heads, where eroded sediment from the inter-gully walls is deposited, and are triggered by snow melt, dead ice melt or or intense autumnal rainstorms, often every year (Ballantyne and Benn, 1994; Mercier et al., 2009). They only occur at slope gradients larger than > 30°, which is also the minimum gradient for the development of gully landforms (Ballantyne and Benn, 1994; Curry, 2000). In addition, snow avalanches can transport sediment on lateral moraine slopes and into glacier forelands from adjacent slopes (Heckmann et al., 2005; Laute and Beylich, 2012).

Jointly, processes operating at the upper lateral moraine slope produce polygenetic debris cones at the slopefoot (Ballantyne, 2002b; Mercier et al., 2009).

2.4.3 Process and landform succession on lateral moraine slopes

Although lateral moraine slopes are reworked by a variety of geomorphic processes at the same time, a sequence of changing process intensity and importance has been indicated for proximal moraine slopes (Figure 2.12 D; Ballantyne, 2002b; Mercier et al., 2009). It can be attributed to changes in slope internal (e.g. dead ice, slope gradient, material properties) and external (e.g. available moisture) controls with increasing terrain age. This sequence has been described as a process and landform succession has been described by Mercier et al. (2009) for a sediment mantled slope in Svalbard, Norway, and can be transferred to lateral moraine slopes (Figure 2.13).

Stage I: Dead ice related mass movements

During glacier retreat and immediately afterwards, dead ice cores in lateral moraine slopes strongly influence their geomorphic dynamics and paraglacial adjustment (Figure 2.13, Stage I). Dead ice melt strongly delays surface stabilization, as it is a main cause of translational and rotational slides and supplies moisture for debris flows (Bennett et al., 2000; Lukas et al., 2012). As a result from these processes, the lateral moraine slope angle can decrease strongly within the first 10 years following deglaciation (Welch, 1970). The ratio between ice and debris determines how long dead ice can control geomorphic dynamics, as a high debris cover can protect dead ice for a long time and thereby prolong this stage (Lukas et al., 2012).

Stage II: Gullying

About 10 to 20 years following glacier retreat, gullying processes start to dominate at slopes with angles larger than 30° (Figure 2.13, Stage II;Ballantyne, 2005; Curry, 2000; Mercier et al., 2009). On lateral moraines without an ice core, this stage will probably start immediately after glacier retreat. Within the first decades, gullies rapidly attain their maximum size and density (Curry et al., 2006; Mercier et al., 2009). The importance of climatic controls increases for gullying processes in time as dead ice melt water becomes less available. After about half a century following deglaciation, gully depth, width, area and volume decrease again due to collapsing gully sidewalls (Curry et al., 2006). Both gully floor slope gradient and and gully sidewall slope gradient decrease and gullies are finally replaced by shallow scars (Figure 2.13). Up- and mid-slope gullying and associated debris flows produces debris cones at the foot slope, often with debris flow heads and levées. Together, upslope erosion and downslope deposition result in a decreasing slope angle (Ballantyne, 2005; Curry et al., 2006; Figure 2.13, Stage II). The slope profile at the end of this stage

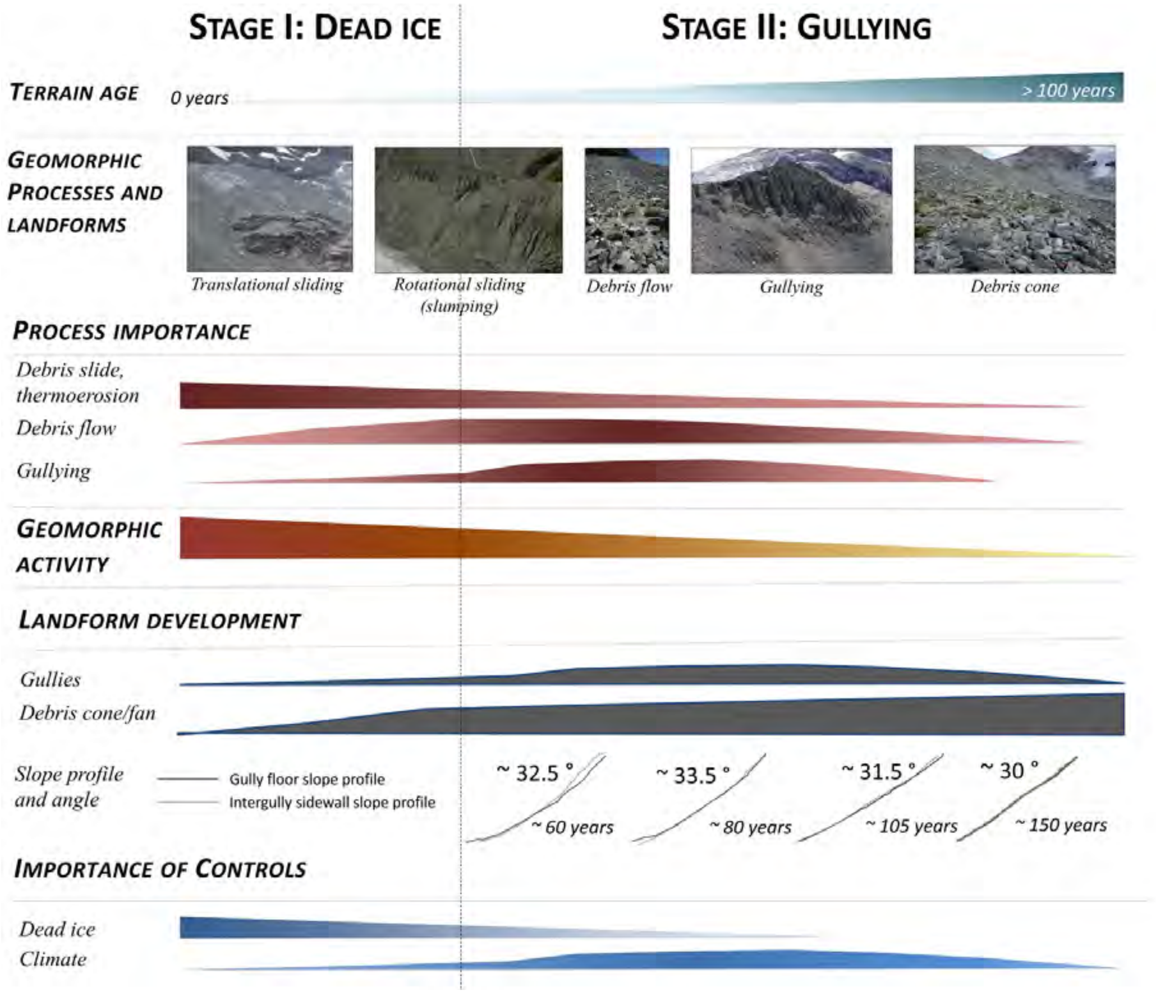

Figure 2.13: Illustration of process and landform succession, showing relevant geomorphic processes and landforms and changes in their importance, geomorphic activity, landform development and importance of control with increasing terrain age. Slope profiles and angles are taken from Curry et al., 2006.

has a mean slope angle of 29 +- 4 ° and is generally characterized by a straight upper slope, a small convex mid-slope, which can be made up by debris cones, and a concave slopefoot (Ballantyne and Benn, 1994; Curry et al., 2006). This lower slope angle can limit the occurrence of processes that need high slope angles, such as debris flows and gullying, and end the gullying stage.

In the central Swiss Alps, Curry et al. (2006) found that 50% of sediment was exhausted on lateral moraine slopes after 10-50 years following deglaciation, while the slope was stabilized (in terms of gullying processes) after 80 (Fee glacier) to 140 years (Glacier du Mont Miné). In glacier forelands in Norway, mature gullies are preserved for a longer time, which could be related to a moraine topography and sedimentology (Curry et al., 2006). Cossart (2008) pointed out that paraglacial processes can well occur intermittently due to intermittent triggers, such as snow melt and rainfall, and thus also re-occur after some years. This complicates the establishment of a timescale for paraglacial adjustment on lateral moraine slopes. In addition, it is not understood which role solifluction processes play during lateral moraine slope stabilization and what causes the end of paraglacial adjustment: vegetation stabilization, depletion of sediments or the attainment of the 'geological norm'.

2.5 Vegetation succession and biogeomorphic interactions in glacier forelands

This section is based on a book chapter currently in review:

Eichel, J. (in review): Vegetation succession and biogeomorphic interactions in glacier forelands. In: Heckmann, T. & D. Morche (eds): Geomorphology of proglacial systems - Landform and sediment dynamics in recently deglaciated alpine landscapes. Springer.

It provides a state-of-the-art summary of vegetation succession and biogeomorphic interactions in glacier forelands and therefore a main background for this thesis. In this section, the questions how long vegetation takes to establish in glacier forelands, which factors can limit vegetation succession and how and when glacial sediments can become stable due to biogeomorphic interactions, are addressed. The state-of-the-art review on vegetation succession in glacier forelands includes vegetation succession models, a general description of primary succession dynamics in glacier forelands and an evaluation of the role of disturbances for vegetation succession. Afterwards, current knowledge on biogeomorphic interactions in glacier forelands is reviewed, including interactions in glaciofluvial floodplains and between periglacial processes and plants. A case study on biogeomorphic dynamics on lateral moraine slopes in the Turtmann glacier foreland (Switzerland) summarizes the process of ecosystem engineering, conditions for biogeomorphic feedbacks and biogeomorphic succession dynamics. These will be explicated in later chapters of the thesis (Chapters 4, 5, 7, 8).

2.5.1 Abstract

Proglacial areas are not only the stage for glacial processes and paraglacial dynamics, which shape the landscape following glacier retreat. At the same time, the new terrain is colonized quickly by plants and animals. Different plant species follow each other in a sequence of successional stages. This sequence is controlled by both abiotic and biotic processes and depends on local, landscape and regional scale environmental factors, such as soil properties, topography and elevation. Yet, successional sequences are often disrupted or changed by disturbances. For example, geomorphic processes delay vegetation succession, limit its development to pioneer stages or change its pathways. However, vegetation succession is not only changed by disturbances, rather, plants can actively influence geomorphic processes. These biogeomorphic interactions control patterned ground, glaciofluvial floodplain and moraine slope development. Once geomorphic activity decreases to a certain degree, ecosystem engineer species can establish, e.g. the dwarf shrub *Dryas octopetala* on lateral moraine slopes. When plant biomass reaches a certain volume, it starts to affect geomorphic processes, e.g. interactions change the dominant process on moraine slopes from slope wash and slide to bound solifluction. These biogeomorphic feedbacks stabilize the glacial sediments and facilitate establishment for later successional species, such as trees.

2.5.2 Introduction

As stated by Jochimseny (1962), a glacier foreland is not a desert (‘*Das Gletschervorfeld – keine Wüste’).* Instead, once this new terrain it is exposed by the retreating glacier ice, it is quickly colonized by plants and animals. Vegetation succession and geomorphic processes interact in the course of paraglacial landscape adjustment. These ‘biogeomorphic interactions’ shape the glacier foreland and are therefore a very relevant control for proglacial landscape development.

In future decades, glacier foreland areas will further expand with ongoing glacier retreat due to climate change (Paul et al., 2004). If we envisage our present-day glacier forelands in 50 years, we do not only expect them to be larger, but also expect the now grey, bare moraine slopes and valley floors to have been colonized by vegetation. This colonization is important, as it stabilizes glacial sediments (Raymond Pralong et al., 2011), which otherwise frequently fill up reservoirs in forelands (Bogen, 1988; Hauenstein, 2005; Raymond Pralong et al., 2011). But how quick can plants colonize? It has been shown that high sediment reworking limits vegetation colonization (Curry et al., 2006; Moreau et al., 2008; Richter, 1994), so how long does it take until sediment reworking decreases sufficiently for vegetation to establish? In addition, plant colonization and development depend on species traits, which determine their ability to survive in active geomorphic environments (response traits) and to actively influence the occurring geomorphic processes (effect traits) (Corenblit et al., 2015; Violle et al., 2007). Based on their traits, some species could be more effective in stabilizing sediment in glacier foreland than others. But which species are these 'ecosystem engineers'? And are vegetated sediments permanently stable? This is important to know not only for sediment management, as debris flow occurring on lateral moraine slopes can also represent a natural hazard. It has been shown that high magnitude geomorphic processes can remove the stabilizing vegetation cover also in later stages of the vegetation succession. So, under which conditions are vegetation covered sediments stable?

The aim of this chapter is to provide some first answers from recent ecologic and biogeomorphic research by illustrating when and how plants and geomorphic processes interact in glacier forelands. In the following, the chapter considers these questions:

(1) Primary vegetation succession in glacier forelands: How long does it take for vegetation to establish after glacier retreat?
(2) Disturbances: What limits vegetation establishment?
(3) Biogeomorphic interactions: When and how are glacial sediments stabilized?

2.5.3 Vegetation establishment and succession

Vegetation succession is a gradual, directional change in the species composition and structure of ecosystems over a longer period of time (Dierschke, 1994; Matthews, 1992). In this process, a sequence of vegetation communities with different species compositions follows each other in a certain space (Tansley, 1920). Vegetation succession is initiated by processes disturbing the ecosystem (White, 1979), for example thunderstorms, volcanic eruptions, fire (Pickett and White, 1987). Based on the degree of 'biological inheritance' left after the disturbance, such as seeds and plant fragments, succession is classified into primary or secondary succession (Walker and del Moral, 2003). During primary succession, plants and animals colonize areas which were previously not colonized, while during secondary succession, species composition and other biotic properties change in an already existing ecosystem following the disturbance (MacDonald 2002). As the retreating glacier usually exposes bare terrain with no biological material (but see Fickert et al., 2007; Sharp, 1958 and others for counterexamples), vegetation succession in glacier forelands is a primary succession (Matthews, 1992).

2.5.4 Vegetation succession models

To understand and describe vegetation succession in time, diverse successional models were developed, which can be roughly divided into resource-based models, interaction-based models and trait-based models, which include strategy-based models (see Table 2.2).

In the resource-based succession model by Tilman (1988, 1985), the *'resource-ratio hypothesis'*, the availability of resources (e.g. nitrogen and light) controls colonization by species. A site is first colonized by the species that is best adapted to the resource level. As resource levels change in time due to soil development or nitrogen fixation, species composition changes with them. Interaction-based succession models comprise the *facilitation-based succession model* by Clements (1928), which is integrated into the *relay floristics model* (Clements, 1928; Egler, 1954) and the *'facilitation, tolerance and inhibition'-model* by Connell & Slatyer (1977). In both *facilitation-based succession* and *relay floristics models,* species change the environment (reaction), which in turn results in a sequential change of dominant species. This modification can improve environmental conditions, but limit the growth of the dominant species themselves. New species arrive and are able to establish due to the positive environment modification (facilitation). They replace the previously dominant species and in turn start to modify their environment.

Connell & Slatyer (1977) added two more types of interactions to Clement's facilitation in their *'facilitation, tolerance, inhibition'-model*. In this model, interactions between early and later successional species control the successional change. In comparison to Clements, this interaction cannot only be positive (facilitation), but also neutral (tolerance) or negative (inhibition). This results in different successional pathways. In the tolerance successional pathway, early-successional species don't affect later successional species, these only appear later because of their life history traits, such as lower growth rates. In the inhibition successional pathway, early-successional species can inhibit or completely exclude the colonization by later successional species. They are only replaced once they are killed, e.g. through a high-magnitude disturbance. The different successional pathways are not exclusive but continuum of possibilities, as early-successional species can have more than one effect on later successional species (Connell and Slatyer, 1977; McCook, 1994). The traits-based models include the *initial floristic composition model* (Egler, 1954), the *r- & K-strategists* (MacArthur and Wilson, 1967) and *CSR primary plant strategies models* (Grime, 1977), and the *'life history trait correlation model'* (MacCook, 1994).

Table 2.2: Summary of vegetation succession models with key statements.

Model type	Model	Nature of model
Resource-based models	‚resource ratio' hypothesis (Tilman, 1985, 1988)	Available resources control occurring species. Result: Changes of resources in time lead to changes of occurring species
Interaction-based models	Facilitation-based succession, relay floristics (Clements, 1928; Egler, 1954)	Dominant species modify their environment ('reaction'), new species arrive and can establish in modified environment ('facilitation'), replacement of previously dominant species. Result: Sequence of dominant species modifying their environment and subsequently replacing each other.
	Facilitation, tolerance, inhibition (Connell and Slatyer, 1977)	In addition to facilitation, early-successional species can occur together with later successional species (tolerance) or permanently inhibit other species (inhibition). Result: Sequential, simultaneous or singular occurrence of species.
Trait-based models, including strategy-based models	Initial floristic composition (Egler, 1954)	All species are present (diaspores) right from the start of succession, but their occurrence in the successional sequence mainly depends on their growth rates. Result: Herbs grow first, followed by shrubs, succeeded by trees.
	r- & K-strategists (MacArthur and Wilson, 1967)	Species strategies depend mainly on dispersal strategy, growth rates, and resource requirements. This determines sequential occurrence of species. Result: quickly growing r-strategists are succeeded by resource-intensive, competitive K- strategists
	CSR primary plant strategies (Grime, 1977)	Resource availability (stress) and disturbance intensity determine plant life history strategy types. These follow after each other depending on environmental conditions. Result: disturbance-adapted ruderal strategists are followed by competitive strategists with low disturbance and high resource levels, followed by stress strategists in a low resource environment
	Life history trait correlation (McCook, 1994)	Main life history traits (dispersal capacity, light requirements) inversely correlate and control successional sequence. Result: species with high dispersal capacities and light requirements produce shade and are replaced by shade-tolerant species

These models commonly assume that the successional sequence of species is controlled by differences in their life history traits (properties of species related to their growth, fertility and survival; Lavorel et al., 2007; Violle et al., 2007). These, and further plant traits (e.g. biomechanical traits such as root strength) also determine in which way resource stress and disturbances influence a species (plant strategy).

The *initial floristic composition (IFC) model* was developed by Egler (1954) as a counterpart to the *relay floristics model*. In the IFC model, all species are present right from the start of the succession as diaspores or plant fragments. Differences in their growth rates explain their sequential occurrence. Quickly growing herbs establish first and are followed by less quickly growing shrubs and trees. Thus, in this model differences in life-cycle traits control the sequential occurrence of species. In the plant strategy models, the sequential occurrence of species is controlled by the species' adaption to environmental constraints. In the r- & K-strategists model (MacArthur and Wilson, 1967), reproduction and growth speed *versus* survival capacity and competitiveness determine the species plant strategy. Colonization starts with r-strategists, which can quickly dispersal and thereby colonize disturbed sites. In time, they are replaced by K-strategists, which grow more slowly and need more resources, but can compete better for these. As an extension of the r- and K- strategist model, Grime (1977) classified plant life history strategy types based on species' adaption to stress (factors that limit photosynthesis) and disturbances (destruction of biomass). In a successional sequence, different strategists follow after each other due as stress and disturbance-levels change in the environment in time. Once disturbance intensity decreases and resource availability increases, the disturbance-adapted ruderal (R) strategist is succeeded by the competitor (C). In time, resource availability (high stress) and disturbance intensity decrease and the stress-tolerator (S) dominates.

The *life history trait correlation model*, MacCook (1994) takes up Egler's idea that life history traits control the sequential occurrence of species. In this model, dispersal and recruitment ability and light requirements are seen as correlated. Plants with wide dispersal and high recruitment ability often need much light, while slower growing species are often shade-tolerant, but grow higher and older.

Huston and Smith (1987) showed that if these life history traits correlate, quickly recruiting light-affine species are replaced slowly growing shade-tolerant species. MacCook (1994) suggests using this trait correlation for a more universal succession model that additionally integrates site-specific factors, such as species availability, disturbance level, history, patch dynamics and starting points.

As these models mainly emphasize biological processes, they have been criticized by Matthews (1992) for their limited power to explain primary succession in glacier forelands. Here, vegetation succession is also controlled by physical processes. In his *geoecological succession model*, Matthews (1992) combines physical and biological processes and describes their changing importance in the successional sequence. In the beginning, abiotic processes determine primary vegetation succession, while biotic processes control succession later (Raab et al., 2012).

Matthew's geoecological model is used to describe an exemplary primary glacier foreland succession in the following section, including its successional stages and trends.

2.5.5 Primary vegetation succession in glacier forelands

For primary successions in glacier forelands, the decreasing importance of abiotic processes with increasing terrain age is linked with a set *of abiotic successional trends*, describing changes in the abiotic environment in time, while the increasing importance of biotic processes is related to certain *biotic successional trends*, describing changes in vegetation properties in time (Figure 2.14) (Matthews, 1992; Milner et al., 2007).

Abiotic successional trends include improving environmental conditions with increasing terrain age, such as a proceeding soil development and increasing temperatures (Andreis et al., 2001; Matthews, 1992; Raffl et al., 2006). Indicators for proceeding soil development are increasing depths of soil horizons, increasing soil organic matter content and decreasing pH values (Matthews, 1992; Rydgren et al., 2014). How nutrient availability develops in time is unclear as it can both increase or decrease (Chapin et al., 1994; Rydgren et al., 2014). Temperatures increase with increasing distance to the glacier terrain age as glacier winds become less strong and the soil heats more easily due to more organic matter (Egli et al., 2011; Kaufmann, 2002).

Biotic successional trends are linked with the abiotic trends. In time, vegetation cover and biomass increase and vegetation stratifies into different layers with a physiognomic vegetation development from lichen and herbaceous plants to trees (Birks, 1980; Garibotti et al., 2011; Lüdi, 1945; Matthews, 1992). With increasing terrain age, more species occur until 40-80 years since deglaciation, afterwards, species numbers decrease (Matthews, 1999). Similarly, succession rates are quick until a terrain age of about 50 years and decrease afterwards (Rydgren et al., 2014). The linked trends in terrain age, soil development, species numbers and vegetation stratification has been termed 'terrain age factor complex' (Matthews, 1992; Matthews and Whittaker, 1987). As species composition changes, the dominant life forms, dispersal strategies and other traits also change (Chapin et al., 1994; Wilmanns, 1993).Caccianiga et al. (2006) found that ruderal species are replaced by stress tolerant species with increasing terrain age. This supports Grime's (1977) CSR-model. Thus, life history traits associated with species strategies strongly control the colonization process and succession rates (Erschbamer and Mayer, 2011; Schwienbacher et al., 2012).

How abiotic and biotic factors are linked to occurring species and their typical traits during succession is described in the following sections using *successional stages*. Successional stages are

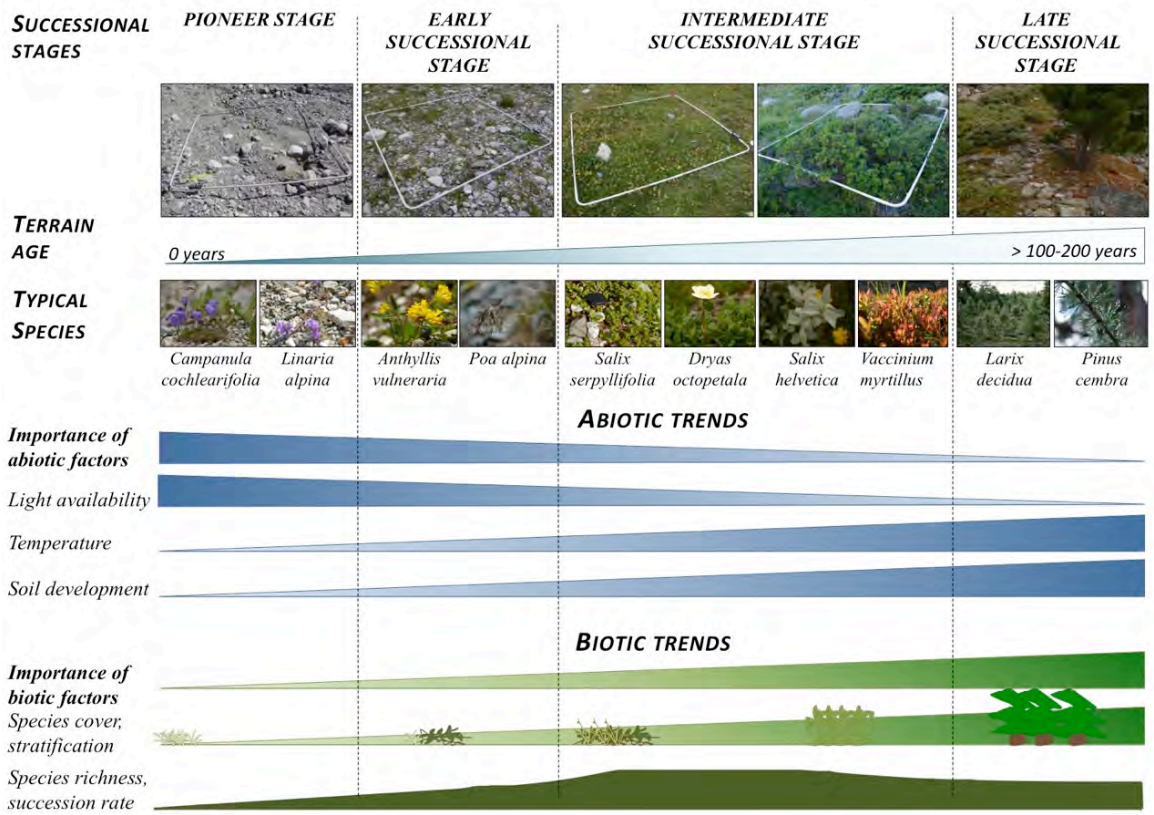

Figure 2.14: Successional stages and linked abiotic and biotic successional trends for primary succession in glacier forelands. Exemplary successional stages and typically occurring species are taken from Turtmann glacier foreland, Switzerland (cf. Eichel et al., 2013, 2016).

classified based on specific species compositions (Matthews, 1992) and can be linked to certain spans of time since deglaciation. Thereby, they are very useful to anchor the sequence of occurring species compositions in time, despite their limitations (cf. Matthews, 1992). The terrain age values used in the following paragraphs represent average values from several alpine glacier foreland successions (Eichel et al., 2013; Ellenberg, 1996; Nagl and Erschbamer, 2010; Robbins and Matthews, 2010).

Pioneer stage (terrain age ~ 0 to 15 years)

After glacier retreat, the newly exposed terrain is colonized within a few years time (Matthews, 1992; Nagl and Erschbamer, 2010), sometimes even within the first year (Cannone et al., 2008). Initial site conditions and species traits determine which species can establish where and after which time.

Initial site conditions include substrate (material) properties, climate and topography (Matthews, 1992; Matthews and Whittaker, 1987). Following glacier retreat, substrate properties change quickly through active processes such as deflation, pervection (downwashing of fine material from the surface) and frost sorting (Matthews and Vater, 2015). Low temperatures and glacier winds affect species growing close to the glacier (Kaufmann, 2002; Matthews, 1992). On a larger spatial scale, elevation and aspect control site-specific climatic properties, such as temperature, wind, solar radiation (Körner, 2003), which in turn control species compositions and successional pathways in glacier forelands (Raffl et al., 2006; Robbins and Matthews, 2014). On a small spatial scale, seedling germination and establishment often depends on microtopographic safe sites, such as depressions or larger rocks. In these protected areas, conditions are more favourable then elsewhere (Cooper et al., 2004; Nagl and Erschbamer, 2010; Raffl et al., 2006).

However, even if conditions are favourable for colonization, diaspores first have to reach the respective site: if none are available, vegetation cannot colonize and develop (Erschbamer et al., 2008; Nagl and Erschbamer, 2010). Pioneer diaspores are often transported by wind (anemochorous), while adapted species traits promote seedling germination and establishment under unfavorable conditions. Pioneer species (e.g. *Linaria alpina, Campanula cochlearifolia, Saxifraga aizoides;* Figure 2.14) are often ruderal strategists (Caccianiga et al., 2006), which can disperse well due numerous (several thousands) small, wind-dispersed seeds that are very fertile (Nagl and Erschbamer, 2010). Pioneer species germinate and survive at cold and moist conditions and can tolerate high solar radiation (Robbins and Matthews, 2014; Stöcklin and Bäumler, 1996). Once established, they possess high growth rates (Marcante et al., 2009). Nevertheless, the mortality of seedlings, plantlets and young individuals is still high (Marcante et al., 2009), while individual density (3-4 individuals per m^2) and vegetation cover are low (< 10%) in the pioneer stage (Nagl and Erschbamer, 2010). In addition, lichen and other cryptogames are also important colonizers at the pioneer stage (Garibotti et al., 2011).

Early-successional stage (terrain age ~ 15 to 40 years)

Within one to two decades, pioneers die back due to age constraints and vanish from the sites. Early-successional species (e.g. *Anthyllis vulneraria, Poa alpina, Trifolium pallescens;* Figure 2.14) start to dominate under improved environmental conditions with higher temperatures, advanced soil development and a stabilized substrate (Matthews and Vater, 2015). They are often ruderal or intermediate strategists and can fix nitrogen in the developing soil (Caccianiga et al., 2006; Kuen and Erschbamer, 2002; Raffl et al., 2006; Schweingruber et al., 2007). At this stage, cryptogamic crusts also commonly develop and stabilize the ground (Matthews and Vater, 2015). Due to this facilitation, further species can establish and vegetation cover (*30-50 %)* and species numbers increase (Matthews, 1992; Raffl et al., 2006).

Intermediate successional stage (terrain age ~ 40 – 80 years)

Most species occur 40-50 years after glacier retreat and create a high vegetation cover (around 60 to 70 %). The larger and less numerous diaspores of the later successional species are often transported into the foreland by geomorphic processes originating at the steep slopes outside the glacier foreland, such as avalanches and debris flows (Nagl and Erschbamer, 2010; Raffl et al., 2006). In the intermediate successional stage, vegetation stratification starts with the occurrence of shrub species (e.g. *Salix* spp.; Andreis et al., 2001; Nagl and Erschbamer, 2010; Raffl et al., 2006). Spatially variable snow and moisture conditions lead to the co-occurrence of different vegetation communities in the intermediate successional stage (Ellenberg, 1996). Common communities are initial alpine grasslands (e.g. *Elynetum*), snowbed communities (e.g. *Salix herbaceae* and *Salix retusae-reticulatae*) in areas with late lying snow or other grassland communities dominated by dwarf shrubs (*Dryadeto-Firmetum*; Eichel et al., 2013; Ellenberg, 1996; Robbins and Matthews, 2014). Intermediate successional species often actively contribute to soil development, for example by producing an organic matter layer (*Elyna myosuroides*) or further nitrogen fixation (*Dryas octopetala*) (Reisigl and Keller, 1994).

Late-successional stage (terrain age > 80-100 years)

In the late-successional stage, stratification is pronounced with the occurrence of tree species (e.g. *Larix decidua*). In their shadows, shade plants (e.g. *Pyrola minor*) replace less competitive light adapted species (Raffl et al., 2006; Robbins and Matthews, 2014; Schweingruber et al., 2007). Late-successional species are often stress strategists (e.g. *Carex curvula*) that are less able to disperse and less fertile than pioneer species, but can grow more quickly and survive despite competition (Caccianiga et al., 2006; Marcante et al., 2009; Stöcklin and Bäumler, 1996). The mature vegetation in the stage has often been called ‘climax community’ (mature plant community determined by climatic conditions; Whittaker, 1974). However, this view has been strongly challenged, as a variety of alternative mature communities (grassland, dwarf shrub, shrub or forest communities) can occur in one area (Matthews and Whittaker, 1987). On a longer time scale, vegetation change is a constant process, thus, a final, permanent ‘climax’ may never reached as it is replaced other communities (Matthews, 1992).

2.5.6 What disrupts the simple successional sequence?

In reality, vegetation succession in glacier forelands is often not a linear, straightforward sequence of successional stages. Instead, vegetation succession rates and successional pathways can strongly differ within and between different glacier forelands (Matthews, 1992; Matthews and

Whittaker, 1987; Raffl et al., 2006). On a local scale, spatially variable environmental conditions affect succession pathways and rates, while aspect and topography create different successional dynamics on a landscape scale (Garibotti et al., 2011; Raffl et al., 2006; Rydgren et al., 2014). On a regional scale, they are controlled by bioclimatic gradients such as altitude, and continentality (Robbins and Matthews, 2010, 2014).

Local scale spatial variability of soil texture and moisture produces fine scale vegetation patterns, as fine material enhances plant establishment by providing a steady water supply due to its a high water retention capacity (Jochimsen, 1962; Nagl and Erschbamer, 2010). In contrast, blocky material is colonized very slowly (Ellenberg, 1996; Lüdi, 1958). Differential successional rates and pathways can result from the differential colonization (Burga et al., 2010). In the course of succession, local scale differences become less important and successional pathways often converge (Garibotti et al., 2011; Prach and Rachlewicz, 2012).

At the landscape scale, Raffl et al. (2006) showed the importance of aspect for vegetation succession in the Rotmoosferner foreland (Austria). They found different successional pathways on the northeast and southwest exposed valley sides, which relate to differences in solar radiation, lithology and the occurrence of geomorphic processes. Furthermore, topographic parameters control vegetation succession dynamics, such as the slope toposequence of lateral moraine slopes (Minami et al., 1997; Vetaas, 1997). Species composition is variable along the toposequence gradient due to different successional trajectories at moraine slope base, mid-slope and crest (Andreis et al., 2001; Garibotti et al., 2011). This gradient was attributed to 'microtopographic factor complex' by Matthews and Whittaker (1987), which is more effective on lateral moraine slopes at the valley bottom (Andreis et al., 2001; Garibotti et al., 2011). Regionally, altitude and climate characteristics (e.g. continentality) influence succession rates and pathways. At higher altitudes, successional rates are slower (Körner, 2003; Robbins and Matthews 2010, 2014) and mature stages often do not contain tree species, as these do not occur above certain altitudinal limits (Ellenberg, 1996; Körner, 2003; Robbins and Matthews, 2010, 2014).

A further important factor influencing succession dynamics at the landscape scale is disturbance (Matthews, 1999; Raffl et al., 2006; Richter, 1994). How disturbances influence vegetation succession will be described in the following section.

2.5.7 The role of disturbances for vegetation succession in glacier forelands

Disturbances are destructive events that disrupt ecosystem, community or population structure, irrespective of if they are normal for the system or not (Pickett and White, 1987). This disruption also includes changes in resources, in substrate availability or in the physical environment in general. How disturbances modify both the physical environment and vegetation succession was often ignored (Matthews, 1999) by preferably selecting stable sites to study undisturbed glacier foreland succession (Prach and Rachlewicz, 2012; Robbins and Matthews, 2014). This bias in data collection may be a main reason for the fact that terrain age has long been considered more important than other environmental factors such as disturbances (Rydgren et al., 2014). Thus, secondary disturbances limit the applicability of the frequently used chronosequence (space for time) approaches by disrupting the time-dependent patterns of vegetation development (Matthews, 1999).

In glacier forelands, geomorphic processes are most important in disturbing vegetation succession, besides wind-related, animal and human disturbances. Secondary disturbances affect large areas (up to 50%) of the glacier foreland (Oliver et al., 1985) and play a fundamental role in primary succession by modifying the substrate (erosion, deposition, mixing), damaging plants and influencing nutrient availability (Caccianiga et al., 2006; Matthews, 1999). Thereby, they can delay, slow down or revert the successional process (retrogressive changes; Birks, 1980; Matthews, 1992; Matthews and Whittaker, 1987). Due to disturbances, species composition and successional pathways can differ at terrain of the same age (Eichel et al., 2013; Matthews, 1999; Moreau et al., 2008; Oliver et al., 1985). However, disturbances can also positively affect succession by transporting diaspores (Matthews, 1999; Raffl et al., 2006).

The glacier and its dynamics of advance and retreat strongly control disturbances in glacier forelands. Based on this relationship, Matthews (1999) classified disturbances in glacier forelands into glacial, glacial-dependent, glacial-conditioned (paraglacial) and glacial-independent.

Glacial disturbances

Glacial disturbances are disturbances due to direct contact between glacier ice and ecosystems, such as overriding during glacier advances, material deposition directly from glacier (especially by debris flows) onto plants or slumping of moraines through dead-ice melt. Thus, glacial disturbances are limited to the area close to the glacier (Matthews, 1999).

Glacier-dependent disturbances: glaciofluvial processes

Though ecosystems are not in a direct contact with the glacier ice, they can still be influenced by it and its melt. These glacier-dependent disturbances include glacio-climatic disturbances, which are often limited to the area close to the glacier, such as glacier winds; glacio-hydrologic disturbances, such an increased soil moisture close to the glacier due to ice melt and glaciofluvial disturbances by meltwater streams. In the foreland of the Midtre Lovénbreen glacier on Svalbard (Norway), (Moreau et al., 2004, 2005, 2008) showed that glaciofluvial processes delay and disrupt vegetation succession and can more strongly determine species composition than terrain age. Pioneer stages continuously occur next to later successional stages at older terrain due to permanent disturbance by active glaciofluvial runoff (Moreau et al., 2004). In addition, newly developing channels on previously stable, older terrain can also trigger a regressive vegetation development: pioneer stages re-occur and replace later successional (Moreau et al., 2008). Thus, glaciofluvial processes produce a time-independent mosaic of vegetation stages in the glacier foreland and different successional pathways (Cowie et al., 2014; Moreau et al., 2008).

Glacier-conditioned (paraglacial) disturbances: periglacial and hillslope processes

Glacier-conditioned disturbances are disturbances conditioned by glacier retreat and its effect on material properties, thus, paraglacial disturbances (Ballantyne, 2002b; Matthews, 1999). They include aeolian deflation, loess-like re-deposition, pervection, periglacial and hillslope processes (Matthews, 1999) and affect vegetation succession in the same way as glaciofluvial processes:

Due to periglacial processes such as cryoturbation and patterned ground development, colonization is delayed, pioneer stages persist on older terrain and local scale vegetation patterns occur in glacier forelands (Haugland, 2006; Haugland and Beatty, 2005; Matthews and Whittaker, 1987). Close to the glacier, patterned ground quickly develops within 10 years of deglaciation (Haugland and Beatty, 2005) Colonization of the patterned ground landforms by vascular plants is however delayed as frost heave damages their roots and dries up the soil (Haugland and Beatty, 2005; Matthews, 1999). Lichen and other bryophytes are important colonizers at this stage, as they can withstand low levels of frost disturbance (Matthews et al., 1998). Pioneer vascular plant species (mainly grasses and sedges) can only colonize once frost activity decreases. This happens first at the patterned ground borders, were frost heave is less active due to reduced moisture in the quickly draining coarse material (D'Amico et al., 2014; Haugland and Beatty, 2005; Thorn, 1976). Patterned ground centres remain active for a longer time due to their frost-susceptible fine material and are colonized several decades later (Haugland and Beatty, 2005). When frost activity declines, shrubs start to replace pioneer species first at the borders and later in the centre. After 70-80 years, the colonization of the centres draws level with the borders, however, a late-successional stage was not reached (Haugland, 2006; Haugland and Beatty, 2005). Similar to vegetation succession, soil development is delayed by active frost processes. Once activity decreases, horizons and organic matter develop together with vegetation colonization at the

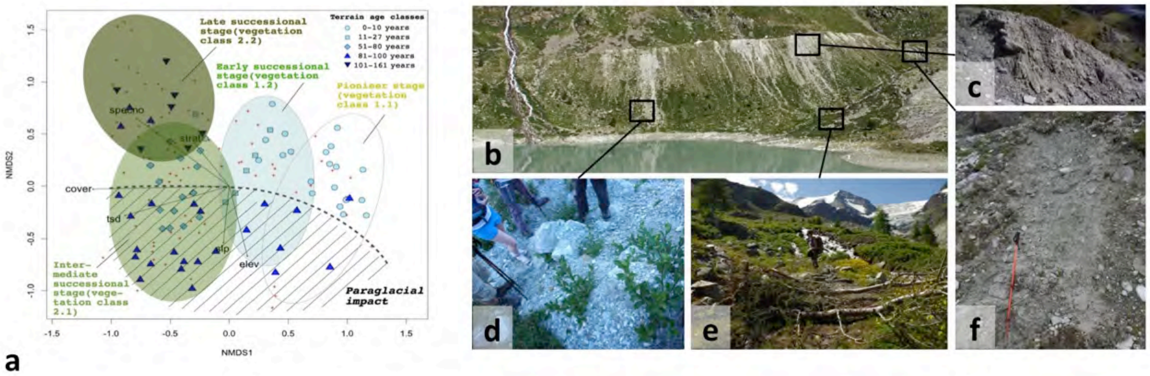

Figure 2.15: Paraglacial impact by slope processes on vegetation succession in the Turtmann glacier foreland. **A** Paraglacial impact showing in the NMDS result of vegetation plot data, overlay with terrain age classes. NMDS1 axis is related to time since deglaciation, ecosystem development (vegetation) cover and a successional sequence. At areas with high slope gradient, elevation (NMDS2 axis) and terrain age (lateral moraine slopes), three different successional stages were found, which can be attributed to a paraglacial impact by slope processes, taken from Eichel et al., 2013. **B** Lateral moraine slope in the Turtmann glacier foreland disturbed by different slope processes. **C** Active slope wash inhibiting vegetation colonization at the lateral moraine crest. **D** *Sali*x spp. shrubs at the lateral moraine foot buried by a debris flow. **E** *Larix decidua* tree uprooted at the moraine slope by a snow avalanche. **F** A small shallow landslide removing vegetation at the moraine crest in 2015

patterned ground borders (Haugland, 2006). Thus, periglacial processes result in different successional pathways and a local scale mosaic of different vegetation and soil development stages in the glacier foreland.

On moraine slopes and in their surroundings, hillslope processes are the main disturbance agent (Eichel et al., 2016; Garibotti et al., 2011; Moreau et al., 2004; Raffl et al., 2006). In the Turtmann glacier foreland (Switzerland), Eichel et al. (2013) found that the sequence of successional stages is disrupted in areas with high slope gradient and elevation at terrain age 81-100 years: the lateral moraine slopes (Figure 2.15). While a later successional stage would be expected at this terrain age (Matthews, 1992), pioneer, early and late-successional stages occur next to each other on the lateral moraine slopes. This can be attributed to active paraglacial slope processes: despite their age, the lateral moraine slopes are still reworked by highly or moderately active processes, such as slope wash (Figure 2.15 C), debris flows (Figure 2.15 D), snow avalanches (Figure 2.15 E) or shallow landslides (Figure 2.15 F). They produce pioneer stages and early-successional stages, delay or reverse vegetation succession and different successional pathways occur (Eichel et al., 2013; Moreau et al., 2004).

According to the paraglacial concept, the impact of glacier-conditioned disturbances should decrease in time as sediment is consolidated or exhausted and slopes stabilize due to a protective vegetation cover (Matthews, 1999; Robbins and Matthews, 2010). However, the described studies show that glaciofluvial, periglacial and slope processes can affect vegetation succession even several decades after deglaciation and leave a persistent imprint on vegetation patterns for more than a century.

Glacier-independent disturbances

Glacier-independent geomorphic disturbances include avalanches, debris flows and other gravitative processes that enter the glacier foreland from adjacent slopes. Further glacier-independent disturbances are nivation from late lying snow, windthrow and animal and human disturbances. In comparison to glacier related disturbances, these processes can be viewed as exogenous to the glacier foreland and are not controlled by terrain age (Matthews, 1999).

2.5.8 Biogeomorphic interactions in glacier forelands

While it was shown for several glacier forelands how disturbances impact vegetation succession, very few studies investigated the reverse effect: how plants influence the occurrence of disturbances, and how vegetation succession and disturbances interact (Eichel et al., 2016; Matthews and Vater, 2015). Biogeomorphology studies these reciprocal interactions between geomorphic processes, landforms, plants and vegetation development. Biogeomorphic research, especially in fluvial, coastal and arid environments showed not only how geomorphic processes influence vegetation colonization and development, but that plants and their spatial patterns can actively control their occurrence (Balke et al., 2014; Corenblit et al., 2007, 2015; Gurnell, 2014; Gurnell et al., 2012). It is believed that biogeomorphic interactions are strongly controlling landscape development in environments with highly active geomorphic and vegetation dynamics (Corenblit et al., 2015; Viles, 2004). Therefore, these environments are called '*biogeomorphic ecosystems*' (Balke, 2013; Corenblit et al., 2015) and glacier forelands, in which geomorphic processes rework high amounts of sediments while vegetation develops at the same time, are one of them.

So far, biogeomorphic interactions have been described for glaciofluvial floodplains (Gurnell et al., 2000; Moreau et al., 2008), patterned ground development (Haugland, 2006; Matthews et al., 1998) and lateral moraine slopes (Eichel et al., 2013; 2016; see next section).

Biogeomorphic interactions in glaciofluvial floodplains

In glaciofluvial floodplains, the channel pattern development is controlled by interactions between riparian vegetation development and glaciofluvial dynamics. Gurnell et al. (2000) describe these interactions in a conceptual model, which links the development of channel patterns with increasing distance to the glacier (downstream gradient) to riparian vegetation succession (Figure 2.16).

How glaciofluvial and vegetation dynamics interact in proglacial areas in time could be interpreted as a '*fluvial biogeomorphic succession*' *sensu* Corenblit et al. (2007). This biogeomorphic succession concept describes how the dominance from physical (geomorphic) to biotic (vegetation) processes changes within a decadal successional timescale following a destructive flood. Four biogeomorphic successional phases show how interactions between plants and fluvial change in time. As for glacier forelands the retreating glacier initiates glaciofluvial floodplain development and vegetation succession, the different phases of channel pattern development could be interpreted as biogeomorphic successional phases (Figure 2.16). (1) *Geomorphic phase*: In the bar braided section close to the glacier, sediment input is high, geomorphic processes dominate and inhibit vegetation colonization. Channel bank strength is low, as stabilizing vegetation cover is missing. Therefore, the multiple channels constantly shift (Gurnell et al., 2000; Moreau et al., 2008). (2) *Pioneer phase*: With increasing distance to the glacier and terrain age, pioneer species start to colonize the channel banks and bars of the braided channel pattern. With developing vegetation cover, plants' above and below ground biomass increases. In the (3) *biogeomorphic phase*, glaciofluvial processes and vegetation start to interact. Below ground biomass, such as roots, increases bank strength, which in turn limits lateral erosion and thereby reduces channel width. Above ground vegetation biomass increases surface roughness, reduces flow velocities, protects from scour and enhances rate of sediment deposition. This promotes floodplain aggradation, which in turn increases bank height. Less sediment is supplied to the downstream sections of the river. The channel pattern type changes to a transitional type with a decreasing number of channels (Gurnell et al., 2000; Moreau et al., 2008). In the Midtre Lovénbreen glacier foreland, Moreau et al. (2008) observed that this takes about 30 years. Woody plant species, such as *Salix* spp. shrubs, play a special role for the transition. Through their adapted traits, such as robust root networks, they act as ecosystem engineers in fluvial systems (Gurnell, 2014). At this stage, vegetation succession proceeds in channels with only intermittent snow or ice-melt runoff or in inactive channels (Moreau et al., 2008). With increasing vegetation cover and channel stabilization, the channel pattern develops to a single thread or island braided with vegetated islands. In this (4) *ecologic phase*, vegetation builds up stable communities (Moreau et al., 2008) and exerts a major control on the glaciofluvial system (Gurnell et al., 2000). The importance of biogeomorphic interactions decreases and biotic processes, such as competition,

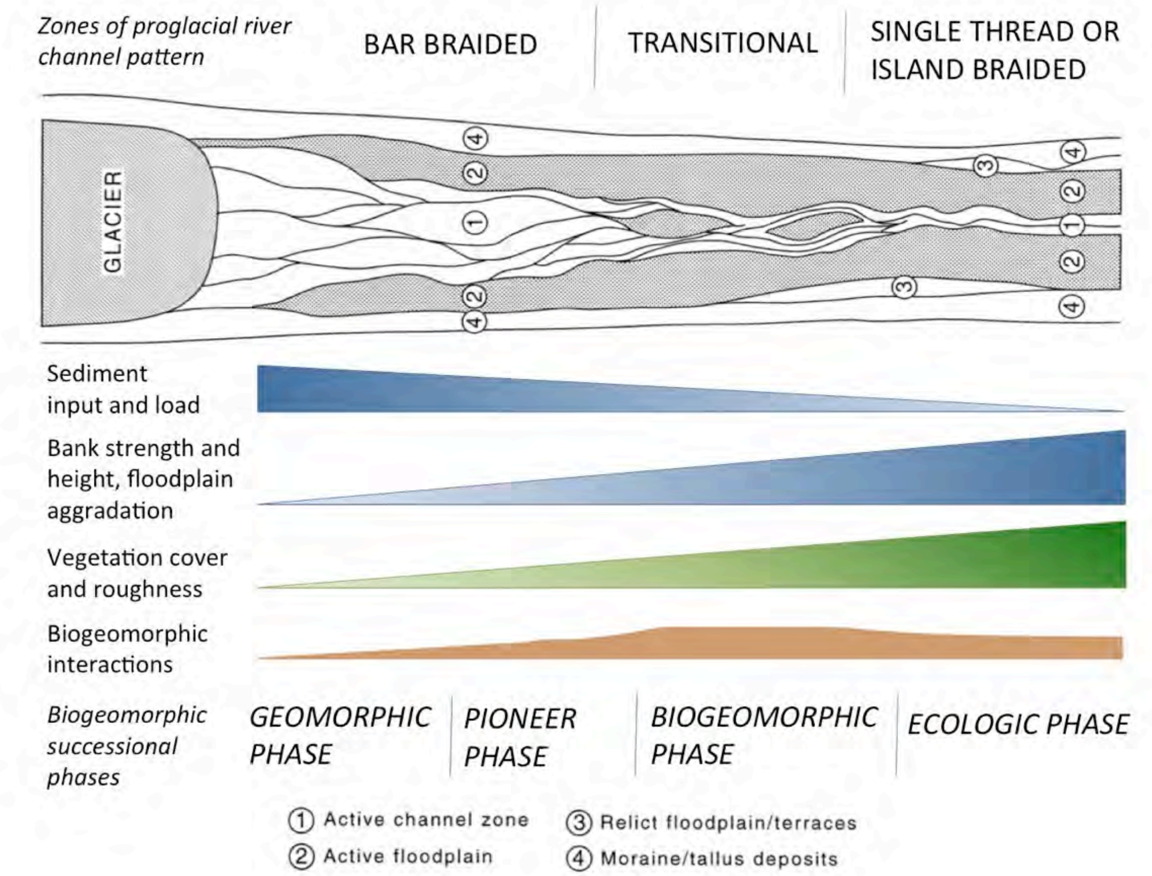

Figure 2.16: Interactions between riparian vegetation and channel pattern development in a glaciofluvial floodplain. Channel pattern changes and associated changes in sediment and vegetation properties are related to biogeomorphic successional phases *sensu* Corenblit et al. (2007). Illustration of channel pattern taken from Gurnell et al., 2000.

become the dominant drivers of vegetation change. Downstream disturbances such as lateral inputs of water or sediment from surrounding slopes or the presence of rock steps can disrupt the sequence of biogeomorphic succession (Gurnell et al., 2000).

Furthermore, whether interactions occur and how quick the biogeomorphic succession proceeds also depends on factors controlling vegetation succession (see above), such altitude, successional pathways and late-successional species composition.

Interactions between periglacial processes and plants

While periglacial processes disturb vegetation succession, plants at the same time influence them through their effects on the thermal, hydrological and mechanical regime of the soil (Benninghoff, 1952; Matthews et al., 1998). These interactions control patterned ground activity and vegetation development and patterns in glacier forelands. In his theoretical geoecological model of patterned ground development, Haugland (2006) explains that plants can only colonizes patterned ground landforms once their activity decreases due to reduced water contents, a decline of slope angle and a textural change. These changes are linked to the proceeding paraglacial adjustment (Matthews et al., 1998). Once plants establish, multidirectional interactions between frost activity, vegetation colonization and soil development start, first at the patterned ground borders and later in the landform centre (Haugland, 2006). Vegetation influences frost activity by changing the thermal and moisture regime of the soil, e.g. by shading, retaining moisture and intercepting rain (Benninghoff, 1952; Ghestem et al., 2011). Plant roots decrease the soil movement by increasing soil shear strength and reinforcing the soil matrix (Ghestem et al., 2011, 2014).

2.5.9 Case study: Biogeomorphic dynamics on lateral moraine slopes in the Turtmann glacier foreland, Switzerland

So far, it is not well understood if and how vegetation stabilizes lateral moraine slopes and which role paraglacial processes play for vegetation succession. Curry et al. (2006) and Mercier et al. (2009) challenged the view that vegetation colonization is a major cause for slope stabilization (Ballantyne, 2002a). They found that plants only colonize moraine slopes once these have reached a certain degree of stability. This research gap was addressed by recent research within the BIMODAL ('Biogeomorphic interactions in the Turtmann glacier foreland, Switzerland') project (Figure 2.17) (Eichel et al., 2013, 2016). This project investigates (i) if some species can stabilize the slopes better than others, (ii) under which conditions these species can establish and interact with occurring geomorphic processes and (iii) how interactions between vegetation and

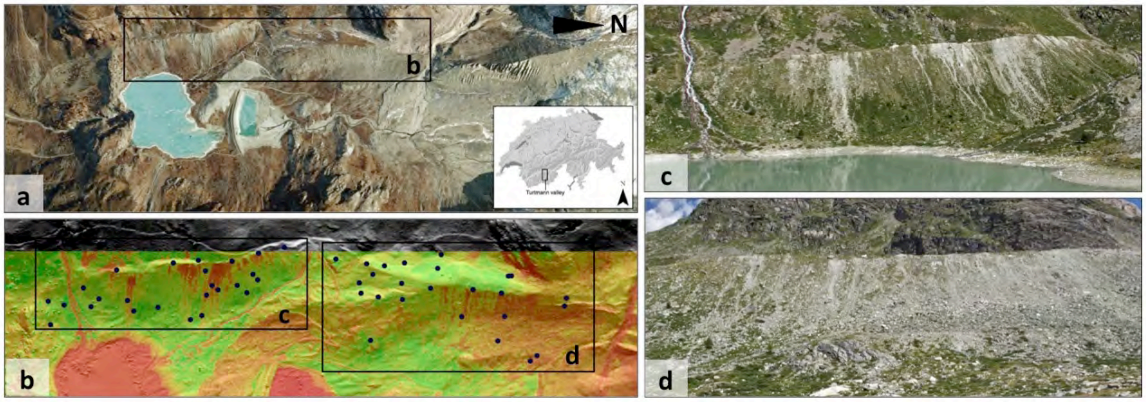

Figure 2.17: Lateral moraines in the Turtmann glacier foreland, Switzerland. **A** Location of Turtmann glacier foreland and location of lateral moraines within the foreland. **B** Location of permanent plots (blue dots) on the lateral moraine slopes. **C** Lateral moraines with a terrain age of 80-100 years, showing complex patterns of geomorphic activity and vegetation. **D** Lateral moraine slopes with a terrain age of 60-80 years.

paraglacial dynamics develop in time. Mainly permanent plot survey data (see Figure 2.17 B for plot location), which included vegetation properties, the occurrence of geomorphic processes, material properties, geomorphometry and terrain age, was used answer to these questions. A summary of the current results is provided below.

Ecosystem engineering by Dryas octopetala *L.*

Biogeomorphic research showed that some species can more effectively effect their environment than others (Corenblit et al., 2015; Gurnell, 2014). These *ecosystem engineers* are species that change their physical environment through their adapted traits and thereby create habitats for other species (Jones et al., 1994; Jones, 2012). On lateral moraine slopes, *D. octopetala* was identified as an ecosystem engineer (Eichel et al., 2016). Permanent plot data showed that geomorphic activity permanently decreases once *D. octopetala* reaches a cover value of 35%. Above this cover value, the dominant geomorphic processes change from slope wash and slide to. *D. octopetala* induces these changes through its adapted morphological and root traits. Through its strong and deeply rooted woody rootstock (Figure 2.18 B), it is firmly anchored even on moving slopes. Its branching fine lateral and coralloid root systems is associated with ectomycorrhiza (Figure 2.18 B; Reisigl and Keller 1994; Ellenberg 1996; Kutschera et al., 1997; Harrington and Mitchell, 2002). Together, they increase soil aggregate and the angle of internal friction and thereby enhance slope stability (Bast et al., 2014; Graf et al., 2009). By growing in a mat with low-lying stems, branches and numerous leaves (Figure 2.18 A), *D. octopetala* accumulates fine sediments, biomass, humus and diaspores (Figure. 2.18 C, D), stores moisture and limits soil erosion at the same time (Körner, 2003; Reisigl and Keller, 1994; Welker et al., 1997). As fine material and soil moisture promote the solifluction process (Harris et al., 2008), solifluction is probably favoured below the *Drya*s mat. These interactions between *D. octopetala* and solifluction could promote the development of turf-banked solifluction lobes, making these ‚biogeomorphic structures' (Corenblit et al., 2010a; Eichel et al., 2016). By stabilizing the slope, accumulating material and fixing nitrogen, *D. octopetala* acts as a nurse plant for other species (Figure 2.18 e, f) and promotes further ecosystem development to grassland associations, e.g. the intermediate or later successional *Elynetum* (Elkington, 1971; Ellenberg, 1996; Klanderud and Totland, 2004; Reisigl and Keller, 1994). Thus, ecosystem engineering by *D. octopetala* influences both paraglacial adjustment and vegetation succession on lateral moraine slopes (Eichel et al., 2016). Probably, species with similar traits, such as the *Salix* dwarf shrubs *Salix reticulata* and *Salix*

Figure 2.18: Engineering traits of *Dryas octopetala* L. **A** Mat growth of *D. octopetala*, covering moving debris. **B** Main root stock, branching after some cm into finer lateral roots. **C** Fine material accumulation in the bottom side of the *Dryas* mat. **D** Humus accumulation and fine roots within the mat. **E, F** Facilitation for other species (*Leontopodium alpinum* CASS. and *Campanula cochlearifolia* LAM). Taken from Eichel et al., 2016, p. 413.

serpyllifolia, also affact lateral moraine slope development, but to a lesser degree as they do not grow in mats as pronounced as *D. octopetala* (cf. Körner, 2003; Schröter et al., 1926).

Conditions for biogeomorphic feedbacks: a ‘biogeomorphic feedback window’

As ecosystem engineers interact with geomorphic processes, they have to be able to establish and reach a certain value of cover or biomass for biogeomorphic interactions to occur (Balke et al., 2014). Permanent plot data from the Turtmann glacier foreland showed that whether *D. octopetala* occurs and develops depends on the magnitude and frequency of the geomorphic processes, the *geomorphic disturbance regime* (Pickett and White, 1987; Turner et al., 2001). Eichel et al. (2016) found that disturbance regime and species composition are interrelated on their lateral moraine slopes. They determined how resistant the dominantly occurring species are towards disturbances and how quickly they can recover after a disturbance (resilience) based on their traits. By linking species resilience and resistance to the geomorphic disturbance regime, Eichel et al. (2016) identified the conditions under which *D. octopetala* can establish and biogeomorphic interactions can occur (biogeomorphic feedback window) (Figure 2.19).

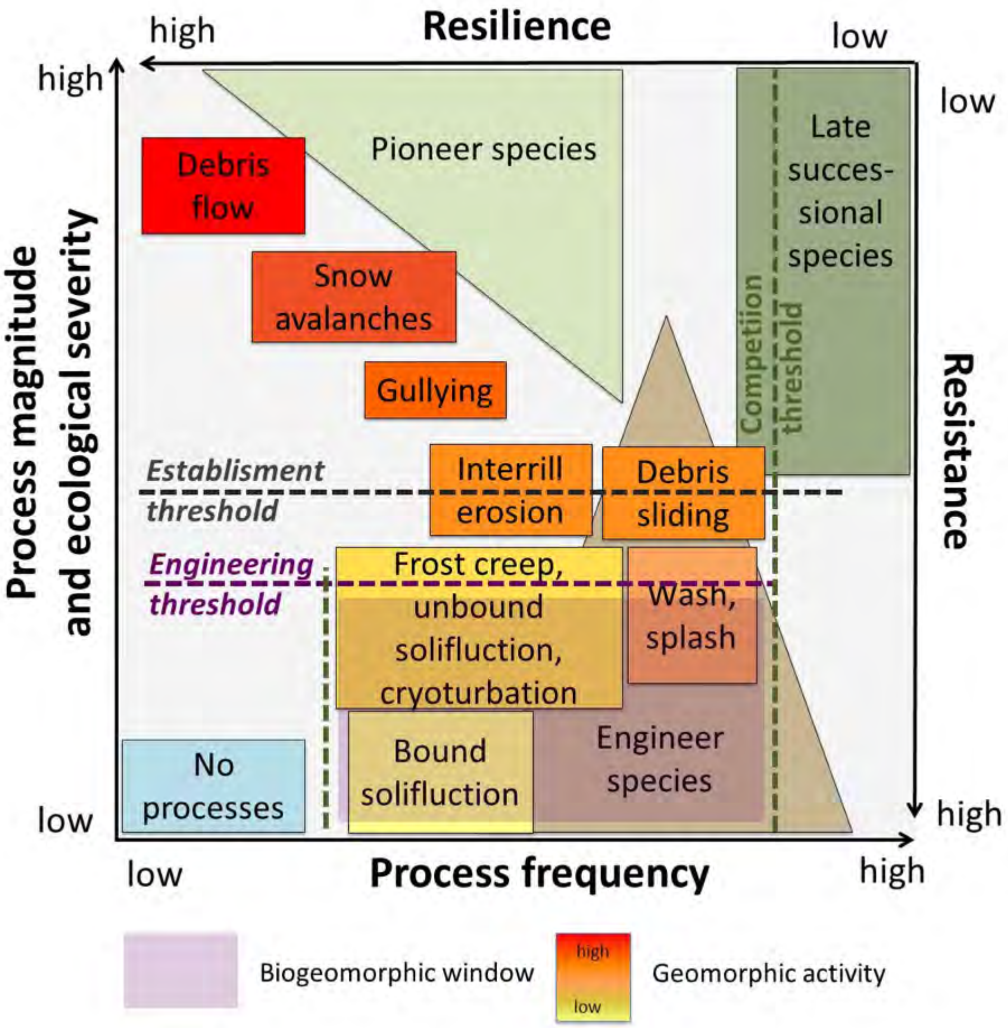

Figure 2.19: The biogeomorphic feedback window, showing how the relationship geomorphic disturbance regime (process magnitude, ecologic severity, process frequency) and plant species traits (resilience and resistance) controls the occurrence of biogeomorphic feedbacks once an establishment and engineering threshold are crossed. Taken from Eichel et al., 2016, p. 415.

When processes with a high magnitude (gullying, debris flows) or frequency (interrill erosion, debris sliding) occur, vegetation colonization is limited. Only species adapted to these conditions can establish and grow, for example the pioneer species *Linaria alpina* (Figure 2.19). Its root system and stems are adapted to debris movements and it can quickly re-establish after being destroyed by disturbance (Ellenberg, 1996; Rauh, 1939; Schröter et al., 1926). Therefore, *Linaria alpina* possesses an intermediate resistance, but high resilience. As the engineer species *D. octopetala* grows very slowly, it needs a long time to re-establish after a disturbance (low resilience) (Hendry and Grime, 1993) and does not grow when disturbances occur frequently. When slopes stabilize in the course of paraglacial adjustment, either the process frequency or the magnitude of the occurring processes decrease (Ballantyne, 2002b; Mercier et al., 2009). This gives *D. octopetala* sufficient time or more suitable conditions (less sediment movements) to successfully establish in a '*window of opportunity*' *sensu* (Balke et al., 2014, 2011). Due to its high root strength, it can firmly anchor in the slope. *Dryas* cover and biomass increase and can cross an engineering threshold: geomorphic activity permanently decreased when *D. octopetala* covered around 35% of the plot. The 'biogeomorphic feedback window' is reached in which *Dryas* limits sediment transport and changes soil texture and moisture. Bound solifluction becomes dominant and the geomorphic disturbance regime changes. Species that are less adapted to slope movement, such as *Salix* shrub species with low-resistant woody roots, can establish. These late-successional species take a long time to establish (low resilience). However, their higher competitiveness enables them to replace the engineer species (Caccianiga et al., 2006). Once this competition threshold is crossed, the 'biogeomorphic feedback window' ends and later successional species dominate in a geomorphically stabilized environment. Thus, biogeomorphic feedbacks on lateral moraine slopes start when the engineer establishes and develops a large cover, thereby changing the disturbance regime to from wash and slide to bound solifluction in the biogeomorphic feedback window (Eichel et al., 2016).

Biogeomorphic succession dynamics

At a terrain age of 81 to 100 years, three different vegetation classes were found in the Turtmann glacier foreland, which are related to different degrees of geomorphic activity (Fig 2.20 A, Eichel et al., 2013). Vegetation class 1 is characterized by pioneer species and occurs in areas with high geomorphic activity. Vegetation class 2 is marked by dwarf shrub species, which occur with moderate geomorphic activity, while vegetation class 3 is characterized by shrub species in areas with low geomorphic activity (Figure 2.20 A) The joint change in species composition and geomorphic activity was interpreted as a biogeomorphic succession with three biogeomorphic successional phases (Figure 2.20 A, B). In the *(1) pioneer phase*, abiotic processes control vegetation establishment, therefore, only vegetation class 1 dominated by pioneer species occurs in this phase in areas with high geomorphic activity. As scree-wanderer and as scree-creeper (Schröter et al., 1926), the pioneer species *Achillea nana* and *Linaria alpina* are adapted to the moving debris (see Figure. 2.20). In the (2) *biogeomorphic phase*, abiotic and biotic processes start to interact. As described in the biogeomorphic feedback window, engineer species (dwarf shrubs)

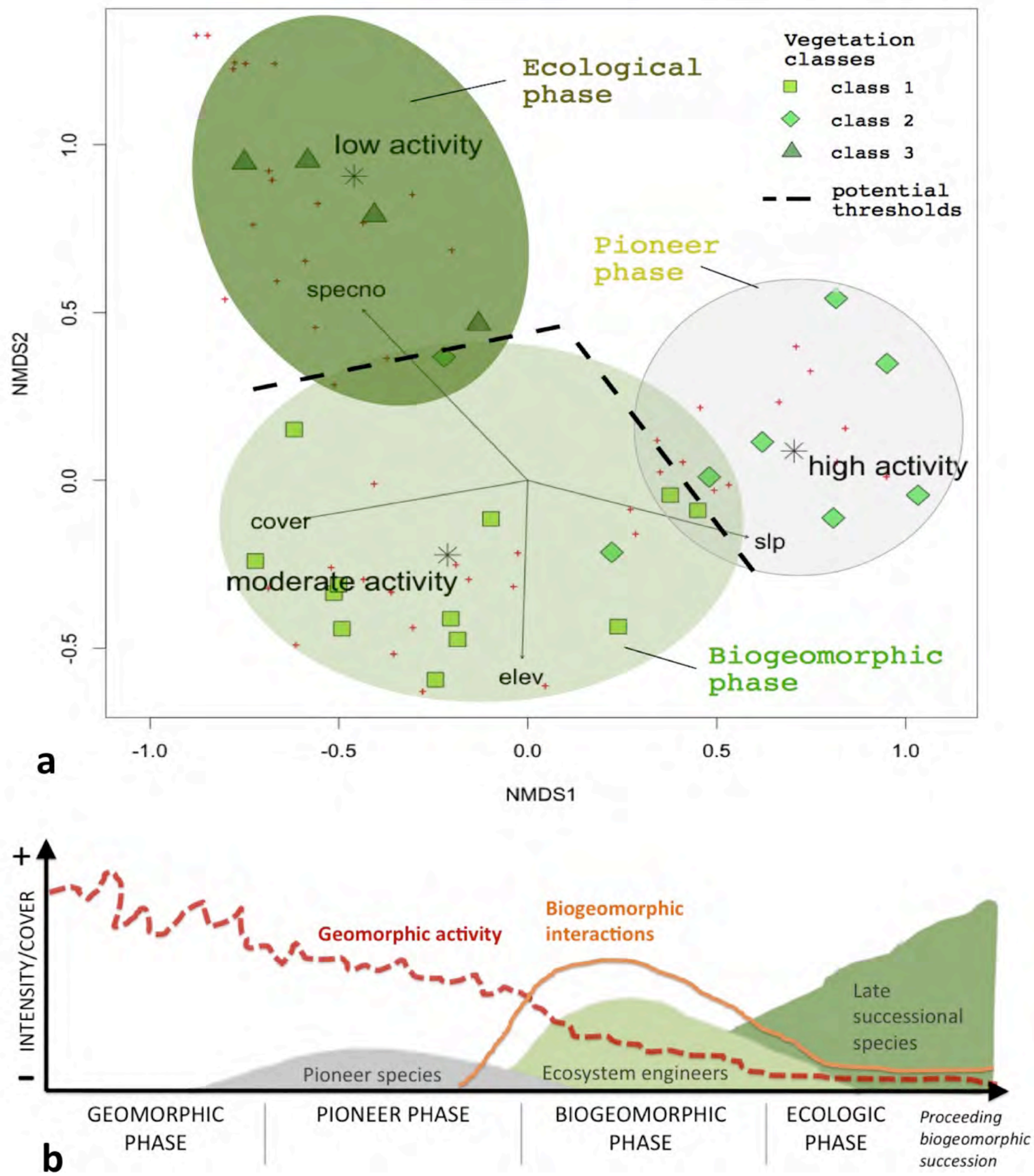

Figure 2.20: Biogeomorphic succession on lateral moraine slopes. **A** NMDS result from Eichel et al. (2013) showing biogeomorphic succession phases at constant terrain age, based on vegetation and activity classes. Environmental parameters: *specno* = species number, *cover* = vegetation cover, *slp* = slope, *elev* = elevation. **B** Conceptual model of biogeomorphic succession at lateral moraine slopes. Decreasing geomorphic activity and increasing biogeomorphic interactions control the changing species composition and cover and interact with each other.

in vegetation class 2 actively influence the occurring geomorphic processes. In this phase, biogeomorphic interactions are most intense. Under moderate geomorphic activity, intermediate successional stages, such as grassland associations (*Dryadeto-Firmetum, Elynetum*) develop. In the *(3) ecologic phase,* geomorphic activity is low and later successional species (vegetation class 3) dominate and the ecosystem engineers are excluded as biotic processes such as competition and inhibition become dominant.

In fluvial environments biogeomorphic successions start after high magnitude disturbances (large floods). However, Eichel et al. (2016) found that biogeomorphic succession is not related to the terrain age of lateral moraine slopes, which would be expected with the retreating glacier as last major disturbance. Instead, changes in species composition are related to decreasing geomorphic activity (Figure 2.20 B). This decrease in geomorphic activity, related to paraglacial adjustment, controls the biogeomorphic succession until biogeomorphic feedbacks are strong enough to amplify the decrease and finally stop geomorphic activity.

Thus, both vegetation succession and paraglacial adjustment are not necessarily time-dependent on lateral moraine slopes, but driven by interactions between plants and geomorphic processes. These biomorphic interactions control the landscape development following glacier retreat (Eichel et al., 2013, 2016).

2.5.10 Conclusion

Interactions between vegetation succession and paraglacial adjustment play a key role for the development of proglacial landscapes following glacier retreat. Based on the ecologic and biogeomorphic knowledge presented in the previous sections, the questions posed in the introduction can be answered:

(1) How long does it take for vegetation to establish after glacier retreat?

Colonization by pioneer species can start within years after glacier retreat. With increasing terrain age, successional stages follow each other with species adapted to the changing environmental conditions. A species composition similar to that outside of the glacier foreland can be reached after decades to centuries, depending on regional (altitude, continentality), landscape (aspect, slope toposequence) and local (soil texture and moisture) conditions.

(2) What limits vegetation establishment and succession?

Vegetation establishment and succession can be inhibited, limited, altered or delayed by disturbances for several decades to centuries. For a long time after glacier retreat, active geomorphic can produce local and landscape scale vegetation patterns that disrupt the time-dependent vegetation succession gradient.

(3) When and how are glacial sediments stabilized?

Ecosystem engineer species can establish on glacial sediments when the magnitude or frequency of paraglacial processes decreases to a certain degree. Once these species reach a certain cover or amount of below-ground biomass, they start to actively influence geomorphic processes by increasing slope stability, limiting soil and lateral erosion, enhancing sediment deposition and changing the hydrological and thermal regimes. Geomorphic activity strongly decreases in this biogeomorphic feedback window and later successional species, such as trees, establish in the stabilized environment.

However, in all successional phases, vegetation can get partly or completely destroyed by high magnitude processes and sediment reworking can recommence with no or pioneer vegetation. Thus, glacial sediments colonized by vegetation are not necessarily permanently stable. More research is needed to understand biogeomorphic dynamics and their role for sediment stabilization in glacier forelands, which also needs to integrate the changing climate.

Acknowledgements

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2.6 Research needs

Based on the provided state-of-the-art overview on biogeomorphology and geomorphic and ecologic dynamics in glacier forelands and on lateral moraine slopes, five main research needs can be identified:

1. **Ecosystem engineer species in glacier forelands:** To understand which species can stabilize sediments in glacier forelands, and how this stabilization works, ecosystem engineer species and their relevant engineer traits need to be identified. The mechanism how they influence their environment needs to be understood and linked to their role for paraglacial adjustment, vegetation succession and the creation and development of biogeomorphic structures.
2. **Conditions for biogeomorphic feedbacks:** In order to understand if and when plants can stabilize lateral moraine slopes, conditions for biogeomorphic feedbacks need to be determined. It needs to be asserted under which conditions ecosystem engineers can establish in glacier forelands (Windows of Opportunity), when can they induce feedbacks (engineering threshold) and under which conditions biogeomorphic feedbacks do not occur.
3. **Creation, configuration and role of biogeomorphic structures:** Landforms potentially resulting from ecosystem engineering in glacier forelands need to be identified. The status of their components (landform elements) needs to be determined to evaluate their ecological role. Furthermore, from a geomorphic perspective, we need to know if biogeomorphic structures are stable in terms of paraglacial sediment reworking, thus, if paraglacial adjustment ends through ecosystem engineering.
4. **Interactions between vegetation succession and paraglacial adjustment and resulting spatial patterns:** The role of interactions between vegetation succession and paraglacial adjustment for landscape development following deglaciation needs to be understood. It needs to be tested if a biogeomorphic succession similar to fluvial and coastal environments occurs in glacier forelands and if this succession depends on terrain age or if further controlling factors are important. Furthermore, spatial geomorphic and ecologic patterns resulting from these interactions need to be determined and their development needs to be understood.
5. **Scale linkages in lateral moraine biogeomorphic ecosystems:** It needs to be tested if lateral moraine are BEs similar to fluvial and coastal environments. To understand their structure, function and dynamics, scale linkages between small scale ecosystem engineering,

biogeomorphic structures, conditions for ecosystem engineering and biogeomorphic succession need to be established.

3 THESIS DESIGN

'No system can be understood or managed by focusing on it at a single scale'
(Resilience Alliance, http://www.resalliance.org/panarchy)

This chapter describes the hierarchical, scale-based approach employed in this thesis and states the thesis' objectives. Three hierarchical levels, linked to specific spatiotemporal scales, are considered in the glacier foreland system. For each level, this chapter provides an overview on relevant geomorphic and ecologic components and processes, as well as related biogeomorphic concepts. Subsequently, thesis objectives are presented, ordered according to the spatiotemporal scale they address.

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3 THESIS DESIGN

3.1 Hierarchical, scale-based approach

The aim of this thesis is to improve the understanding of biogeomorphic dynamics in glacier forelands, particularly on lateral moraine slopes, with respect to the stated research needs. This necessitates a hierarchical, scale-based approach, which addresses biogeomorphic feedbacks in glacier forelands and on lateral moraine slopes at different spatiotemporal scales (Figure 3.1).

The glacier foreland can be described as an assemblage of hierarchical geomorphic and ecologic systems, in which processes and components relate to different spatiotemporal scales. The Little Ice Age (LIA) maximum glacier advance determines the spatial extent of the glacier foreland and sets the time scale for geomorphic and ecological processes with approximately one and a half centuries (1850 to today). External forcing such as deglaciation, climate and geology, represent state variables for both geomorphic and ecologic system.

According to hierarchy theory, three hierarchical levels of a system need to be investigated to understand a system (O’Neill et al., 1986; Wu, 1999). Level 0 represents the focal level of research related to the research questions, and is embedded between a higher level (level 1) and a lower level (level -1). Level 1 provides top-down constraints for processes at the focal level, while level -1 contains focal level components and provides the mechanistic explanation for its processes (O’Neill et al., 1986).

In this thesis, the focal level 0 relates to interactions between geomorphic processes and landforms in the geomorphic system, as well as to vegetation communities, disturbances and resulting patches in the ecologic system. These occur at an intermediate spatial scale of approximately 5 m² to 1 ha and in a moderate timescale of months to decades. In biogeomorphology, the ‘Windows of Opportunity’ concept explains the establishment of ecosystem engineers at this scale, while the concept of biogeomorphic structures describes the development of mesoscale landforms through ecosystem engineering.

The lower level -1 contains the components of the focal level, consisting of mechanical, thermal and hydrological material and surface properties and individual species with their root and above-ground biomass traits. They relate to a small spatial scale of 1 cm² to 5 m² and a short timescale of seconds to years. In biogeomorphology, the concept of ecosystem engineering describes at this scale how species through plant functional traits influence geomorphic processes and landforms in their environment.

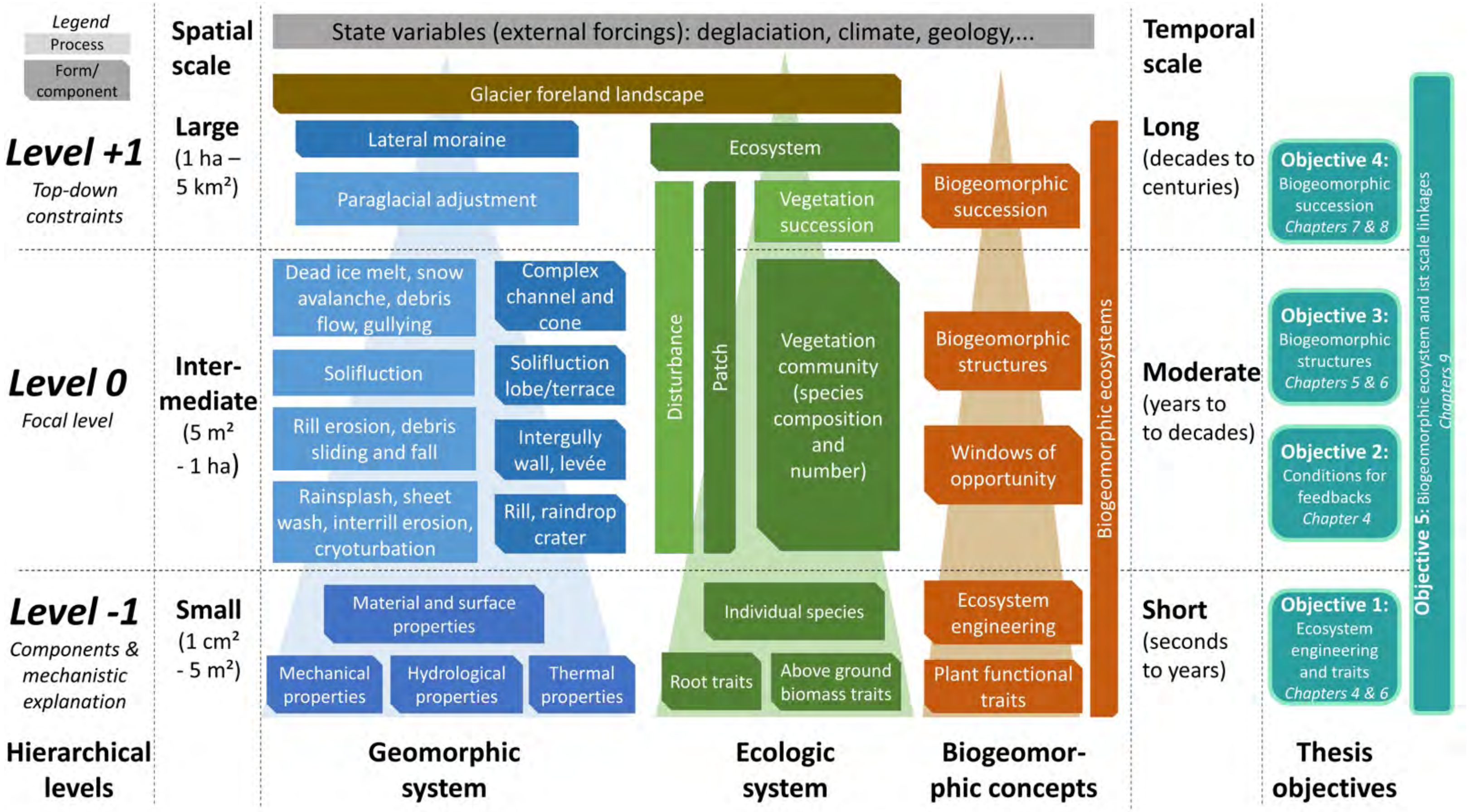

Figure 3.1: Illustration of hierarchical, scale-based approach employed to assess biogeomorphic dynamics in the studied glacier foreland and lateral moraine slope system. Considered hierarchical levels, geomorphic (blue) and ecologic (green) system components (truncated rectangles) and processes (rectangles) and biogeomorphic concepts (orange) are shown according to their spatiotemporal scale. Research objectives of this thesis (turquoise) are indicated on the right hand side.

The higher level +1 provides the constraints for lower level biogeomorphic interactions, related to the processes of paraglacial adjustment of the lateral moraine and vegetation succession in the lateral moraine ecosystem. They occur on a large spatial scale of 1 ha to 5 km² and in a long timescale of decades to centuries. In biogeomorphology, the concept of biogeomorphic succession explains how interactions between geomorphic processes and plants develop in this timescale.

All levels with their components and interactions are contained in the biogeomorphic ecosystem concept.

3.2 Thesis objectives

Following the presented biogeomorphic scale approach, the objectives of this thesis (Figure 3.1) are:

Objective 1: To identify **ecosystem engineers** and their engineer traits on lateral moraine slopes. This objective relates to level -1 and is addressed in Chapters 4 and 6.

Objective 2: To determine **conditions for** the occurrence of **biogeomorphic feedbacks** on lateral moraine slopes. This objective relates to level 0 and is addressed in Chapter 4.

Objective 3: To recognize **biogeomorphic structures** on lateral moraine slopes and describe their development, configuration as well as geomorphic and ecologic role. This objective relates to level 0 and is addressed in Chapters 5 and 6.

Objective 4: To analyse interactions between paraglacial adjustment and vegetation succession in glacier forelands and on lateral moraine slopes, their relation to **biogeomorphic succession,** resulting **spatial patterns** and their role for landscape development. This objective relates to level +1 is addressed in Chapters 7 and 8.

Objective 5: To describe lateral moraine as **biogeomorphic ecosystems** and understand their structure, functioning and dynamics by establishing **scale linkages in a panarchy approach.** This objective integrates all level and is addressed in the synthesis in Chapter 9.

Thesis structure follows these objectives from Chapters 4 to 9. The study area, the Turtmann glacier foreland, and methods are described in each chapter. Chapter 9, the synthesis, integrates results from all chapters to describe lateral moraine slopes as biogeomorphic ecosystems and links scale-related feedbacks using a panarchy approach.

4 CONDITIONS FOR FEEDBACKS BETWEEN GEOMORPHIC AND VEGETATION DYNAMICS ON LATERAL MORAINE SLOPES: A BIOGEOMORPHIC FEEDBACK WINDOW

> *‚Vegetation colonisation is often identified as a major factor in stabilising glacier forelands' (Ballantyne, 2002b, p. 1957)*
>
> *‚Vegetation colonisation [...] is considered to be a response to ground surface stabilisation rather than a causal mechanism' (Curry et al., 2006, p. 218)*

This chapter is based on a journal article published as:

Eichel, J., Corenblit, D. and R. Dikau (2016): Conditions for feedbacks between geomorphic and vegetation dynamics on lateral moraine slopes: a biogeomorphic feedback window. In: Earth Surface Processes and Landforms 41, p. 406 - 419.

In this chapter, thesis objectives 1 and 2 are addressed. The dwarf shrub Dryas octopetala is identified as an ecosystem engineer on a small scale (Objective 1) and conditions for biogeomorphic feedbacks are determined on an intermediate scale (Objective 2). Engineer traits of *D. octopetala* and their effects on geomorphic processes are described, an ecosystem engineering threshold based on *D. octopetala* cover is identified using permanent plot data from Turtmann glacier foreland. Conditions for biogeomorphic feedbacks are determined by the relationship between geomorphic activity and and traits of occurring plant species, which is showing in this data. This relationship is described in the biogeomorphic feedback window concept. Ecosystem engineering by *D. octopetala* is further described in Chapter 6, while the biogeomorphic feedback window concept is related to biogeomorphic succession in Chapter 8.

4 CONDITIONS FOR BIOGEOMORPHIC FEEDBACKS

4.1 Abstract

Little Ice Age lateral moraines represent one of the most important sediment storages and dynamic areas in glacier forelands. Following glacier retreat, simultaneous paraglacial adjustment and vegetation succession affect the moraine slopes. Geomorphic processes (e.g. debris flows, interrill erosion, gullying, solifluction) disturb and limit vegetation development, while increasing vegetation cover decreases geomorphic activity. Thus, feedbacks between geomorphic and vegetation dynamics strongly control moraine slope development. However, the conditions under which these biogeomorphic feedbacks can occur are insufficiently understood and major knowledge gaps remain. This study determines feedback conditions through the analysis of geomorphic and vegetation data from permanent plots in the Turtmann glacier foreland, Switzerland. Results from multivariate statistical analysis (i) confirm that *Dryas octopetala* L. is an alpine ecosystem engineer species which influences geomorphic processes on lateral moraines and thereby controls ecosystem structure and function, and (ii) demonstrate that biogeomorphic feedbacks can occur once geomorphic activity sufficiently decreases for *D. octopetala* to establish and cross a cover threshold. In the subsequent ecosystem engineering process, the dominant geomorphic processes change from flow and slide to bound solifluction. Increasing slope stabilization induces a decline in biogeomorphic feedbacks and the suppression of *D. octopetala* by shrubs. We conceptualize this relationship between process magnitude, frequency and species resilience and resistance to disturbances in a 'biogeomorphic feedback window' concept. Our approach enhances the understanding of feedbacks between geomorphic and alpine vegetation dynamics on lateral moraine slopes and highlights the importance of integrating geomorphic and ecologic approaches for biogeomorphic research.

4.2 Introduction

During the Little Ice Age (LIA), large lateral moraines were formed in many glacier forelands in the Alps and elsewhere. Nowadays, they are among the most important sediment storages (Otto et al., 2009) and most dynamic areas (Irvine-Fynn et al., 2011). Following glacier retreat, paraglacial adjustment and vegetation succession simultaneously act on this new terrain (Ballantyne, 2002b; Matthews, 1992). These processes are currently modified and enhanced by climate change (Cannone et al., 2008; Carrivick et al., 2013). Enhanced geomorphic activity with often high rates of sediment reworking (Ballantyne, 2002a) quickly fills up hydropower basins located in glacier forelands (Bogen, 1988; Hauenstein, 2005). This strongly decreases their cost-effectiveness

(Raymond Pralong et al., 2011). In addition, paraglacial processes on lateral moraine slopes can represent natural hazards and a risk for society (Moore et al., 2009). Sediment reworking and the occurrence of paraglacial processes can be limited by increasing vegetation cover (Ballantyne, 2002b; Matthews et al., 1998).

Paraglacial processes include debris flows, gullying, landsliding, solifluction, slope wash, splash, interrill erosion, debris sliding and frost creep (Ballantyne, 2002b; Curry et al., 2006; Jäger and Winkler, 2012; Lukas et al., 2012; Rose, 1991). Besides vegetation cover, process occurrence and intensity depend on material properties (e.g. sediment texture, available moisture, ice cores) and moraine geomorphometry (e.g. slope gradient) (Curry et al., 2006; Ewertowski and Tomczyk, 2015; Feuillet and Mercier, 2012; Jäger and Winkler, 2012; Lukas et al., 2012; Midgley et al., 2013; Teysseire, 2006b). It has been suggested these geomorphic processes succeed in a temporal sequence within the paraglacial adjustment (Lukas et al., 2012; Mercier et al., 2009). Immediately after glacier retreat, moraines are often ice-cored and adjust to the new conditions through backwasting and downwasting (Ewertowski and Tomczyk, 2015; Schomacker, 2008). This can induce gravitational mass movements (Ewertowski and Tomczyk, 2015) and debris flows (Chiarle et al., 2007; Curry et al., 2006; Ewertowski et al., 2012). In parallel, rill erosion occurs, with initial rills developing into gullies with maximum gully dimensions about 50 years after glacier retreat (Ballantyne, 2002b; Curry et al., 2006; Deline et al., 2015). Subsequently, gully relief decreases due to gully sedimentation or gully sidewall removal (Curry et al., 2006).

Likewise, vegetation colonization and succession are strongly driven by terrain age (Matthews, 1992; Raffl et al., 2006), which also determines the importance of abiotic and biotic factors and their interplay (Matthews, 1992). Abiotic processes and influencing factors (e.g. physical disturbances, substrate properties) are dominant at the beginning of vegetation succession (Andreis et al., 2001; Cannone et al., 2008; Matthews, 1999; Raab et al., 2012), while biotic succession drivers and controls (e.g. species traits and interactions) gain importance later in the course of succession (Cichini et al., 2011; Erschbamer et al., 2008).

Feedbacks between geomorphic and vegetation dynamics are investigated in biogeomorphology (Corenblit et al., 2011; Rice et al., 2012). Recent research showed biogeomorphic feedbacks in many highly dynamic environments such as rivers (Corenblit et al., 2007, 2009; Gurnell et al., 2012), salt marshes (Balke et al., 2014; Bouma et al., 2009), coastal dunes (Stallins, 2005; Vinent and Moore, 2015), periglacial environments (Haugland, 2006; Hjort and Luoto, 2009; Matthews et al., 1998), on hillslopes (Gyssels et al., 2005; Marston, 2010) and in glacier forelands (Gurnell et al., 2000; Moreau et al., 2008). For lateral moraine slopes, feedbacks between paraglacial adjustment and vegetation succession have been indicated (Eichel et al., 2013). Yet, the stabilizing effect of vegetation in the course of paraglacial adjustment (Ballantyne, 2002b; Matthews et al., 1998) has been challenged by Curry et al. (2006) and Mercier et al. (2009) who found that vegetation only colonizes the slope once it has already attained stability. This demonstrates that feedbacks between geomorphic and vegetation dynamics on lateral moraine slopes are insufficiently understood. Specifically, the drivers of these feedbacks and the conditions, under which feedbacks can occur, remain unclear.

A biogeomorphic approach for lateral moraine slopes can help to address this knowledge gap. Concepts developed in ecology and biogeomorphology noticeably promoted the investigation and understanding of feedbacks between geomorphic and vegetation dynamics in various environments (e.g. coastal and fluvial systems, deserts). Key biogeomorphic concepts include *ecosystem engineers* (Jones et al., 1994; Jones, 2012) and *niche construction* (Odling-Smee et al., 2013). Ecosystem engineering relates to the cases in which ecosystem structure and function are controlled by species changing their physical environment and thereby creating habitats for other species. In such case assembly rules at the community level can be at least partially related to ecosystem engineer effects on the habitat. In the case of niche construction, selection pressures for ecosystem engineers themselves and other species are affected through the biotically controlled modulation of the geomorphic environment. In such case organism traits and fitness can be related to the biotically induced habitat changes. The concept of *Windows of Opportunity* proposed by Balke et al. (2011, 2014) also represents an operational framework for the identification of the conditions for biogeomorphic feedbacks to occur within biogeomorphic ecosystems (Corenblit et al., 2015). These concepts demonstrate that (i) some species have a stronger influence on geomorphic and ecologic dynamics in their environment than others (Corenblit et al., 2011; Gurnell, 2014) and that (ii) biogeomorphic feedbacks can occur once these engineer species are able to establish (establishment threshold) and exceed a critical engineering threshold (e.g. in terms of species cover) (Balke et al., 2014; Corenblit et al., 2007). For glacier forelands, it has been indicated that *Dryas octopetala* L. can act as ecosystem engineer (Eichel et al., 2013).

Our aim is to improve the understanding of feedbacks between geomorphic and vegetation dynamics on lateral moraine slopes by empirically investigating their relationship and subsequently interpreting our data with the help of biogeomorphic concepts.

Our objectives are:

1) to confirm *D. octopetala* as an alpine ecosystem engineer species on lateral moraine slopes;
2) to determine the conditions under which feedbacks between geomorphic processes and landforms and plants can occur; and
3) to conceptualize these conditions in a 'biogeomorphic feedback window' for lateral moraine slopes

4.3 Study site

The investigated lateral moraines are located in the foreland of the Turtmann glacier (Valais, Switzerland) (Figure 4.1 A). The Turtmann glacier has been retreating since the end of the LIA in 1850 (total 1284 m from 1885 to 2005), interrupted by advances in the 1980s/90s. Since the beginning of the twenty-first century, its retreat is accelerating (Bauder and Ruegg, 2009). Foreland sediments comprise middle-penninic marbles (Barrhorn series) and paragneiss/schist rocks (Mischabel crystalline complex), as well as higher penninic calcareous shales and greenstones (Tsaté nappe) and austroalpine gneiss and gabbro (Dent Blanche nappe) (Bearth, 1980; Labhart, 2009).

The LIA lateral moraines, extending about 1900 m along the eastern valley side, represent one of the most prominent landforms in the foreland (Otto et al., 2009; Figure 4.1 A, B). Their mean height is about 120 m. On the moraine slopes, Eichel et al. (2013) identified debris flows, avalanches, gullying, debris sliding, interrill erosion, wash, and splash as main processes in a glacial-denudative process domain and solifluction and cryoturbation in a glacial-cryogenic process domain (Eichel et al., 2013; Figure 4.1 C, D). The ice-cored southern part of the lateral moraine system was not included in this study due to limited accessibility.

As a consequence of substrate characteristics, both siliceous and calcareous vegetation, consisting of alpine pioneer species, dwarf shrubs, alpine grassland associations (*Dryadeto-Firmetum*, *Elynetum*) and Salix shrubs (*Salicetum helveticae*), are found at the study site (Eichel et al., 2013). On older terrain (> 80 years), heterogeneous patterns of both vegetation and geomorphic activity were observed (Eichel et al., 2013; Figure 4.1C, D). Human and animal impact can be mostly neglected on the lateral moraine slopes.

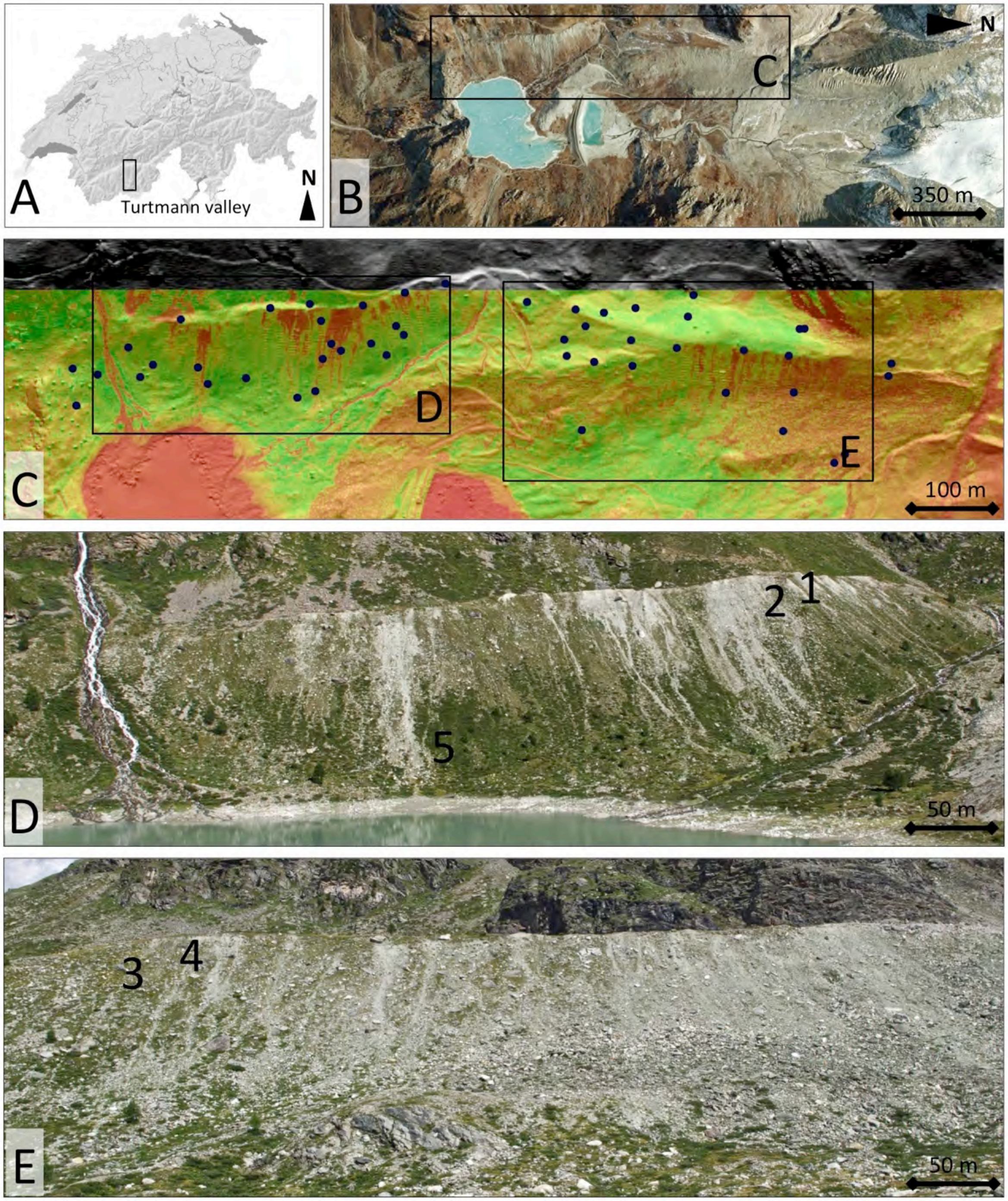

Figure 4.1: Overview of the study site. **A** Location of the Turtmann valley in Switzerland. **B** Aerial image of the Turtmann glacier foreland (Google Earth, 2009). **C** Location of permanent plots (blue dots) on lateral moraines, displayed on a Normalized Difference Vegetation Index (NDVI) image of the area (Swisstopo, 2011). **D** Complex patterns of geomorphic activity and vegetation at oldest lateral moraines (terrain age from 80 to 110 years). Numbers (1, 2, 5) indicate location of plots from Figure 7. **E** Patterns of geomorphic activity and vegetation at mid-section lateral moraines (terrain age from 60 to 80 years). Numbers (3, 4) indicate location of plots from Figure 5.7.

4.4 Methods

The study’s methodological approach is summarized in Figure 4.2. A permanent plot survey was conducted on the lateral moraine slopes. Acquired permanent plot data was subsequently processed and analyzed using multivariate statistical methods. Relation of the results to the study’s objectives is illustrated.

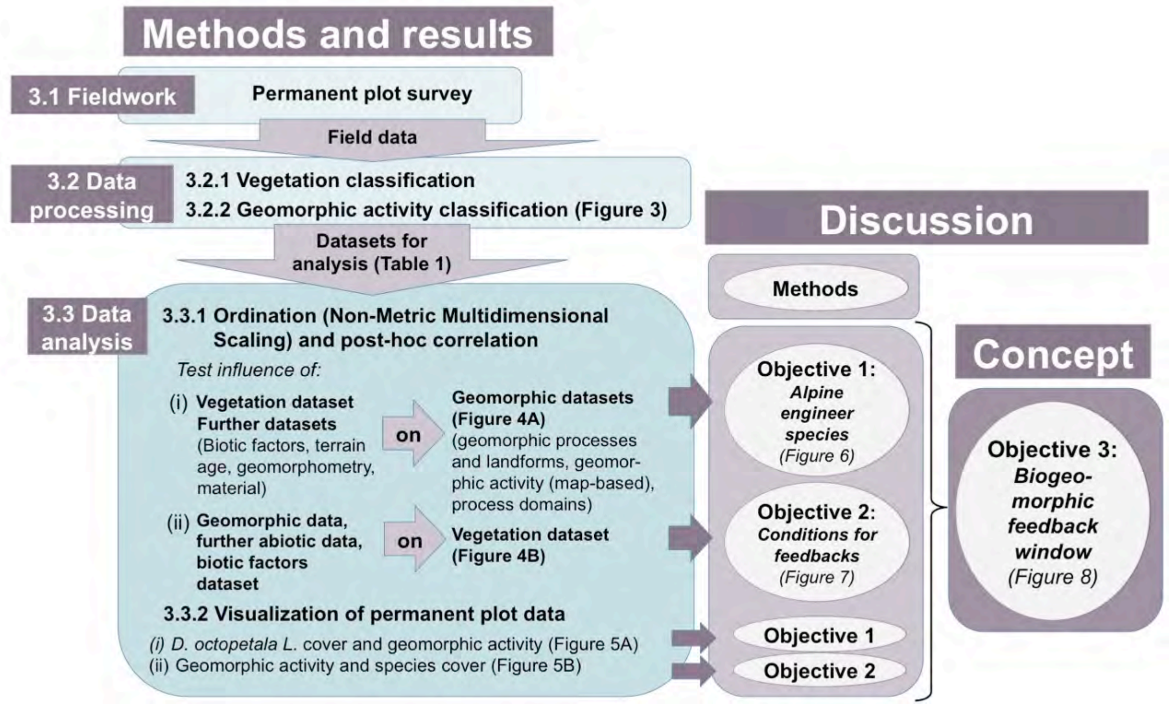

Figure 4.2: Methodological approach illustrating methodical steps, results and their relation to the study’s objectives.

4.4.1 Fieldwork

In summer 2013, a permanent plot survey (50 plots, size 2x2 m) was conducted on the lateral moraines slopes (see Figure 4.1B for plot location). Plot location was selected in ArcGIS using a random-stratified approach based on vegetation criteria (Normalized Difference Vegetation Index value) (Hawth’s Analysis Tools; Beyer, 2004). Plot survey included assessment of vegetation (cover of occurring species, total vegetation cover), geomorphic processes and landforms, geomorphometry, soil horizons, grain sizes and biotic parameters (see Table 4.1). The taxonomic nomenclature of the vascular plants is according to Lauber and Wagner (2007).

4.4.2 Data preparation and processing

Field data was supplemented with datasets for geomorphic activity, terrain age and process domains from Eichel et al. (2013). In order to assess similarities in geomorphic and vegetation characteristics, geomorphic activity and vegetation of the plots were classified and respective datasets were derived for further analysis (Table 4.1). For all statistical analyses, plots with less than two species were excluded from analysis, as well as species/landforms/processes only occurring once.

Vegetation classification

Vegetation classification was carried out using the *Isopam* algorithm (Schmidtlein et al., 2010; implemented in R). This algorithm classifies vegetation data based on floristic similarity (distance Bray–Curtis) and subsequently assigns a vegetation class to each plot. Vegetation classes are characterized by typical species that are most frequently occurring in this class. The 'expert classification' configuration was used to derive three vegetation classes.

Geomorphic activity classification

Geomorphic activity was classified using a qualitative approach based on process frequency and magnitude (Böhmer and Richter, 1997; Flageollet, 1996; Otto and Dikau, 2004). Process sediment transport and mechanical stress were used as a proxy for process magnitude. For subsequent statistical analysis, each occurring process was attributed with a geomorphic activity value based on the process' magnitude and frequency. Activity values range from two (low magnitude and frequency) to eight (high magnitude, low frequency) (Table 4.1). Value 'one' indicates no occurring processes. Based on these values, all processes were subsequently clustered into four geomorphic activity classes (no, low, moderate and high activity). Depending on the most active process occurring in the respective plot, plots were assigned a geomorphic activity value and a geomorphic activity class.

4.4.3 Data analysis

In order to assess relationships between species composition, geomorphic characteristics and further abiotic and biotic factors, datasets were analysed using multivariate statistics (ordinations with post-hoc correlation). All analyses were carried out with the statistical computing software R (R Development Core Team, 2014). In addition, permanent plot data were visualized to facilitate interpretation.

Ordination (non-metric multidimensional scaling) and post-hoc correlation

Ordination techniques analyse the similarity of different objects in terms of certain variables, e.g. the occurrence of certain geomorphic processes or cover values of occurring species. Based on the variable values, a similarity matrix is calculated for the objects (e.g. plots) and illustrated in an n-dimensional ordination space. Proximity of objects in the illustrated space indicates similar values of the variables, while ordination axes indicate the main variation (gradient) in variable values. The fitting of the illustration with the calculated similarity matrix is expressed by the measure 'stress'.

We used a non-metric multidimensional scaling (NMDS; Kruskal, 1964; distance Bray–Curtis) ordination to (i) assess which factors (e.g. species cover) influence the occurrence of geomorphic processes and landforms in the plots and (ii) to assess which factors (e.g. geomorphic activity) influence species composition in the plots (Figure 4.2). For (i) the NMDS was carried out for a geomorphic dataset (combination of datasets geomorphic processes and landforms, geomorphic activity (map) and process domains; presence-absence data). Subsequent post-hoc analysis was carried out to identify influencing factors (datasets vegetation, biotic factors, terrain age, geomorphometry, material). For (ii) the NMDS was performed with the vegetation dataset. The datasets geomorphic processes and landforms, soil, material, geomorphic activity (process based), terrain age, biotic factors and geomorphometry were used for post-hoc correlation.

The analysis was carried out with *metaMDS* in R vegan (version 1.17-12, J. Oksanen). Settings included a Wisconsin double standardization, a maximum number of 100 runs to find the best solution and 1000 permutations for calculating the coefficient of determination (r^2) and significance (p-value) (Kruskal, 1964). Automatic rotation of the ordination space displays the value's main gradient in the first axis (NMDS1). *Envfit* and *factorfit* (R vegan) were used for post-hoc correlation. Correlations with $p < 0.01$ were seen as significant, non-significant correlations are not displayed. To highlight the variable gradients, the plots in the NMDS illustrations were overlaid with (i) vegetation classes and (ii) geomorphic activity classes.

Visualization of permanent plot data

To visualize relationships between geomorphic activity and species occurrence and cover, we plotted permanent plot data with (i) increasing *D. octopetala* L. cover and geomorphic activity (process-based) (values per plot) and (ii) decreasing geomorphic activity (process-based) and cover of typical species from vegetation classes.

Table 4.1: Overview and description of vegetation, biotic, geomorphic and abiotic datasets used for statistical analyses.

Dataset	Parameter	Description
Vegetation and biotic data		
Vegetation	Species cover	Cover for all plant species occurring more than once in plots, total species number for analysis 63.
Biotic factors	Total vegetation cover	Total vegetation cover of plot.
	Stratification	Maximum measured vegetation height.
	Species number	Total number of species occurring in plot.
Vegetation classes	Vegetation class 1	Pioneer vegetation class with typical species *Linaria alpina (L.) MILL. s.l.*
	Vegetation class 2	Dwarf shrub vegetation class with typical species *Dryas octopetala* L.*,* *Bartsia alpina* L., *Salix retusa* L.*,* *Pinus cembra* L.
	Vegetation class 3	Shrub vegetation class, typical species *Salix hastata L.*
Geomorphic data		
Geomorphic processes and landforms	Landforms: Polygenetic cone, solifluction step, solifluction lobe, detachment scarp, gully Processes: Debris flow, avalanche, debris slide, interrill erosion, wash, solifluction, cryoturbation, gullying	Occurring geomorphic processes and landforms based on geomorphic mapping. Multiple landforms/processes per plot possible. For post-hoc correlation, detachment scarp and gully were treated as one variable, as were solifluction forms and process.
Geomorphic activity (process-based; based on most active occurring process)	No geomorphic activity	No processes occurring (1)
	Low geomorphic activity	Frost creep (3), solifluction (2), cryoturbation (3)
	Moderate geomorphic activity	Interrill erosion (5), debris sliding (5), wash (4)
	High geomorphic activity	Debris flows (8), snow avalanches (7), gullying (6)
	Degree of geomorphic activity	Continuous rating of geomorphic activity, ranging from 1 (no activity) to 8 (debris flows; see above).
Geomorphometry	Slope	Slope gradient of plot.
	Crest position	Position of plot in slope toposequence.
	Slopefoot position	
Material properties	Minimum grain size	Grain sizes (b-axis) measured for 25 particles chosen in 8 cm intervals next to plot.
	Maximum grain size	
	Mean grain size	

Table 4.2 (continued): Overview and description of vegetation, biotic, geomorphic and abiotic datasets used for statistical analyses.

Dataset	**Parameter**	**Description**
Process domains (Eichel et al., 2013)	Glacial-denudative	Glacier-influenced areas with dominance of denudative processes, e.g. interrill erosion.
	Glacial-cryogenic	Glacier-influenced areas with dominance of cryogenic processes, e.g. solifluction.
Geomorphic activity (map-based, Eichel et al., 2013)	High activity Moderate activity Low activity	Based on plot location in geomorphic activity map (three activity classes) (Eichel et al., 2013).
Further abiotic data		
Soil	Depth organic (O) horizon Depth A horizon	Measured soil horizon depths.
Terrain age	Terrain age at plot position	Based on glacier stages from Eichel et al. (2013); 10 year steps.

4.5 Results

4.5.1 Vegetation classification

Vegetation was classified into three non-hierarchical vegetation classes. *Linaria alpina* (L.) MILL. s.l. is the typical species of a pioneer vegetation class (mostly herbaceous chamaephytes). *D. octopetala* L.*,* *Bartsia alpina* L., *Salix retusa* L. and *Pinus cembra* L. typically occur in a second class. *D. octopetala* is the most important indicator of this class and therefore used as typical species for this dwarf shrub class in subsequent analyses. *Salix hastata L.* is the typical species of a shrub class.

4.5.2 Geomorphic activity classification

Based on process magnitude, ecologic severity (degree of damage to pre-disturbance vegetation; Pickett and White, 1985) and process frequency, geomorphic activity was classified into four classes, ranging from no processes to high geomorphic activity (Figure 4.3). Debris flows (activity value 8), snow avalanches (7) and gullying (6) possess a high magnitude (effective sediment transport and deposition, high erosion rates and large mechanical stress; Deline et al., 2014; Lamberti et al., 1991; Major, 1977; Patten and Knight, 1994; Stoffel, 2010) and a low to moderate frequency (often depending on specific initial conditions and triggers; Jäger and Winkler, 2012; Jomelli et al., 2007). These constitute a high geomorphic activity class. Interrill erosion (5), debris sliding (5) and wash (4) possess a higher frequency (e.g. frequently occurring during heavy rainfall events), but a lower magnitude and ecological severity (intermediate sediment transport rates; Schrott and Glade, 2008; Toy et al., 2002). These are grouped into a moderate activity class. Frost creep (3), cryoturbation (3) and solifluction (2) possess the lowest magnitude (small average slope movement; Dietrich and Dunne, 1978; Matsuoka, 2001; Rapp, 1960) and frequency (occurring during frost cycles and thaw; Harris et al., 2011; Matsuoka, 2001). They make up the low geomorphic activity class.

4.5.3 Ordination and post-hoc correlation results

Factors influencing the occurrence of geomorphic processes and landforms

Remarkably, gradients in geomorphic process and landform occurrence relate more strongly to vegetation parameters than to geomorphometric and material properties (Figure 4.4A). The main gradient (NMDS1 axis, high to low/moderate geomorphic activity) relates to *D. octopetala* L. cover (r^2=0.47) and total vegetation cover (r^2=0.47). The second gradient (NMDS2 axis) relates to

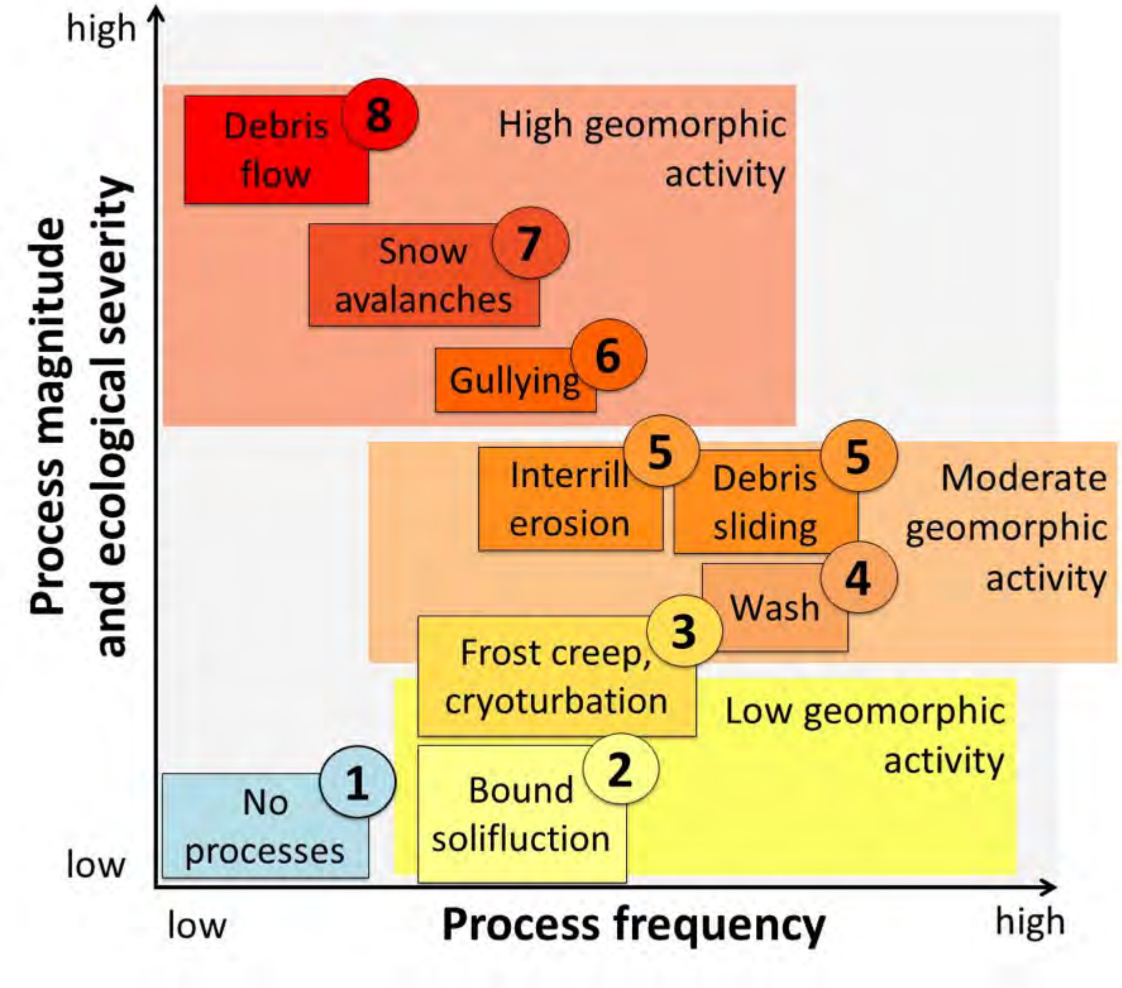

Figure 4.3: Geomorphic activity classification based on process frequency, magnitude and ecologic severity. Numbers show activity values for individual processes.

geomorphometric and material parameters (crest position: r^2=0.39, slopefoot position: r^2=0.19, grain size: r^2=0.24, slope gradient: r^2=0.33). This indicates that at slope positions (e.g. crest position) with similar geomorphometric and material properties, different geomorphic processes occur, which relate to vegetation properties. In fact, process occurrence relates to occurring species: pioneer vegetation occurs with flow and slide processes (r^2=0.39), while solifluction processes and landforms occur with high *D. octopetala* cover (r^2=0.47) and the dwarf shrub vegetation class (r^2=0.56). No processes occur with shrub and late successional species cover (r^2=0.28). Surprisingly, terrain does not significantly relate to process occurrence and geomorphic activity patterns.

Factors influencing species occurrence and composition

Gradients in species composition relate to geomorphic activity, slope gradient and ecosystem development (Figure 4.4B). The main gradient (NMDS1 axis, pioneer vegetation to dwarf shrub vegetation) relates to geomorphic activity (r^2=0.52) and slope (r^2=0.20), opposed to species number (r^2=0.46), vegetation cover (r^2=0.46), depth of organic soil horizon (r^2=0.32) and minimal grain size (r^2=0.2). Remarkably, terrain age does not significantly relate to the species composition. Instead, different vegetation classes relate to different geomorphic, biotic and abiotic factors. The pioneer species class relates to high geomorphic activity (r^2=0.31), highest slope gradient and high magnitude processes, e.g. gullying (r^2=0.22) and debris sliding (r^2=0.37). Pioneer vegetation often occurs at the moraine crest (r^2=0.21). The dwarf shrub class relates to low geomorphic activity (r^2=0.25) and solifluction (r^2=0.37). The shrub class relates to no occurring processes (r^2=0.27). Furthermore, both dwarf shrub and shrub class relate to the highest species numbers, highest vegetation cover, minimal grain size and depth of organic soil horizon.

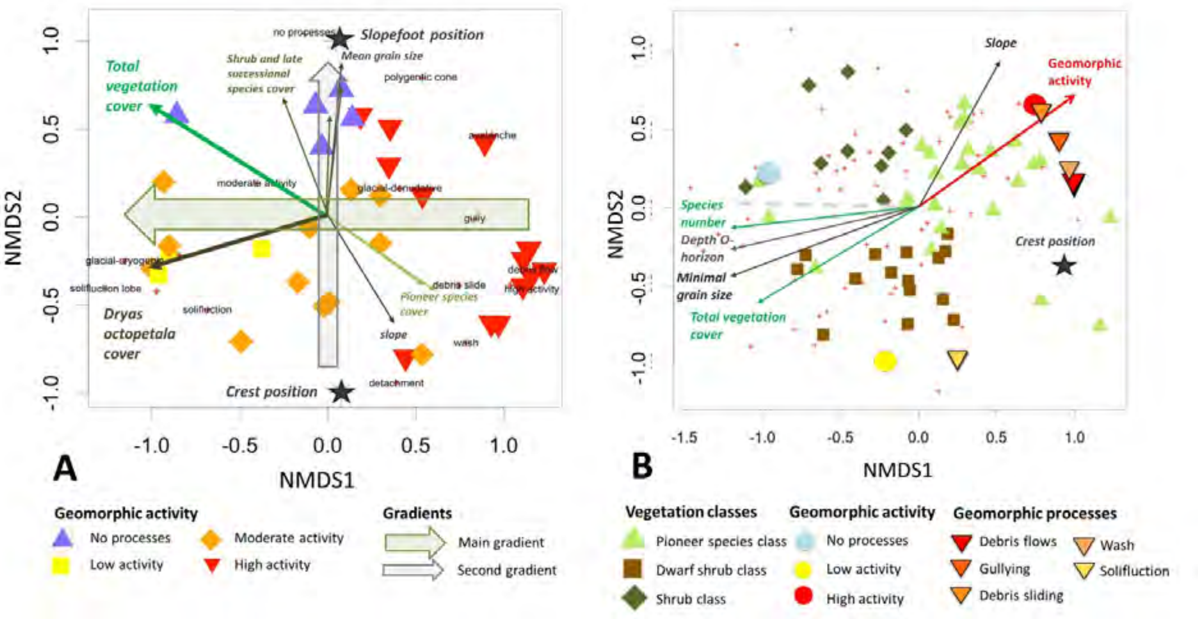

Figure 4.4: Ordination results. **A** NMDS result for the geomorphic dataset, overlay with geomorphic activity classes (symbols) and environmental fit of significant ($p < 0.01$) variables (arrows and stars). Proximity of plots indicates similar geomorphic characteristics, arrows point in the direction of maximum variable change. Arrow length depends on r^2. Gradients are represented by large arrows. Three dimensions, stress 6.76. **B** NMDS results for vegetation dataset. Overlay with vegetation classes and environmental fit of significant ($p < 0.01$) variables (arrows and symbols, see legend). Three dimensions, stress 16.37.

4.5.4 Visualized permanent plot data

Relationship between D. octopetala L. cover and geomorphic activity

The permanent plot data reveals that geomorphic activity decreases with increasing *D. octopetala* cover (Figure 4.5A). With low *D. octopetala* cover, geomorphic activity is high (activity values up to eight; debris flows and gullying occurring) and strongly fluctuates. Once *D. octopetala* cover reaches a value of about 35% of the plot area, geomorphic activity permanently decreases and wash (activity value 4) is the most active occurring process. High magnitude processes, such as debris flows, gullying, interrill erosion and debris sliding, do not occur above this *D. octopetala* cover value.

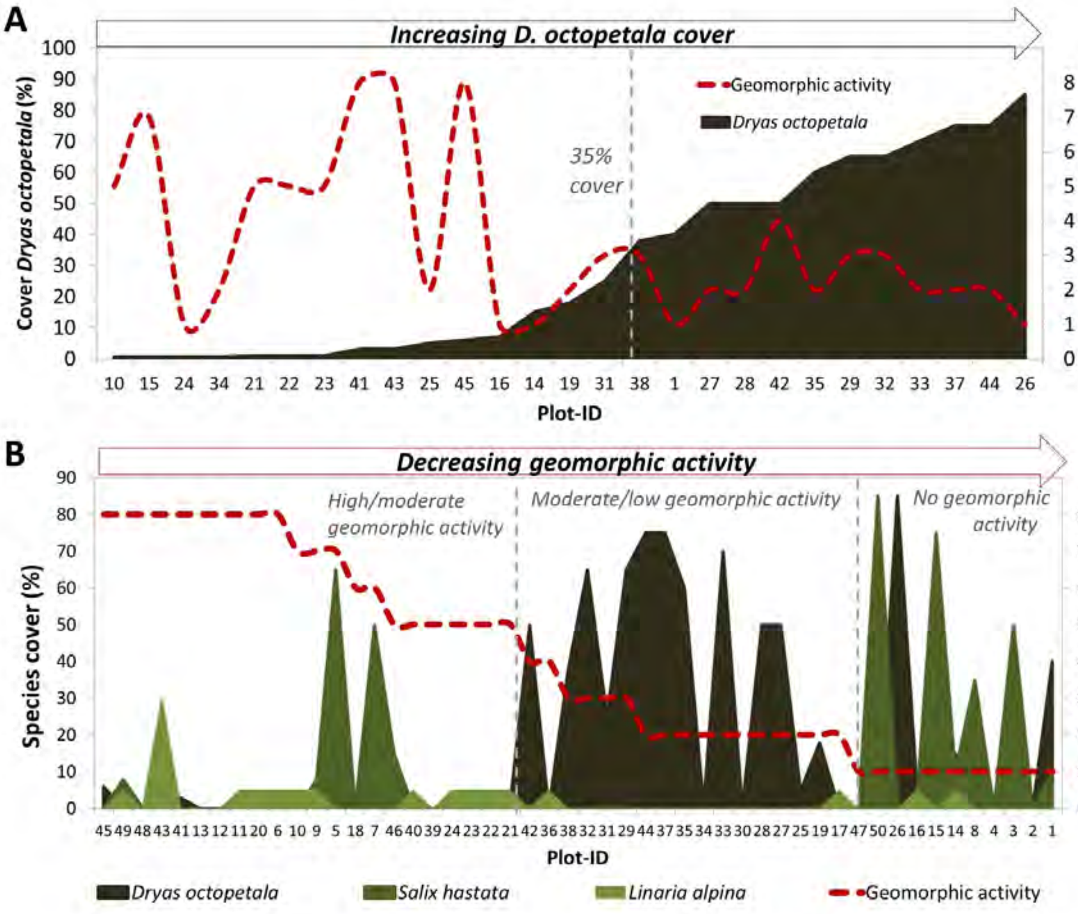

Figure 4.5: Visualized permanent plot data. **A** Increasing values of *D. octopetala* L. cover in permanent plots plotted against geomorphic activity (process based) in respective plots. **B** Decreasing geomorphic activity (process based) of permanent plots plotted with cover of typical vegetation class species. Cover values of *L. alpina* were multiplied by ten to improve visibility.

Relationship between geomorphic activity and species cover

When integrating further species into the plotted data, a coupled sequence of decreasing geomorphic activity and changes in species occurrence and cover occurs (Figure 4.5B). With high/moderate geomorphic activity (activity values between five and eight; high to moderate magnitude processes), *L. alpina* is frequently occurring and species cover is generally low (with exception of *S. hastata* cover in plots 5 and 7). Once geomorphic activity decreases to moderate/low geomorphic activity (activity values below 5, most active process wash), *D. octopetala* cover increases and *L. alpina* does not occur any longer. When geomorphic activity stops (activity value 1, no active processes), *S. hastata* cover is dominant in the plots. *D. octopetala* and *L. alpina* also occur with, respectively, mostly moderate and low cover values.

4.6 Discussion

4.6.1 Methods

Geomorphic activity classification

Common geomorphic activity classifications often require a long observational period (> 2 years) and frequently use vegetation cover as a main activity indicator. This results in a good correlation between geomorphic activity classes and vegetation parameters. Our conceptual classification avoids this bias, as it is based on magnitude-frequency relationships. A further advantage of our conceptual approach is that process magnitude and frequency do not need to be measured in field, which can be labour-intensive and time-consuming. Thus, geomorphic activity can be classified even for short observational periods. However, magnitude frequency relationships also possess limitations, as they have been criticized to be valid only when the studied system is in equilibrium conditions (Crozier, 1999). Nevertheless, we believe that the advantages of our approach justify its use in our biogeomorphic study, as our classification allows to determine the direct relationship between geomorphic activity and vegetation development efficiently in a limited fieldwork time period. Data to support our classification are currently gathered.

Vegetation classification and ordination

Both *Isopam* vegetation classification and NMDS ordinations showed good results in previous biogeomorphic studies (Eichel et al., 2013), as well as in comparison with other methods (Kent, 2006; McCune and Grace, 2002; Schmidtlein et al., 2010). Ordinations' stress with values between 6 and 17 can be seen as normal for ecologic data analyses with large samples (McCune and Grace, 2002).

Further influencing factors

Both geomorphic and vegetation dynamics are influenced by a variety of factors (Lukas et al., 2012; Matthews, 1992). In our biogeomorphic approach, we focused our field sampling and analysis on parameters most relevant for our objectives. Further influencing factors (e.g. soil type, soil moisture) are certainly important, but could not be quantified in our approach. As especially soil development is closely linked with vegetation succession (cf. Matthews, 1992), we believe the integration of these parameters would not radically change our results but support the relationship between the decrease in geomorphic activity and the increasing ecosystem development.

4.6.2 Alpine ecosystem engineer species

Our results showed a strong relation between *D. octopetala* cover, geomorphic activity and occurring processes (Figure 4.4A), which supports the identification of *D. octopetala* as an ecosystem engineer species.

The detected permanent decrease of geomorphic activity once *D. octopetala* covers more than 35% of a permanent plot can be explained by *D. octopetala*'s morphological and root traits. *D. octopetala* L. is a prostrate, evergreen chameaphyte (Elkington, 1971), which, with its low-lying stems, branches and numerous leaves, forms mats of up to a few meters in diameter (Körner, 2003; Reisigl and Keller, 1994; Welker et al., 1997). Within these mats, fine sediments, biomass, and humus accumulate (Figure 4.6C, D) (Ellenberg, 1996; McGraw, 1985; Reisigl and Keller, 1994)and moisture can be stored (Van Vliet-Lanoe, 1993). Below the mats, significantly less material is exposed to erosional processes (Graf and Gerber, 1997). In addition, *D. octopetala* possesses a strong and deeply rooted woody rootstock, which branches into fine lateral roots and coralloid root systems with ectomycorrhiza (Figure 4.6B, C; Ellenberg, 1996; Harrington and Mitchell, 2002; Kutschera et al., 1997; Reisigl and Keller, 1994). It has been indicated that the co-occurrence of mycorrhiza with plant roots increases the soil aggregate stability and results in a higher angle of internal friction (Bast et al., 2014; Graf et al., 2009). Thus, through this combination of traits, *D. octopetala* is able to increase slope stability and limit the occurrence of flow and slide processes.

Moreover, the strong relation between *D. octopetala* cover and the occurrence of solifluction processes and landforms is related to the ability of its mat to trap fine sediment and store moisture (Figure 4.6C). It has been shown that fine sediment (especially silt) and moisture promote solifluction (Harris et al., 2008). Turf-banked solifluction landforms, which are often associated with dwarf shrub vegetation (Akerman, 1993; Zuber, 1968), could result from these interactions and therefore be interpreted as biogeomorphic structures (Eichel et al., 2015).

Figure 4.6: *Dryas octopetala* L. and its engineering traits. **A** *Dryas octopetala* mat covering debris and rocks. **B** Stock root and underground branching. **C** Bottom side of a mat with accumulated fine sediment and biomass. **D** Humus accumulation and fine root system. **E, F** Facilitation for *Leontopodium alpinum* CASS. and *Campanula cochlearifolia* LAM.

Similarly, the relation of advanced ecosystem development (fine grain sizes, highest organic soil horizon depth and highest species numbers) to the dwarf shrub vegetation class (Figure 4.4A) could also be explained by *D. octopetala*'s traits. Through humus accumulation, trapping of seeds and organic matter, nitrogen fixation and stabilization of the moving debris (Elkington, 1971), D. octopetala facilitates colonization for other species, e.g. Leontopodium alpinum CASS. and Campanula cochlearifolia LAM. (Figure 4.6E, F) and acts as nurse plant (Klanderud and Totland, 2004). This advances ecosystem development to grassland associations, such as Caricetum firmae (Kerner), Seslerieto-Semperviretum or Elynetum (Elkington, 1971; Ellenberg, 1996; Reisigl and Keller, 1994).

Consequently, based on our observations and *D. octopetala*'s traits, we identify this species as an alpine ecosystem engineer species. Its effect on lateral moraine slopes is comparable to the effects of riparian willow (*Salix* spp.) and poplar (*Populus* spp.) species (Corenblit et al., 2014; Gurnell, 2014) in river systems. Moreover, our findings indicate that other dwarf shrub species with similar traits (e.g. *Salix serpyllifolia*, *Salix reticulata*; cf. Ellenberg, 1996; Körner, 2003; Schröter et al., 1926) are also potential alpine ecosystem engineers.

Whereas material properties and moraine slope geomorphometry have been previously identified as most important parameters for geomorphic activity and process occurrence on lateral moraine slopes (Curry et al., 2006; Jäger and Winkler, 2012), our findings demonstrate that *D. octopetala* as an engineer species can have at least a similarly strong influence. This highlights the importance of particular plant species and their functional traits for geomorphic dynamics on lateral moraine slopes and stresses the necessity of integrating ecologic knowledge into geomorphic research. From an applied point of view, these engineer species could be utilized to improve slope stabilization and restoration in alpine environments, e.g. on ski slopes (Pohl et al., 2012).

4.6.3 Conditions for feedbacks

A core aspect of our results is the strong reciprocal coupling of geomorphic and vegetation dynamics, as indicated in both NMDS results and in the visualized permanent plot data (Figures 4.4, 4.5). We interpret their relation as a coupled sequence of paraglacial adjustment and vegetation succession, which has been previously described as a biogeomorphic succession (Eichel et al., 2013). Within this sequence, the engineer species *D. octopetala* starts to occur with moderate geomorphic activity (interrill erosion, debris sliding, wash). Thus, a decrease in geomorphic activity can be interpreted as condition for engineer occurrence, while the subsequent decrease in geomorphic activity with increasing *D. octopetala* L. cover (Figure 4.5B) can be interpreted as the result of biogeomorphic feedbacks.

As a consequence, we can determine the conditions for biogeomorphic feedbacks by interpreting the relationship between vegetation (species occurrence, composition, degree of ecosystem development) and geomorphic properties (occurring processes, geomorphometry, material properties, geomorphic activity) (Figures 4.4, 4.5B).

The dominance of pioneer species with high geomorphic activity, high slope gradient and high magnitude processes (e.g. gullying) indicates that vegetation colonization is limited under these conditions. Only species adapted to frequent disturbances, such as *L. alpina*, can occur. *L. alpina* is a debris vegetation species whose root system and stems can adapt to moving debris and which can quickly re-establish after a disturbance due to wind-dispersed, highly germinable seeds (Ellenberg, 1996; Rauh, 1939; Schröter et al., 1926). The engineer species *D. octopetala* occurs only infrequently with a low cover under these conditions (Figure 4.5B; Figure 4.7, plot 1). This could result from its low growth rates (Hendry and Grime, 1993; Pierce et al., 2013), which imply that *D. octopetala* requires a sufficiently long disturbance-free period, or a lower disturbance level, to establish successfully and become resistant against medium intensity disturbances. Thus, high geomorphic activity conditions are not suitable for *D. octopetala* establishment.

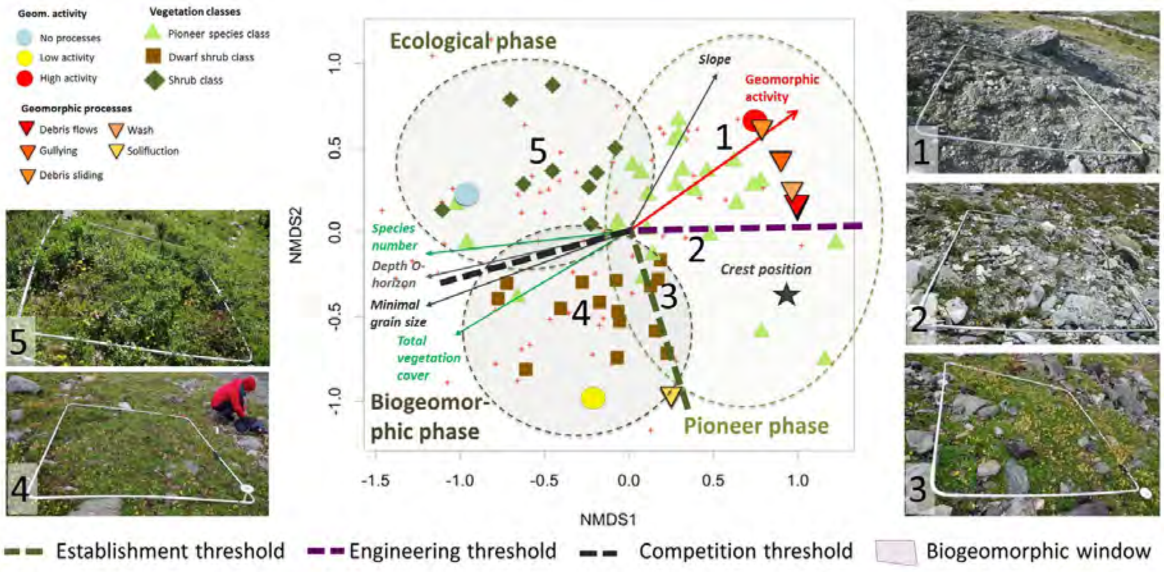

Figure 4.7: Interpretation of the NMDS vegetation dataset result (cf. Figure 4.4 B). An establishment, engineering and competition threshold, as well as the biogeomorphic feedback window, can be identified. Vegetation and geomorphic conditions are illustrated by photographs of selected plots (plots 1–5). Plot location is marked in the NMDS plot and on the lateral moraine slopes in Figures 4.1C and 4.1D.

D. octopetala starts to occur more frequently and with high cover values once geomorphic activity decreases permanently to a certain level (Figure 4B). This decrease could be related to on-going paraglacial adjustment (Ballantyne, 2002b). In addition, *D. octopetala* could also establish when intervals between higher magnitude processes (e.g. debris flows) are sufficiently long (Figure 4.5B; Figure 4.7). We interpret these conditions as Windows of Opportunity (WoO) *sensu* Balke et al. (2014) and the necessary decrease in geomorphic activity as an engineer establishment threshold (Figure 4.7). High frequency, low magnitude processes still occur, but do not inhibit *D. octopetala* establishment (see earlier; Figure 4.7, plot 2). In fluvial and coastal environments, WoO length is usually some days to month (Balke et al., 2014). However, in the case of our lateral moraine slopes, we estimate the required length of the disturbance-free period, or the time until paraglacial adjustment reaches these conditions, to be substantially longer. In general, debris flow return time is some years to decades (Stoffel, 2010), while gullying intensity usually starts to decrease after some decades (Curry et al., 2006). Our data indicate that *D. octopetala* can only successfully establish and grow if none of these high magnitude processes occur. A quantification of the WoO lengths for *D. octopetala* establishment is needed.

The permanent decrease of geomorphic activity once *D. octopetala* cover reaches a value of 35% (Figure 4.5A) can be interpreted as density or biomass engineering threshold (Figure 4.7; Balke et al., 2014). A similar vegetation cover threshold, delimiting active from inactive sediment-mantled slopes, was also found on Svalbard (Mercier et al., 2009). Once this threshold is crossed, increasing *D. octopetala* cover amplifies the decrease of geomorphic activity by permanently inhibiting higher magnitude/frequency processes through its aboveground and belowground morphological and biomechanical traits (see earlier; Figure 4.7, plot 3). Deep solifluction processes are promoted through the retention of moisture and fine material in the dwarf shrub mats (Harris et al., 2008; Matsuoka, 2001; Van Vliet-Lanoe, 1993). This explains the strong relation between *D. octopetala* and solifluction processes (Figure 4.4A, Figure 4.7) and the co-occurrence of the dwarf shrub class with low geomorphic activity (Figure 4.7, plot 4). Possibly, *D. octopetala* is even favoured by occurring solifluction processes as its roots can adapt to soil movements, e.g. by stretching out in the direction of the movement (Anderson, 1906; Kutschera and Lichtenegger, 2013). This can be a competitive advantage, as roots of other species can be less adapted to solifluction. In addition, carbon and nutrients are redistributed by solifluction (Horwarth et al., 2008), which could increase *D. octopetala*'s growth performance. It is likely that the engineer plant modifies geomorphology in a way that favours its own success of establishment and reproduction. This hypothesis signifies that bound solifluction could be considered as a positive niche construction *sensu* Odling-Smee et al. (2013). This will require further investigations. Whereas previous studies used vegetation colonization as indicator for completed paraglacial adjustment (Ballantyne, 2002a; Mercier et al., 2009), the on-going reworking of glacial sediments by low magnitude and frequency processes under high vegetation cover indicates that paraglacial adjustment can continue despite vegetation colonization.

The infrequent occurrence of *D. octopetala*, together with the dominance of the shrub vegetation class, in plots with no geomorphic activity and most pronounced ecosystem development (high O-horizon depth, fine grained material) could be explained by the improvement of habitat conditions in the ecosystem engineering process (Gutiérrez and Jones, 2008). Ecosystem engineering induces structural and abiotic changes (e.g. accumulation of organic material and fine sediments) in the engineer's environment, which in turn induce biotic changes, such as changes in species composition and richness (Gutiérrez and Jones, 2008). These changes can negatively affect the engineer species, e.g. through increasing interspecific competition. In our data, this could explain the decrease of engineer cover with increasing shrub cover, which limits light incidence (Figure 4.7, plot 5). Shade-intolerant *D. octopetala* is subsequently suppressed. However, shrubs and trees can also establish in more stable areas without facilitation by *D. octopetala* (Eichel et al., 2013). We interpret the increasing interspecific competition through late successional species as a competition threshold (Figure 4.7), which marks the end of intensive biogeomorphic feedbacks.

Our findings demonstrate that vegetation colonization is neither the primary cause nor solely a response to slope stabilization (cf. Ballantyne 2002b; Curry et al., 2006; Mercier et al., 2009). Instead, ecosystem engineers can actively stabilize lateral moraine slopes once a certain degree of slope stabilization (reduced process magnitude/frequency; establishment threshold) and engineer cover (engineering threshold) has been reached. Thus, vegetation colonization is not a passive response to slope stabilization, but plays an active role for paraglacial adjustment.

Finally, our observations demonstrate that both processes, and therefore also the occurrence of biogeomorphic feedbacks, are not necessarily time-dependent, as they do not relate to terrain age in our study area. This implies that more research is needed to understand feedbacks between geomorphic and vegetation dynamics on lateral moraine slopes in time and space. Thereby, sediment management in glacier forelands could be improved.

4.6.4 Biogeomorphic feedback window

Our results demonstrate that biogeomorphic feedbacks on lateral moraines can occur in a specific envelope of conditions, which depend on the relationship between geomorphic disturbance regime (process magnitude, ecologic severity and frequency) and plant species traits that determine species response to disturbances. These traits can be distinguished in traits relating to plant species resilience (speed of a system to return to equilibrium after a disruptive event; Gunderson, 2000; Gunderson and Holling, 2002) and plant species resistance (magnitude of disturbance that can be absorbed; Gunderson and Holling, 2002). We conceptualize this relationship between process magnitude, ecologic severity, process frequency and species resilience and resistance to identify a ‘biogeomorphic feedback window’ for lateral moraine slopes (Figure 4.8).

Large infrequent disturbances with high magnitudes, such as debris flows and avalanches, often strongly damage vegetation (Lamberti et al., 1991; Major, 1977; Patten and Knight, 1994). Similarly, highly frequent disturbances, such as gullying, wash and debris sliding, limit vegetation colonization (Curry et al., 2006; Mercier et al., 2009). Only pioneer species can colonize these habitats. These species possess a high resilience, as they can quickly re-establish after a disturbance (Ellenberg, 1996; Rauh, 1939; Schröter et al., 1926), but a low resistance towards disturbances (Figure 4.8), as they are short-lived ruderal strategists (Caccianiga et al., 2006) and aim at reproduction instead of long-time establishment (Erschbamer et al., 2008). Alpine pioneer

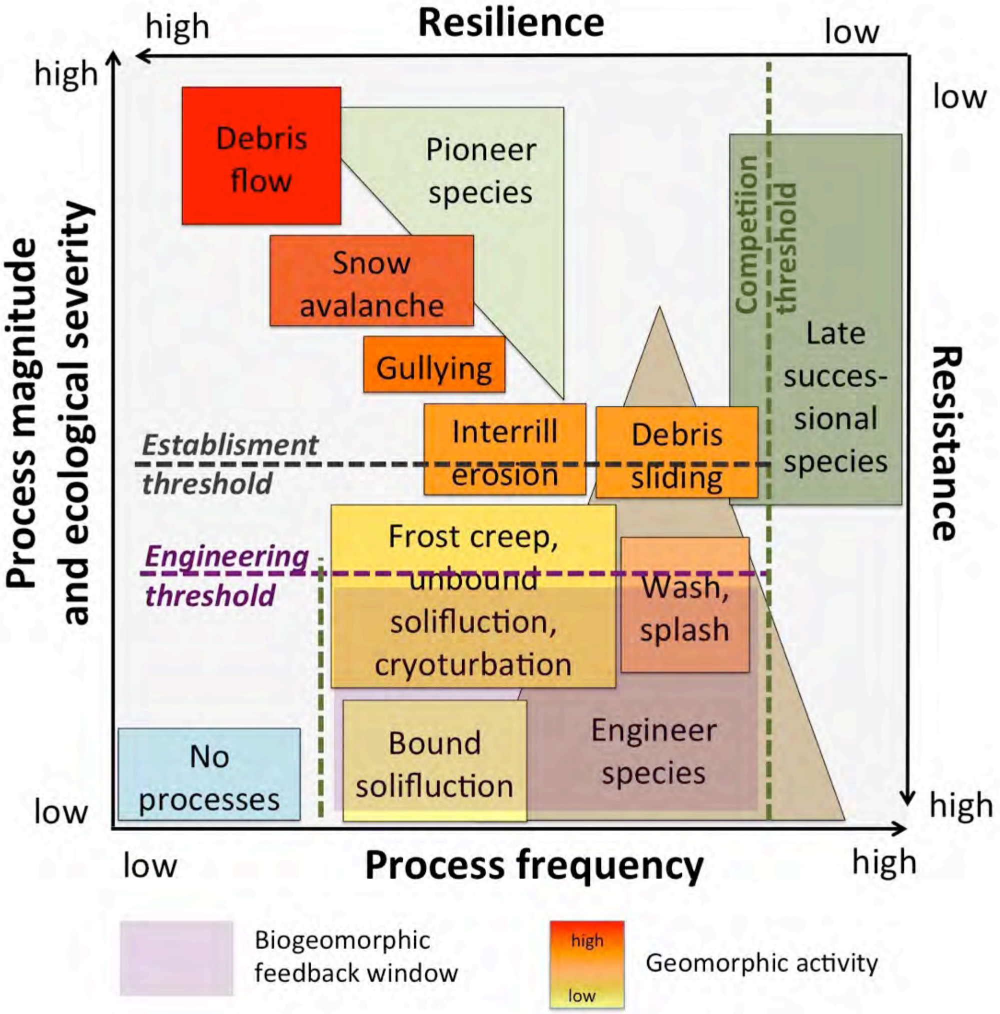

Figure 4.8: The 'biogeomorphic feedback window' on lateral moraines, depending on the geomorphic disturbance regime (process magnitude, ecologic severity, process frequency) and plant species traits (resilience and resistance). Thresholds preconditioning (establishment threshold) and confining the biogeomorphic feedback window (engineering and competition threshold) are shown

successional stages possess a low vegetation cover (Raffl et al., 2006) and therefore a low engineering potential. This contrasts with coastal systems, e.g. mangroves, salt marshes and dunes, in which pioneer species often also act as engineer species (Balke et al., 2013; Corenblit et al., 2015).

Under lower magnitude, higher frequency processes, or in-between large magnitude disturbances, the establishment threshold for engineer species can be crossed (Figure 4.8). These dwarf shrub species possess a higher resilience, as they often grow more slowly than pioneers (e.g. *D. octopetala*; Elkington, 1971), thus, they need a long time to successfully establish.

However, they possess a higher resistance towards disturbance, e.g. due to their strong roots and low-lying morphology (Körner, 2003; Schröter et al., 1926). Once the engineer population crosses a critical biomass (above- and/or below-ground), size or density threshold (engineering threshold; Balke et al., 2014), biogeomorphic feedbacks start and the biogeomorphic feedback window is reached (Figure 4.8). At this stage, the occurrence of erosional and frost creep processes is influenced by engineer plants: mats with high cover trap and retain fine sediments and moisture (Van Vliet-Lanoe, 1993; Zuber, 1968), while slope wash and needle ice creep are limited below the mats (Graf and Gerber, 1997; Gyssels et al., 2005; Matsuoka, 2001). Thereby, the dominant process can change: flow, slide and frost creep are attenuated, bound solifluction becomes dominant with turf-banked solifluction steps and lobes as biogeomorphic structures (Eichel et al., 2015). Increasing slope stabilization due to abiotic and structural changes in the ecosystem engineering process enables the establishment of late successional species. These are shrub and tree species (e.g. *Salix hastata* L., *Larix decidua* MILL.), which possess a slightly higher resistance than pioneer species, but are less adapted to disturbances than engineer species (Figure 4.8). Conifers, for example, possess a deeply rooting, extensive root network (cf. *Larix decidua* MILL.; Kutschera and Lichtenegger, 2013) that improves their anchorage on steep slopes, but their above-ground biomass is often strongly damaged by rockfall and avalanches (Stokes et al., 2005). Their resilience is low as it usually takes some decades until a late successional stage (e.g. alpine pine forest) is reached (Matthews, 1992). Often, these late successional species are stronger competitors than engineer species (Caccianiga et al., 2006), which are suppressed once a competition threshold is crossed. The biogeomorphic window is left and no geomorphic processes occur in the stabilized environment, in which late successional shrub and tree species dominate.

The feedback conditions described in the biogeomorphic feedback window concept are similar to conditions described in other biogeomorphic concepts, e.g. the biogeomorphic transient form ratio (Corenblit et al., 2011; Phillips, 1999), the Windows of Opportunity (Balke et al., 2014) or hotspots of plant ecosystem engineering (Gurnell, 2014). However, on lateral moraine slopes, geomorphic processes are more diverse (Ballantyne, 2002b; Eichel et al., 2013; Lukas et al., 2012) than in previously studied environments. While in coastal and river system a single disturbance regime (inundation or flood) determines its geomorphic and ecologic dynamics, a variety of different geomorphic processes with individual magnitudes and frequencies, and therefore also different disturbance regimes, occur on lateral moraines. In addition, pioneer species often do not act as engineer species, as opposed to rivers, and mangroves, salt marshes and dunes in coastal environments (Corenblit et al., 2015). The biogeomorphic feedback window takes these differences into account and provides the first framework to understand the occurrence of feedbacks between geomorphic and vegetation dynamics in geomorphic diverse high mountain environments.

4.6 Conclusion

Lateral moraines are highly dynamic environments, which are shaped simultaneously by geomorphic and vegetation dynamics following glacier retreat. Feedbacks between this paraglacial adjustment and vegetation succession have been previously suggested, however, drivers and conditions for feedbacks remained unclear. These research gaps were addressed in our biogeomorphic approach on lateral moraine slopes in the Turtmann glacier foreland.

Based on our results, we show for the first time that:

1) *Dryas octopetala* is an alpine ecosystem engineer. Through its specific traits, it induces biogeomorphic feedbacks and changes geomorphic dynamics from flow and slide to bound solifluction.
2) Conditions for biogeomorphic feedbacks are determined by the relationship between geomorphic activity and occurring species. Our observations show that biogeomorphic feedbacks occur once geomorphic activity sufficiently decreases for (i) *D. octopetala* to establish and (ii) reach a cover value of around 35%. Once these conditions are met, biogeomorphic feedbacks start and the engineer directly amplifies the decrease in geomorphic activity. This engineering process also induces biotic changes. Biogeomorphic feedbacks stop in a stabilized environment, in which shrubs dominate and *D. octopetala* is progressively suppressed due to interspecific competition. Thus, (engineer) vegetation can be seen as both cause and response to slope stabilization in the paraglacial adjustment.
3) Biogeomorphic feedbacks occur in a specific envelope of conditions, which depend on the relationship between geomorphic disturbance regime and plant species resilience and resistance. This ‘biogeomorphic feedback window’ is preconditioned by an establishment threshold and constrained by an engineering threshold dependent on engineer cover and a competition threshold after which biotic processes (e.g. competition) become dominant. The biogeomorphic feedback window provides the first framework to understand biogeomorphic feedbacks in geomorphic diverse high mountain environments.

4 CONDITIONS FOR BIOGEOMORPHIC FEEDBACKS

Moreover, in a biogeomorphic context, our findings demonstrate that lateral moraines in their geomorphic and ecologic properties partly differ from previously studied land-water interface biogeomorphic ecosystems (rivers and coasts; Corenblit et al., 2015). Therefore, a new biogeomorphic concept is needed to understand conditions for biogeomorphic feedbacks, which we provide in our study with the 'biogeomorphic feedback window'.

The transferability of this concept to other lateral moraine slopes and high mountain systems with similar geomorphic and vegetation dynamics, e.g. debris flow cones or talus slopes, needs to be tested. For this, more explicit biogeomorphic research needs to be conducted in glacier forelands and other alpine areas.

Acknowledgements

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5 SPATIAL CONTROLS OF TURF-BANKED SOLIFLUCTION LOBES AND THEIR ROLE FOR PARAGLACIAL ADJUSTMENT IN GLACIER FORELANDS

'Vegetation is a major factor in the analysis of variables controlling soil creep' (Anderson and Cox, 1978, p. 84)

This chapter is based on a journal article accepted for publication:

Draebing, D. & J. Eichel (accepted): Spatial controls on turf-banked solifluction lobes and their role for paraglacial adjustment in glacier forelands. Accepted for publication in Permafrost and Periglacial Processes.

This chapter addresses thesis objective 3 by determining the geomorphic and ecologic configuration of a turf-banked solifluction lobe (TBL) and identifying its role for paraglacial adjustment identified. For this purpose, detailed geomorphic, geophysical and ecologic investigations were carried out at a TBL in Turtmann glacier foreland. The applicability of Electrical Resistivity Tomography for the non-destructive investigation of subsurface TBL material properties is shown. Interactions between material properties, soil moisture and species composition at the TBL are described and related to the lobe elements frontal and lateral risers, lobe tread and ridge. Large TBL size despite low terrain age is explained by biogeomorphic feedbacks and used to highlight the role of solifluction for paraglacial adjustment. This chapter provides the background for the conceptual biogeomorphic model of TBL development presented in Chapter 6. Its results underpin a model of paraglacial process and landform succession presented in Chapter 8.

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5 SPATIAL CONTROLS OF TURF-BANKED SOLIFLUCTION LOBES

5.1 Abstract

In glacier forelands, solifluction is a major and fast-responding paraglacial process in the adjustment of low- or moderately-inclined moraine slopes. However, the spatial pattern of the factors that control solifluction and their interactions are poorly understood. In this study, we combine geomorphic and vegetation mapping, analysis of borehole material and Time Domain Reflectometry (TDR) with two-dimensional (2D) and three-dimensional (3D) Electrical Resistivity Tomography (ERT) to quantify the controlling factors and evaluate their influence on sediment transport. The investigated turf-banked solifluction lobe is located on the distal slope of a 1920s lateral moraine in the foreland of the Turtmann glacier in the southern Swiss Alps. Our data demonstrate the interaction between material, soil moisture and vegetation, which results in geomorphometric features such as (i) frontal and lateral risers, (ii) a lobe tread and (iii) a ridge. Lobe size indicates intense solifluction movement in the last 100 years. The interaction of controlling factors results in a negative feedback which stabilizes the lobe and, thus, limits paraglacial sediment transport to frost heave processes on the ridge.

5.2 Introduction

In the paraglacial concept, solifluction plays an important role by modifying gentle to moderate-slopes on recently deglaciated terrain (Ballantyne, 2002b). Solifluction lobes have been described as reworking glacial sediments on moraines slopes in glacier forelands in New Zealand (Archer et al., 1973), the Nepal Himalaya (Watanabe et al., 1989), Norway (Harris, 1982; Matthews et al., 1998), Switzerland (Eichel et al., 2013, 2016) and Antarctica (Fitzsimons, 1996; Oliva and Ruiz-Fernández, 2016). Monitoring of solifluction in Jotunheimen, southern Norway, has shown that solifluction rates are high near the glacier margins, remain enhanced for about 30 years after deglaciation and slowly decline thereafter (Matthews et al., 1998). The high rates of solifluction immediately following deglaciation are assumed to be associated with high soil moisture contents, which promote ice-lens growth in frost-susceptible sediment and, thus, enhances the occurrence of solifluction landforms (Ballantyne and Matthews, 1982; Matthews et al., 1998). Furthermore, Matthews et al. (1998) suggested that vegetation cover enhances solifluction by increasing surface cohesion and retaining soil moisture.

Ecosystem engineers are organisms that change the physical state of biotic or abiotic materials and thereby modify, maintain or create habitats for themselves and other species (Jones et al., 1994). Eichel et al. (2016) demonstrated that these engineering species have a strong impact on the occurrence of solifluction processes on lateral moraine slopes and influence slope stability by increasing shear strength (Ghestem et al.,2014) and internal friction (Graf et al., 2009). In turn, solifluction influences the species composition by favouring the establishment of movement-resistant plants (Eichel et al., 2016).

Alpine and Arctic glaciated areas are highly sensitive to climate warming and the resultant increase of paraglacial processes will become the most significant processes controlling sediment supply and landscape change over the next few hundred years (Knight and Harrison, 2009). Therefore, an understanding of the interaction of material, vegetation and soil moisture in solifluction processes and implications on sediment transport are essential to predict slope adjustment of moraines and sediment supply to glacio-fluvial systems. In our study, we combine for the first time traditional geomorphic and vegetation mapping approaches with novel geophysical measurements on a solifluction lobe. The aim of our investigation is to identify spatial patterns of geomorphometric and environmental factors as well as their interaction within a turf-banked solifluction lobe (TBL) on a lateral moraine slope in the Turtmann glacier foreland, Swiss Alps. For this purpose, we developed a novel 2D/3D ERT approach to gain spatial information of the solifluction lobe and the surrounding moraine slope. We use our data to quantify geomorphometric properties of the TBL and evaluate spatial patterns within the solifluction lobe in the context of interaction. Finally, we show implications of our findings for paraglacial slope adjustment by solifluction.

5.3 Study area

The investigated TBL is located on the distal slope of a 1920s lateral moraine in the Turtmann glacier foreland, in the southern Swiss Alps (Figure 5.1). Stone-banked solifluction lobes (SBLs) and TBLs are widespread landforms in the Turtmann Valley and occur on talus slopes in the hanging valleys (Otto and Dikau, 2004) and moraine slopes of the Turtmann glacier foreland (see geomorphic map in Eichel et al., 2013). The glacier foreland is located 250 – 300 m below the lower limit of permafrost inferred from rock glacier distribution (Nyenhuis et al., 2005); therefore the observed solifluction lobe is currently not affected by permafrost. However, buried ice is abundant in the southern part of the lateral moraine, which lacks solifluction lobes and where sediment transport is dominated by gullying (Eichel et al., 2013). Meteorological conditions are provided by a nearby MeteoSwiss station at 2180 m above sea level (a.s.l.) in the glacier foreland.

In 2013 and 2014, annual mean air temperature was 0.8° and 1.8°C, respectively, while annual precipitation ranged from 790 mm in 2013 to 833 mm in 2014 (MeteoSwiss, 2016).

The Turtmann glacier foreland is influenced by the Turtmann and neighbouring Brunegg glaciers. The former has retreated since the end of the Little Ice Age (LIA), interrupted by occasional advances in the 1980s/1990s (Bauder and Ruegg, 2009). The lateral moraine hosting the solifluction lobe was formed by a smaller advance in the 1920s (Tscherrig, 1965). Till within the moraine comprises Middle Penninic marbles from the Barrhorn series, paragneiss and schistose rocks from the Mischabel nappe, Upper Penninic calcareous shales and greenstones from the Tsaté nappe and austroalpine gneiss and gabbro from the Dent Blanche nappe (Bearth, 1980; Labhart, 2009). As a result, both siliceous and calcareous vegetation occurs, with alpine grassland associations (*Dryadeto-Firmetum, Elynetum*) covering large areas of the lateral moraine, including the solifluction lobe (Eichel et al. 2013, 2016).

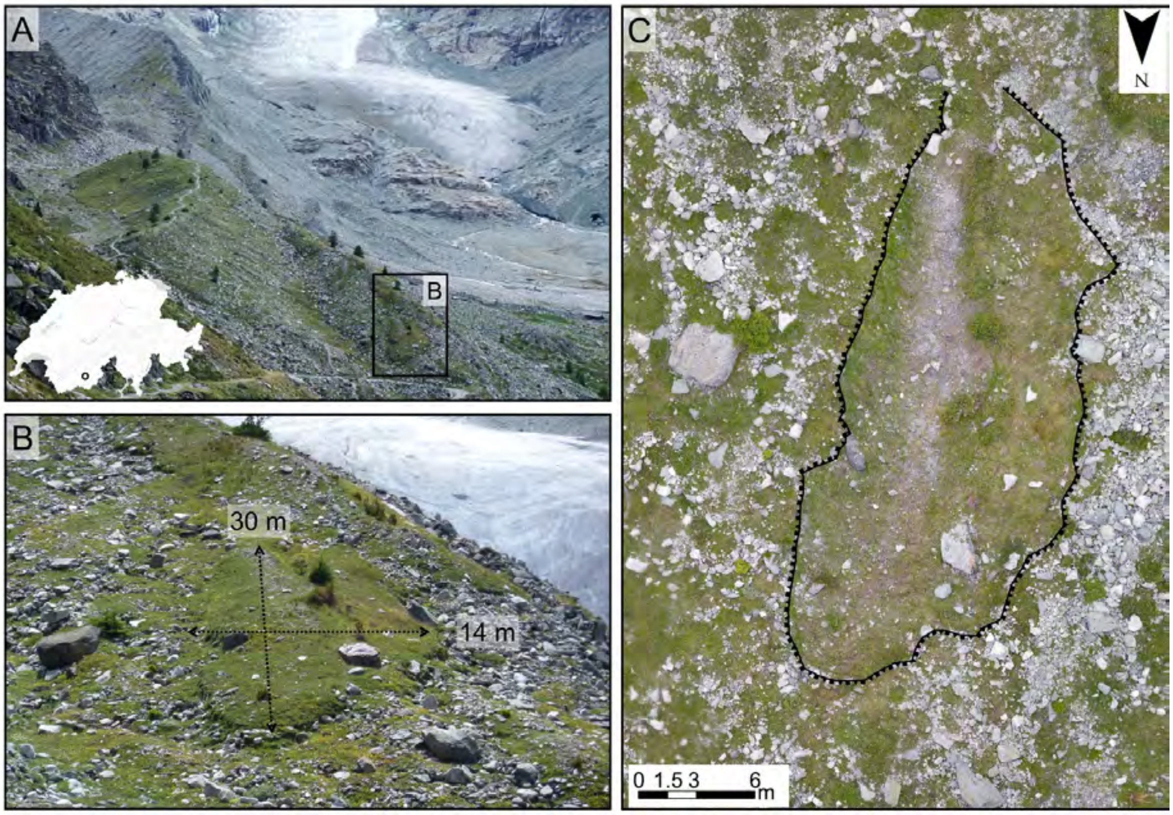

Figure 5.1: A The Turtmann glacier foreland at the southern end of the Turtmann Valley encompasses lateral moraines of different ages, which **B** represent parent slopes for solifluction lobes. **C** Orthophoto of the turf-banked solifluction lobe. The location of the Turtmann Valley in Switzerland is indicated by the inset map in Figure 5.1 A. For a general overview about geomorphic processes in the Turtmann glacier foreland see geomorphic map in Eichel et al. (2013).

5.4 Methods

5.4.1 Geomorphic and vegetation mapping

To determine the geomorphic properties of the solifluction lobe, a detailed geomorphic map (1:50 scale) was created. Mapping was based on the three-dimensional (3D) electrodes of the electrical resistivity tomography (ERT) setup (Figure 5.2), with 4 electrodes producing a rectangle plot used for orientation. Visible lobe material was mapped qualitatively and classified into fine and coarse soil (< 63 mm), cobbles (63 to < 200 mm) and boulders (≥ 200 mm) according to Ad-hoc-AG Boden (2005). Simultaneously, vegetation mapping was conducted to determine species occurrence and spatial distribution. Species taxonomic nomenclature is according to Lauber and Wagner (2007). Maps showing geomorphic features and species distributions were subsequently created in ArcGIS.

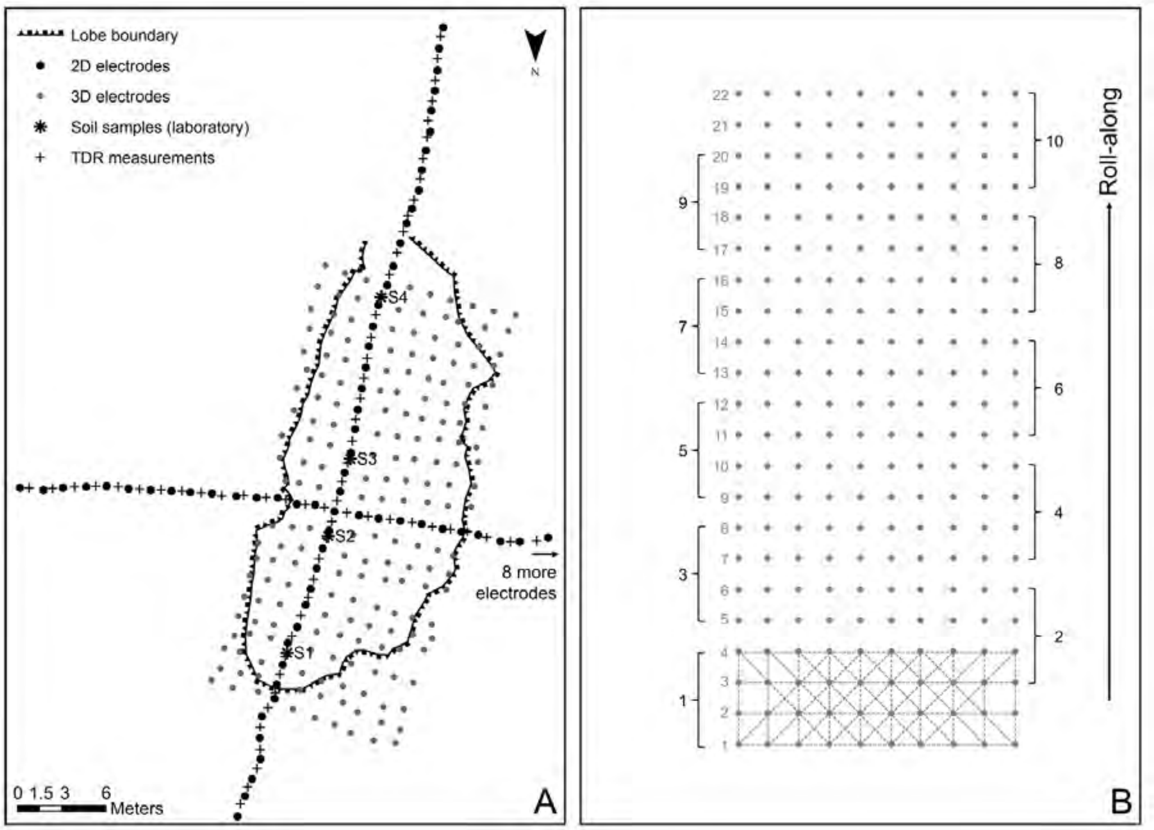

Figure 5.2: A Location of 2D/3D ERT transects, TDR measurements and soil sampling. **B** The 3D ERT consists of 22 parallel transects, thereof four transects (1-10) will be measured simultaneously in parallel, perpendicular and diagonal direction before the set up will be moved to the next pair of four transects using a roll-along. Lobe boundary is based on the geomorphic map (Figure 5.3 A).

5.4.2 Soil texture

To distinguish lateral and vertical differences in soil texture within the solifluction lobe, borehole measurements using a Pürckhauer drill with 1 m penetration depth were obtained at four locations along the longitudinal two-dimensional (2D) ERT transect (S1-S4, see Figure 5.2 for positions). Soil was sampled from the borehole cores at depth increments of 25 cm. Soil samples were air-dried, carefully broken down with a pestle and sieved using a 2 mm sieve. Organic material was destroyed by heating the sample to 430°C. Soil finer than 2 mm was dispersed in water and tetrasodium pyrophosphate, treated by an ultrasonic device and grain size subsequently analysed using a Retsch HORIBA LA-950 particle analyser.

5.4.3 Soil moisture

We measured volumetric soil moisture content manually by Time-Domain Reflectometry (TDR), using an IMKO Trime HD in combination with an IMKO Trime Pico64 soil moisture sensor. The sensor contains a thermometer and provides a measurement accuracy of 1% for a soil moisture range between 0 and 40 %. We used the preinstalled standard calibration by the manufacturer applicable for most soils. Measurements were conducted between every electrode along the longitudinal transect on the lobe (9 – 40 m) on 30 July 2014 and along the complete longitudinal transect (0 – 60 m) and cross-section (0 – 38 m) on 11 September 2014 (Figure 5.2). In the week before the first measurements, 76.4 mm precipitation fell, with 26.2 mm on the day before the July measurement. In contrast, the precipitation was only 10.9 mm within the week before the second measurements, thereof 0.2 mm on 10 September 2014. TDR probe measurements can be difficult to apply on stony soils due to problems in positioning the probes in the soil and the presence of air pockets that impede the contact and influence the measured result (Calamita et al., 2012). Therefore, measurements on stony moraine sections were excluded from the analysis.

5.4.4 ERT

Theoretical basis of ERT application

According to Archie's Law, resistivity is expressed as

$$\rho = a\,\rho_w / P^m \qquad (1)$$

with ρ constituting the bulk resistivity of the saturated porous medium, P the fractional porosity, ρ_w the pore fluid resistivity and m and a as empirical constants determined by pore geometry. Spherical grains, e.g. in silts and sands, show values of m around 1.2. Assuming that porosity and pore water resistivity remain constant over short periods such as 43 days, changes of resistivity depend on saturation (Krautblatter and Hauck, 2007). When water-saturated sediment freezes, the resistivity of pore water and saturation are reduced due to ice formation. Saturation decreases when ice begins to form until only unfrozen water content in form of unfrozen layers around mineral grains exist due to capillary and surface adsorption effects. Therefore, freezing decreases electrical conductivity transport in the soil solution of the remaining unfrozen water content (King et al., 1988).

Due to contact resistances, apparent resistivity is used instead of resistivity. When using a Wenner array, the apparent resistivity ρ_a can be derived from measured resistances R by applying the geometric factor a to each electrode pair and is calculated according to:

$$\rho_a = 2\pi\ a\ R. \qquad (2)$$

Wenner arrays enable a moderate investigation depth, good resolution of horizontal layers with vertical changes and a decreased sensitivity to weak signal strength (Kneisel, 2006). Therefore, they are suited for measurements on solifluction lobes where a high vertical resolution with shallow depth is required.

Applied data acquisition and processing of 2D and 3D ERT data

We measured resistivity in a 2D and true 3D approach. For this purpose, we installed a 60 m longitudinal transect consisting of 41 electrodes and a 49.5 m cross-section consisting of 34 electrodes on our TBL (Figure 5.2). In addition, a 3D setup consisting of 220 electrodes in 22 parallel transects of ten electrodes each was aligned on the lobe, incorporating the parts of the longitudinal and cross-section transects (Figure 5.2). Spacing between electrodes and parallel transects was 1.5 m. In the 3D ERT, four parallel lines were measured in parallel, perpendicular and diagonal direction. After each measurement, devices were moved in the form of a roll-along to the next four parallel transects with two overlapping transects (Figure 5.2). This set-up was selected to resolve the whole solifluction body and conduct measurements on a single day. To enable this set up, a custom-made Wenner array was established. We used an ABEM Terrameter LS, which measured the current and voltage of each electrode pair and automatically calculated the resistance. The apparent resistivity was calculated using Eq. 2. The 2D data were inverted using Res2DInv, while 3D data were inverted using Res3DInv to derive a true 3D ERT. In both inversions, robust inversion with a half-spacing solution of 0.75 m was selected, which produces models with sharp boundaries (Loke and Barker, 1996, 1995). The inversion stopped when data misfit between measured and modelled resistivity did not change anymore or the maximum iteration number was reached. The mathematical quality of the final tomography was quantified by the root mean square error (RMS), which ranges between 1.9 % and 2.5 % in the 2D ERT and between 6.35 % and

6.58 % in the 3D ERT. However, a small RMS does not necessarily correspond to a more realistic model, as a large number of iterations tends to decrease the RMS but overfits the data and tends to increase large resistivity contrasts (Hauck and Vonder Mühll, 2003). To avoid overfitting, only five iterations were selected. For the 3D ERT, time slices were inverted separately using Res3DInv and time-lapse resistivity changes were calculated manually to enable spatial differentiation of soil moisture changes.

5.5 Results

Based on geomorphometric, material, soil moisture and vegetation characteristics, the solifluction lobe can be differentiated into three landform elements: (i) frontal and lateral risers, (ii) tread and (iii) ridge.

5.5.1 Geomorphometric, material and vegetation characteristics

The TBL consisted of a tread 29 m long and up to 14 m wide inclined at 22° and located on a distal moraine slope inclides at 23° (Figure 5.1 A, B). The lobe front had a riser 1.8 m high consisting of several small steps (< 0.5 m) at the centre of the lobe front and small and high (> 0.5 m) steps at the eastern and western frontal lobe parts (Figure 5.3 A). Both frontal and lateral lobe risers showed a pronounced accumulation of blocky material (Figure 5.3 B). Main species occurring at and below the lobe risers are *Trifolium badium* Schreb., *Salix hastata* L., *Campanula cochleariifolia* Lam., *Salix reticulata* L. and *Epilobium fleischeri* Hochst. (Figure 5.3 C). The tread body was clearly delimited from the eastern and western parent slopes by a 1.0 m high step, while the rear of the tread passed into the parent slope (Figure 5.3 A). On the tread, a small ridge existed in the upper two thirds of the tread and small steps (< 0.5 m high) occurred to the west of this ridge. The whole tread was covered dominantly by *Dryas octopetala* (Figure 3 D), exept for the nearly vegetation-free ridge, consisting of cobbles and sandy silt material interspersed with individual plants of *Silene exscapa* All., *Trifolium pallescens* Schreb. and *Linaria alpina* (L.) Mill. s.str. (Figure 5.3 E). A boulder 3 m in diameter was located on the frontal part of the lobe, while west of the lobe, blocky moraine material dominateed (Figure 5.1 C). In contrast, the surface east of the lobe was partly covered by by vegetation, cobbles and boulders. No differentiation of soil texture with depth was observed in the boreholes. Therefore, the mean texture was calculated for every borehole core. Soil material from the longitudinal transect (Figure 5.2) shows a sand fraction between 37.2 and 42.9 %, a silt fraction between 55.1 and 57.2 % and clay content between 1.7 and 4.1 % (Figure

5.4). Thus, the lobe material is sandy silt and no substantial differences in soil texture were detected along the longitudinal transect.

5.5.2 Near-surface soil moisture measurements

The TDR measurements in the lobe tread showed soil moisture values at 10 cm depth between 7 and 10 % at the end of July and between 3 and 7 % at the beginning of September (see Figure 5.5 for tread boundaries). The spatial distribution of soil moisture measurements shows no obvious patterns or spatial concentrations of moisture, although the eastern and western risers of the lobe (Figure 5.5 B) are much dryer than the lobe or parent slope. Within the cross-section, soil moisture could not be measured beyond 38 m (western parent slope of the lobe) due to coarse material (see Figure 5.1 C).

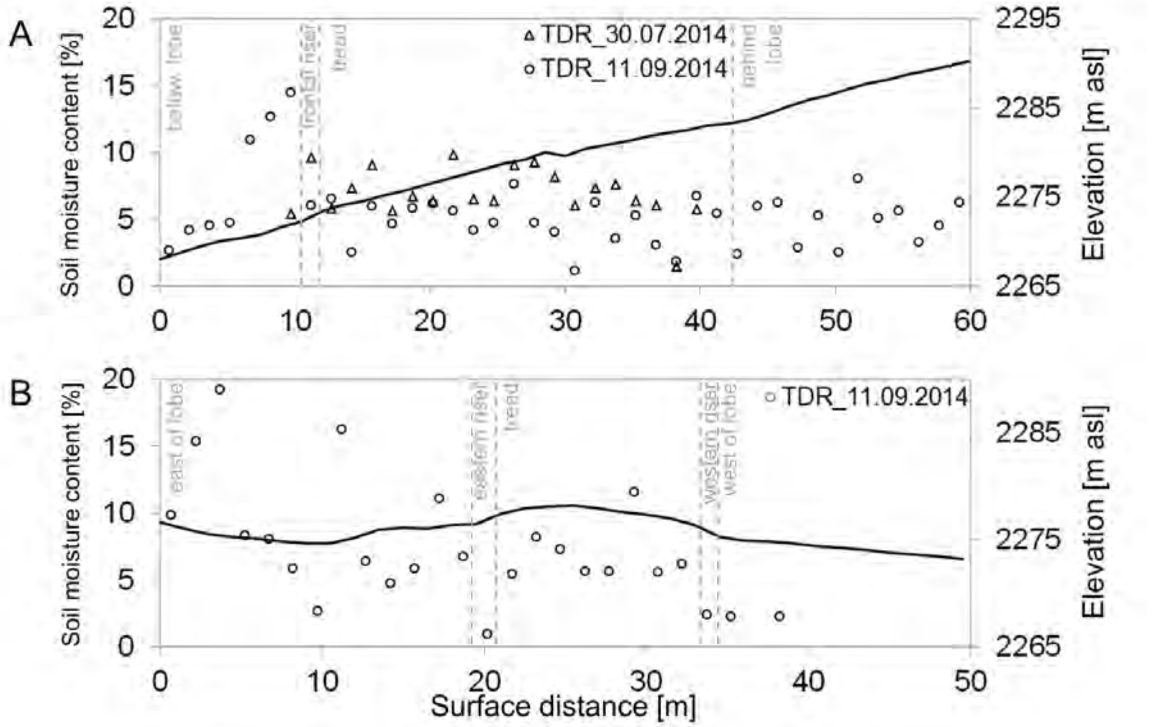

Figure 5.3: **A** Topography of the longitudinal transect with results from TDR measurements. **B** Topography of cross section with results from TDR measurements.

5.5.3 Subsurface conditions

2D electric resistivity tomographies

On 30 July, the 2D ER tomography (Figure 5.6 A) showed resistivity differences between the lower lobe tread (transect length 11 to 19 m), middle lobe tread (19 – 28 m) and upper lobe tread (28 – 40 m). In the lower lobe tread, there was a low-resistivity cell (<0.95 kΩm) from the surface to 1 m depth. Below was a 0.75 m thick low-resistivity body (0.95 – 1.69 kΩm) followed by a body with resistivities between 1.69 and 3.0 kΩm. The middle of the lobe tread consisted of a 2 m thick low-resistant area (0.95 – 1.69 kΩm) with underlying areas of higher resistivities (>1.69 kΩm). The upper lobe tread (28 – 40 m) showed resistivities between 1.69 and 3.0 kΩm with a high-resistant area (3.0 – 12.6 kΩm) from 36 to 43 m. The area behind the lobe showed resistivities between 1.69 and 3.0 kΩm, while resistivities were up to 22.5 kΩm below the lobe.

Forty-three days later (Figure 5.6 B), the ERT showed a general trend of increasing resistivities at the lobe body from 10 to 40 m, with remaining resistivity contrasts between the lower, middle and upper lobe tread. The observed low-resistant cell (<0.95 kΩm) decreased to a small cell at 16 m while resistivities increase to a range between 0.95 and 1.25 kΩm in the residual area of this former low-resistant cell. At depths exceeding 3 m below this area, resistivities increased from 3.0 to 4.0 kΩm. The middle and upper lobe tread shows slight increased of resistivities restricted to areas with 2 - 2.5 m depth while no changes occured in underlying areas. Below and behind the lobe, resistivities slightly increased.

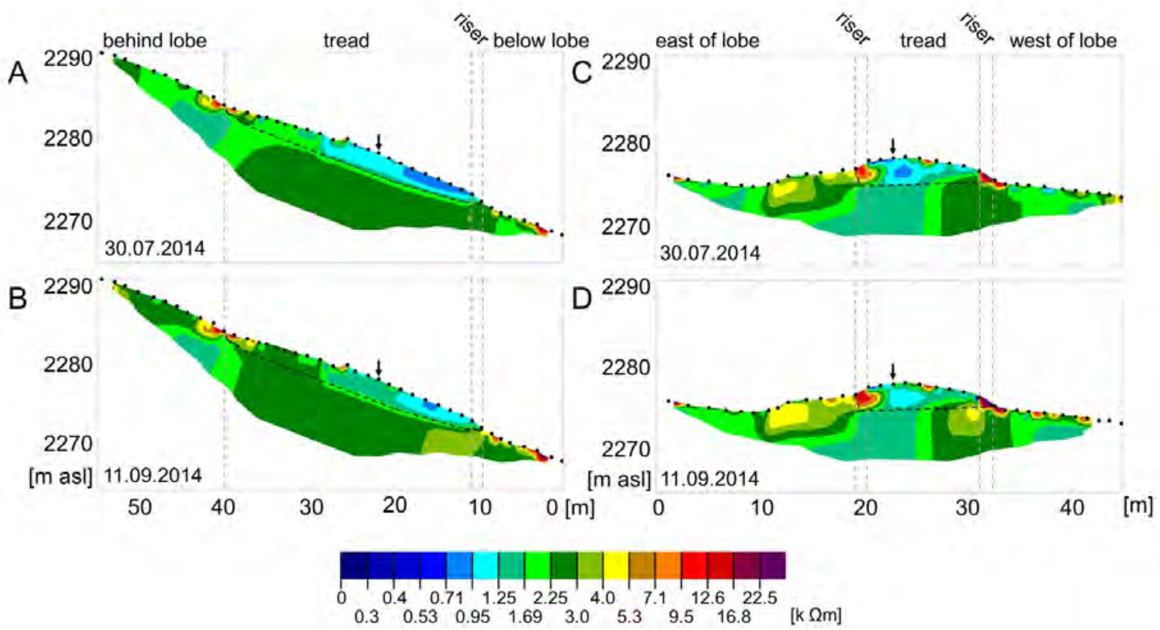

Figure 5.4: A 2D-ERT of the longitudinal transect along the length axis of the solifluction lobe on 30 July and **B** on 11 September 2014. **C** Cross section 2D-ERT across the tread of the solifluction lobe on 30 July and **D** on 11 September 2014. The black arrows mark the intersection with the cross section at 22 m, black dots indicate the electrode positions and the black dotted lines highlight the interpreted lower boundary of the lobe.

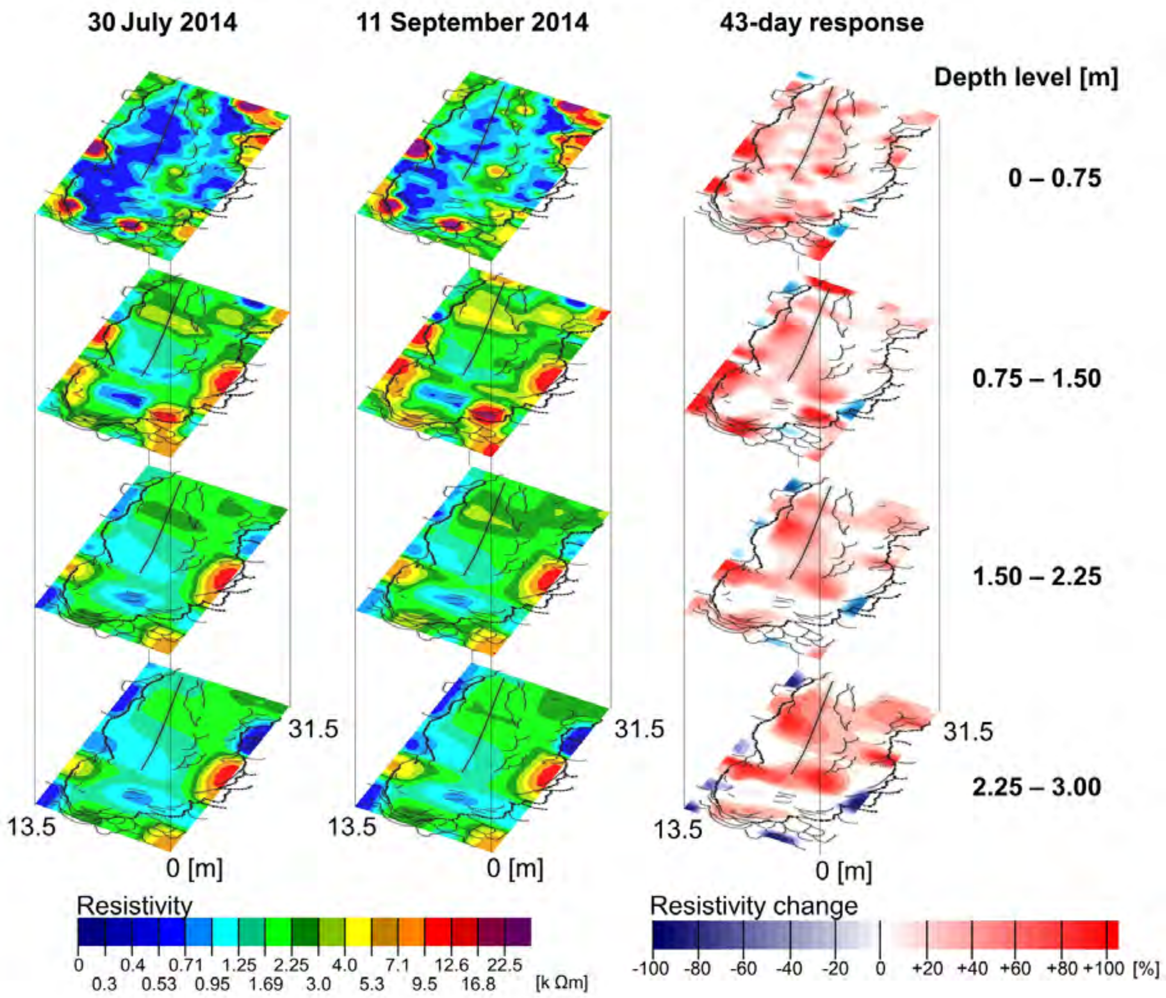

Figure 5.5: 3D ER tomographies from 30 July and 11 September 2014 and resistivity changes shown by time-lapse ERT. Solifluction lobe is indicated by lobe boundary

For the cross-section on 30 July (Figure 5.6 C), the lowest resistivities (<1.25 kΩm) were located in the centre of the lobe (22 – 27 m) at depths of up to 2 m, with increasing resistivities between 4.0 and 22.5 kΩm towards the lateral risers. East of the lobe, resistivities ranged from 1.69 to 3.0 kΩm (0 – 10 m), followed by a higher resistant area (10 - 19 m) with resistivities between 3.0 and 7.1 kΩm. West of the lobe (32 – 42 m) near-surface (<1 m) areas showed high resistivities (up to 12.6 kΩm) above regions of lower resistivities (1.25 – 3.0 kΩm). The second measurement (Figure 5.6 D) showed slightly higher resistivities along the transverse transect. Low resistivity values within the centre of the lobe body slightly increased; however, the lobe body was still delimited by low resistivities from higher-resistant risers and surroundings.

3D electric resistivity tomographies

In July 2014, the 3D ER tomographies (Figure 5.7) showed low resistivities (<1.25 kΩm) in the lobe tread between 0 and 0.75 m depth, except for higher resistant areas (1.69 – 5.3 kΩm) around the small steps west of the ridge. In contrast, the lateral risers of the lobe and areas close to the lobe were highly resistant (>4.0 kΩm) to a depth of up to 1.5 m. At greater depths, resistivity generally increased, although low-resistant cells in the middle and close to the lobe front persisted. Lateral risers showed a reverse resistivity change in most areas, where near-surface (0 – 0.75 m) high-resistant areas changed to underlying (>0.75 m depth) low-resistant areas, while near-surface low-resistant areas increased in resistivity with depth. Forty-three days later, low-resistant tread areas had decreased in size, while high-resistant areas at lateral risers had increased. However, the resistivity pattern from the first measurement persisted. The observed resistivity increase is supported by time-lapse tomographies (43-day response, Figure 5.7), which show an overall increase of resistivity on the lobe tread, while at lateral risers small cells with reduced resistivities exist.

5.6 Discussion

5.6.1 Geomorphic and material properties of the solifluction lobe

Solifluction lobes reflect the parent slope material, with silt increasing frost-susceptibility and promoting solifluction. The analysis of borehole material showed a high proportion of silt (55.1 – 56.6 %) and sand (37.2 – 42.9 %) and a low proportion of clay which is characteristic for TBL material (Benedict, 1970a; Matthews et al., 1986). The higher content of fine material in TBLs compared to parent slopes (Matthews et al., 1986) has been explained by previous colluviation (Strömquist, 1983) or solifluction lobe failures (Price, 1974). Due to the dominance of silt, the lobe material is frost-susceptible and favours the development of ice lenses (Figure 5.4), which are required to impede drainage and generate pore water pressure when clay layers and permafrost are absent (Harris, 1981).

The solifluction lobe is approximately 2 m thick and currently not affected by permafrost or buried glacier ice. The ERTs (Figure 5.6) demonstrate a resistivity change at the lobe body from low resistivities (<3.0 kΩm) to high resistivities (>3.0 kΩm) at 2 m depth which is more pronounced in the longitudinal transect. We interpret this boundary (black dotted lines) as the boundary between fine lobe material and underlying till. Laboratory measurements by Vanhala et al. (2009) showed resistivities for unfrozen till of 4 - 6 kΩm, which are slightly higher than the observed resistivities in the Turtmann lobe. As a consequence, the ERT suggests a lobe thickness of 2.0 m, which is similar to the riser height of 1.8 m. Differences could result from the coarse resolution (0.75 m) of the tomographies. In addition, the ERT demonstrates that permafrost or buried ice are absent in the upper 10 m. High-resistant areas with resistivities above 30 kΩm (Kneisel, 2010) or above 50 kΩm (Vanhala et al., 2009) can be interpreted as frozen sediment or ice. Permafrost would be expected beneath a low-resistant active layer. However, the tomographies show that these areas are limited next to the surface, where large boulders are abundant (Figure 5.3 B). Low-porosity boulders are consequently drier than surrounding soil, and thus, the abundance of dry boulders results in near-surface high-resistant areas.

The young age and large size of the solifluction lobe indicate a fast development. The solifluction lobe has large dimensions compared to TBLs from different periglacial environments (e.g. Costin et al., 1967; Hugenholtz and Lewkowicz, 2002; Smith, 1987), which developed over several hundred years (Kinnard and Lewkowicz, 2006; Price, 1974). Therefore, the relatively young age (< 100 years) of the parent material points to a fast evolution.

5.6.2 Spatial differentiation within the turf-banked solifluction lobe

Frontal and lateral risers

Boulders act as obstacles that impede the movement of the risers, which are densified due to applied stress by faster movement of the tread and increase in height. Geomorphic mapping (Figure 5.3 B) and high-resistant areas in 3D ERTs (Figure 5.7) show a boulder concentration at the frontal and lateral risers of the lobe, similar to stratigraphic analysis of TBLs in Norway (Elliott and Worsley, 1999; Matthews et al., 1986; Williams, 1957).

This boulder pattern can result from increased frost-heave processes or ploughing boulder activity. In stone-banked lobes, coarse material moves faster than fine material due to frost-heave processes and so reaches the lobe front more quickly (Benedict, 1976; Harris, 1981). Thus, Harris (1981) concluded that a similar boulder concentration at TBLs results from frost-heave processes and that a continuum exists between TBLs and SBLs. Alternatively, ploughing boulders, which are associated with gelifluction, move faster than surrounding TBL material (Ballantyne, 2001; Berthling et al., 2001) and could accumulate at the riser. Ploughing boulders leave a furrow and a mound in front of them (Ballantyne, 2001; Hall et al., 2001). However, both characteristics are not observed, only the observed steps on the tread parallel to the ridge could be interpreted as the furrow of the large ploughing block near the tread front (Figure 5.1 C, Figure 5.3 B). The lack of characteristic features could result from reworking by subsequent solifluction processes.

Vegetation species composition probably results from the exclusion of engineering species by later-successional species and indicates stable riser conditions. The vegetation data (Figure 5.3 C) show a dominance of shrubs (e.g. *Salix hastata*) and other later-successional species (e.g. *Trifolium badium*, *S. reticulata*) on the frontal and lateral risers of the lobe. As these species need a certain degree of habitat stabilization and humus accumulation for establishment (Erschbamer et al., 2008; Stöcklin and Bäumler, 1996), they indicate stable riser conditions. In addition, species composition contrasts to active fronts and risers of solifluction lobes where *D. octopetala* is the dominant species (Benedict, 1970a; Gamper, 1981). This suggests a replacement of engineering species with later-successional species as soon as solifluction movement decreased sufficiently. Similar differences between tread and riser vegetation observed at our lobe were found at TBLs by Price (1971), who attributed this pattern to the existence of different microhabitats.

The observed multiple-fronted riser, consisting of several smaller steps (<0.5 m), could result from several solifluction episodes. Previous studies show evidence for episodes of increasing solifluction activity, with intervals of hundreds or thousand years, derived from ^{14}C dating of buried organic horizons (Matthews et al., 2005; Oliva et al., 2011; Veit et al., 2012). Solifluction lobes enlarge with time in a cyclic way (Price, 1974) until reaching a maximum size that depends on environmental conditions (Kinnard and Lewkowicz, 2006). Continuous movement of material results in either frontal advance or collapse of the lobe (Hugenholtz and Lewkowicz, 2002). Kinnard and Lewkowicz (2006) estimated the time for a full cycle of development of TBLs in Yukon to be in the order of a few hundred years. However, our solifluction lobe is less than 100 years old, as the moraine was formed in the 1920s, which implies a much faster episodic solifluction lobe development probably driven by moisture channelization effects resulting from the risers (see next section).

Tread

As shown by Aalto et al. (2013), soil moisture distribution in the lobe tread depends on short-term weather and small-scale material conditions. The differences in ranges of manual TDR measurements from 7 to 10 % at 30 July and from 3 to 7 % at 11 September 2014 (Figure 5.5) suggest that soil moisture contents reflect the occurrence of a precipitation event of 26.2 mm on 30 July, one day before the measurement. However, the observed soil moisture ranges are much lower than summer soil water content ranges of SBLs in the Engadin (15 - 22 %) (Matsuoka, 2010) and at Mt Ainodake in Japan (20 - 30 %) (Matsuoka, 2014) or TBLs in the Glatzbachtal catchment (27 - 30 %) (Jaesche et al., 2003) and in the Abisko region (10 – 85 %) (Ridefelt and Boelhouwers, 2006). The low soil moisture and persistent spatial soil moisture distribution indicated by 3D ERT indicates a material dependency of soil moisture. The soil analysis shows high contents of silt and sand (Figure 5.4), and therefore, the lobe material is highly permeable, which results in fast drainage of rain. Due to the absence of clay layers or permafrost, ice-lens development promoted in frost-susceptible material is necessary to impede drainage and develop critical pore pressure required for solifluction movement.

Soil moisture distribution shows persistent spatial patterns, with increased moisture content towards the centre and the front of the TBL. As soil moisture controls movement in solifluction lobes, its spatial variability affects the distribution of movement (Benedict, 1970a; Harris, 1977). Our cross-section 2D ERTs (Figure 5.6 C, D) and 3D ERTs (Figure 5.7) demonstrate low-resistant areas in the centre of the lobe, with increasing resistivity towards the lateral risers, which we interpret as soil moisture decrease from the centre to the lateral risers. Near-surface TDR results also indicate dry conditions at the lateral risers of the lobe (Figure 5.5 B). The findings are in good accordance with observations of decreasing moisture towards the lateral risers at TBLs in Okstindan, Norway, and at Niwot Ridge, Colorado (Benedict, 1970a, Harris, 1977). Therefore, the blocky lateral risers impede movement of tread material, which results in soil thickening and compaction close to the lateral risers. The compacted low-permeable soil enhances the concentration of moisture along the long axis of the lobe and results in a channelization of soil moisture. Benedict (1970a) argued that this channelization controls the development of a solifluction lobe, while uniform moisture patterns result in solifluction terrace development. Furthermore, the longitudinal ERTs (Figure 6 A, B) and 3D ERTs (Figure 5.7) show that the wettest areas are in the frontal part (<0.95 kΩm), which cannot be supported by TDR measurements. The observed concentration of soil moisture contrasts with previous studies (Benedict, 1970a, Harris, 1977) and could result from downward moisture transport due to high slope angle and permeable sandy silt. The thickened frontal risers possess a lower permeability as a result of soil compaction (Benedict, 1976), which results in subsequent impeding of drainage and in the measured soil moisture concentration. Channelization effects of soil moisture can further amplify the moisture concentration at the frontal riser.

The ecosystem engineer *Dryas octopetala* can both promote and reduce solifluction. Vegetation mapping demonstrated the dominance of *D. octopetala* on the tread. This species occurs on lateral moraine slopes in the Turtmann glacier foreland and induces a change from slope wash to solifluction processes (Eichel et al., 2016) through its growth form and root traits (Harrington and

Mitchell, 2002; Kutschera et al., 1997). *D. octopetala* grows in mats and promotes solifluction by trapping fine, frost-susceptible sediments from surface runoff (Ellenberg, 1996; McGraw, 1985; Reisigl and Keller, 1994). However, its strong and deep roots increase shear strength (Ghestem et al., 2014) by increasing internal friction (Graf et al., 2009) and, thus, increase soil stability and reduce solifluction. Besides root effects, vegetation prevents needle-ice creep and reduces frost creep (Matsuoka, 2001). This effect is probably strong below *D. octopetala* mats with thicknesses of several centimeters. Benedict (1970a) and Gamper (1981, 1983) observed a reduced movement of *D. octopetala* covered solifluction lobe and terraces fronts, and therefore, we argue that combined root and mat cover effects at our lobe tread probably reduce current solifluction in comparison to the unvegetated ridge.

Ridge

The unvegetated part on the tread, which is parallel to the long-axis (Figure 5.3 A), is developed by a combination of frost-cracking processes and represents the fastest areas of TBLs. Small-scale differences of both material and soil moisture (Aalto et al., 2013) can result in differential frost heave and tension crack development, which can be amplified by gravity-induced movement away from the axis of the lobe (Benedict, 1970b). The latter effect is indicated by the slight inclination of the eastern and western tread from the ridge towards the lateral risers. This could explain why the crack width is an order of magnitude larger than frost crack widths observed at Niwot Ridge (Benedict, 1970b) and also the unusual location of the maximum lobe width (14 m) at the centre of the lobe. Subsequent frost heave with lateral sorting into the crack (Ballantyne and Matthews, 1983) and colluviation processes (Strömquist, 1983) fill the crack. Therefore, ridge material is fine-grained with interspersed cobbles (Figure 5.3 B) (Benedict, 1970b) and enables the concentration of soil moisture near the surface as demonstrated by 3D ERT (Figure 5.7).

The ridge is probably strongly affected by frost heave processes which increase surface movement. The low vegetation cover indicates disturbance due to colluviation and frost heave and in turn enables a higher frequency of freeze-thaw cycles due to the lack of *D. octopetala* mat. As a consequence, frost-resistant species such as *Silene exscapa* (Körner, 2003; Larcher et al., 2010) are dominant. The observed sparse vegetation cover and species composition corresponds to filled cracks which were identified as fastest moving areas of the TBLs (Benedict, 1970b; Furrer, 1971; Gamper, 1981).

5.6.3 Electrical Resistivity Tomography as a tool for solifluction prospecting

The application of ERT enables identification of the solifluction lobe body, solifluction material thickness and permafrost occurrence. As Figure 5.6 (black dotted lines) shows, the solifluction body can be clearly delineated with 2D ERT. This information can be incorporated to establish solifluction rates (e.g. Matsuoka, 2001), geomorphic work (e.g. Ridefelt et al., 2011; Smith, 1992) or sediment budgets (e.g. Otto et al., 2009). Furthermore, ERT provides spatial information on the occurrence or absence of permafrost in solifluction landforms (e.g. Kneisel, 2006, 2010), which influences solifluction movement (Matsuoka, 2001).

The inversion process of electrical resistivity data by Res2DInv and Res3DInv increases large resistivity contrasts. Raw data analysis demonstrated that abnormally high resistivity values (>4.0 kΩm) are absent. However, in ERT sections where low-resistant areas indicating wet conditions border high-resistant areas indicating dry conditions, the latter are increased to abnormally high values. This artefact occurs especially in areas where boulders are abundant such as at frontal or lateral risers. Unfortunately, uncertainty and sensitivity analysis provided by Res2DInv and Res3DInv fail to highlight these artefacts. Previous studies by Hauck and Vonder Mühll (2003) and Rings et al. (2008) observed the same effect in permafrost and soil moisture investigations. Therefore, this effect does not affect the interpretation but does prohibit interpreting abnormally high resistivity values quantitatively.

Material heterogeneity in combination with electrode spacing of 1.5 m prevents the calibration of resistivity with TDR values, and, therefore, only enables a qualitative interpretation. While TDR measurements are used to calibrate ERT measurements in soil studies with homogenous material (Calamita et al., 2012), highly heterogeneous material and complex geomorphometry of the lobe result in large small-scale variation of soil moisture (Aalto et al., 2013) and prevent ERT calibration. As soil texture analysis showed, lobe tread material is built up of homogeneous fine-grained material such as sandy silt (Figure 5.4), interspersed by coarser material identified by geomorphic mapping (Figure 5.3 A, B). Therefore, the use of standard calibration scheme of the TDR device can be problematic. In addition, Walker and Houser (2002) demonstrated that near-surface (10 cm depth) TDR measurements on a small scale are poorly correlated with low-resolution resistivity measurements (>1.0 m) that integrate a larger soil column. Thus, the calibration of resistivity values with TDR measurements failed and spatial resistivity differences can only be interpreted as qualitative soil moisture differences, as in landslide studies (Perrone et al., 2014).

The ERT is a novel approach in solifluction studies that provides spatial information on material and moisture conditions without disturbing the landform. Previous monitoring of soil moisture was restricted to one point on the lobe (e.g. Jaesche et al., 2003; Matsuoka, 2010) or was conducted using transects of manual groundwater pipe measurements (Benedict, 1970a, Harris, 1977). ERT provides a higher spatial coverage which can be further increased by the application of 3D roll along measurements (Dahlin et al., 2002; Doetsch et al., 2012), as in this study. A laboratory or field calibration approach (Calamita et al., 2012) in combination with a smaller electrode spacing (Walker and Houser, 2002) could be applied to use ERT for soil moisture quantification in solifluction studies. The automation into AERT can enable continuous monitoring of soil moisture evolution, as applied at a debris-covered slope at the Schilthorn by Scherler et al. (2010).

5.6.4 Implications of solifluction lobe movement for paraglacial sediment transport

Our study indicates that paraglacial activity does not necessarily stop under vegetation cover, as solifluction processes can occur below vegetation and can even be promoted by ecosystem engineers. Previous studies considered paraglacial adjustment to be completed when no more sediments are available for reworking or when they are stabilized by vegetation, which synchronously colonizes lateral moraine slope in the course of vegetation succession (Ballantyne, 2002b; Garibotti et al., 2011; Klaar et al., 2015). On steep moraine slopes with initial slope gradients >30°, debris flows and gullying are the main sediment reworking processes (Ballantyne, 1995; Curry, 2000; Curry et al., 2006) and limit vegetation succession to pioneer stages due to their high magnitude and frequency (Eichel et al., 2013, 2016; Matthews, 1999). However, once process magnitude and frequency sufficiently decrease, ecosystem engineer species, such as *D. octopetala*, can establish and actively change the dominant processes from linear erosion and slope wash to solifluction in a biogeomorphic feedback window (Eichel et al., 2016). While solifluction processes can generally only occur at slope gradients below 30° (Benedict, 1976; Matsuoka, 2001), *D. octopetala* occurs independently of slope angle and promotes solifluction by accumulating fine sediments, storing moisture, limiting soil erosion and increasing slope stability once it crosses a cover threshold of 35% (Eichel et al., 2016). Therefore, this ecosystem engineering has the potential to enhance solifluction occurrence even on steeper slopes.

The large dimensions of our lobe imply that the observed positive feedbacks between solifluction, material, soil moisture and vegetation strongly amplify solifluction lobe development on lateral moraine slopes, either once engineer species can establish or once gullying and debris flows have adjusted moraine slope to an equilibrium gradient of 29±4° (Curry, 1999). Thus, paraglacial adjustment does not stop once vegetation colonizes bare sediments but continues with bound solifluction for some decades until the observed interaction of coarse material at the risers and vegetation effects impede the lobe and restrain movement. Then, positive feedbacks are reversed into negative feedbacks that decrease solifluction. Soil can further thicken at the riser resulting in changes of the groundwater regime which could amplify the impounding of material (Benedict, 1976). Solifluction lobe activity decreases and paraglacial sediment transport by solifluction is limited to frost heave processes in the unvegetated areas, as observed on the ridge. Our data indicates that this process of lobe development on lateral moraine slopes takes about 100 years. Due to this short time span, the large dimension of our lobe and the widespread occurrence of solifluction on moraine slopes (Eichel et al., 2013), we believe that solifluction, promoted by ecosystem engineering, could contribute significantly to paraglacial sediment reworking, even after vegetation colonization. Thus, spatial geomorphic, species distribution and material patterns and an understanding of how interactions operate, as provided in this study, can provide important information on solifluction lobe activity, especially in the context of paraglacial adjustment.

5.7 Conclusions

For the first time, a biogeomorphic approach was applied to quantify geomorphometric, material and vegetation properties of a TBL and demonstrate their role in the course of paraglacial adjustment. Our findings show that:

1. ERT is a y valuable tool to provide spatial information on material properties and soil moisture conditions in TBLs and other periglacial landforms. The 2D ERT allowed us to differentiate the fine-grained TBL body from the surrounding till, while our novel roll-along 3D ERT provided a spatial insight on soil moisture differentiation within the lobe body.
2. Geomorphometric, material/soil and vegetation properties of the TBL differ between (i) frontal and lateral risers, (ii) the lobe tread and (iii) the ridge. (i) The riser geomorphometry implies several episodes of past solifluction movement. However, large boulders, which are currently abundant, impede riser movement and increase stability, with the latter indicated by the occurrence of later-successional species, such as shrubs. (ii) The solifluction lobe tread shows persistent spatial patterns of soil moisture which increase towards the lower tread, probably due to downslope moisture transport and moisture channelization by the impeding lateral risers. The tread is completely covered by the engineering species *Dryas octopetala* which potentially reduces the movement due to root and mat effects. (iii) A ridge parallel to

the long-axis of the lobe and located at the upper part of the tread originates from differential frost heave and is probably the fastest moving area. The fined-grained material promotes an increased frost heave frequency which results in the predominance of frost-resistant species.

3. Despite its young age (< 100 years) and an absence of permafrost in the underlying moraine till, the iTBL is large. This suggests that solifluction plays an important role in the paraglacial adjustment of intermediate to gently inclined (<30°) moraine slopes, even under vegetation cover. Our study suggests that ecosystem engineering can even promote solifluction processes. In time, the importance of solifluction for sediment transport ceases when interactions between material, vegetation and soil moisture decrease solifluction lobe activity at the tread and risers and restrict paraglacial adjustment to small-scale frost heave processes on the lobe ridge.

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6 SOLIFLUCTION MEETS VEGETATION: THE ROLE OF BIOGEOMORPHIC FEEDBACKS FOR TURF-BANKED SOLIFLUCTION LOBE STRUCTURE AND DEVELOPMENT

> *‚Landforms are a control of vegetation, and vegetation is a regulator of landform evolution; to understand either requires the study of both’ (Osterkamp et al., 2011, p. 23)*

This chapter is based on a journal article currently under review:

Eichel, J., Draebing, D., Eling, C., Klingbeil, L., Wieland, M., Schmidtlein, S., Kuhlmann, H. and R. Dikau (in review): Solifluction meets vegetation: the role of biogeomorphic feedbacks for turf-banked solifluction lobe structure and development. Submitted to Earth Surface Processes and Landforms.

It addresses thesis objective 3 by demonstrating how turf-banked solifluction lobes (TBLs) can be created in an ecosystem engineering processes by the dwarf shrub *Dryas octopetala.* Results from Chapters 4 and 5 are followed up, as ecosystem engineer traits are linked with TBL material and surface properties, geomorphic processes, as well as TBL geomorphometry and ecology. A four stage conceptual biogeomorphic model of TBL development is developed and TBLs are identified as biogeomorphic structures. The TBL development model is linked to biogeomorphic succession dynamics in Chapter 8.

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6 TURF-BANKED SOLIFLUCTION LOBES AS BIOGEOMORPHIC STRUCTURES

6.1 Abstract

Vegetation is an important factor influencing solifluction processes, while at the same time, solifluction processes and landforms influence species composition, fine-scale distribution and corresponding ecosystem functioning. However, how feedbacks between plants and solifluction processes influence the development of turf-banked solifluction lobes (TBLs) and their geomorphic and vegetation patterns is still poorly understood. We addressed this knowledge gap in a detailed biogeomorphic investigation in the Turtmann glacier foreland (Switzerland). Methods employed include geomorphic and vegetation mapping, terrain assessment with unmanned aerial vehicle (UAV), Electrical Resistivity Tomography, soil sampling and analysis, temperature logging. Results were subsequently integrated with knowledge from previous geomorphic and ecologic studies into a conceptual model. Our results show that geomorphic and vegetation patterns at TBLs are closely linked through the lobe elements tread, risers and ridge. A conceptual four-stage biogeomorphic model of TBL development with ecosystem engineering by the dwarf shrub *Dryas octopetala* as the dominant process can explain these interlinked patterns. Based on this model, we demonstrate that TBLs are biogeomorphic structures and follow a cyclic development, during which the role of their components for engineer and non-engineer species changes. Our study presents the first biogeomorphic model of TBL development and highlights the applicability and necessity of biogeomorphic approaches and research in periglacial environments.

6.2 Introduction

Solifluction is the slow downslope movement of soil mass resulting from freeze-thaw processes, which occurs on hillslopes in Polar and Alpine regions (French, 2007; Matsuoka, 2001). In addition to soil texture, moisture, topography, permafrost and climate, vegetation is recognized as an important factor influencing solifluction processes and landform development (Benedict, 1970a, 1976; Gamper, 1981; Matsuoka, 2001). Periglacial research showed that though vegetation covered turf-banked solifluction lobes (TBLs) possess lower surface velocities than vegetation-free stone-banked lobes (SBLs), their movement extends to greater depths. Consequently, TBLs possess convex-concave movement profiles and higher sediment thickness and risers (Harris et al., 2008; Kirkby, 1967; Matsuoka, 2001), which has been explained by the inhibition of freeze-thaw cycles by vegetation cover and the binding effects of roots at the soil surface (Matsuoka, 2001). In turn, solifluction processes disturb plant growth and establishment (Jonasson, 1986; Körner, 2003). Yet, solifluction landforms also provide microtopographic (cm to dm scale) and microclimatic habitat variation and thereby control plant species composition and fine-scale distribution patterns (Cannone and Guglielmin, 2010; Kozłowska and Rączkowska, 2002; Parker and Bendix, 1996; Rose and Malanson, 2012).

To understand how solifluction processes and plants interact is crucial in the context of global warming. Changing climatic conditions will affect both future solifluction processes and plant species composition, diversity and distribution (Alatalo et al., 2016; Jaesche et al., 2002; Matsuoka, 2001; Virtanen et al., 2010; Wilson and Nilsson, 2009), and thereby also their interactions (Hjort and Luoto, 2009). As these interactions influence solifluction rates and associated sediment transport, their change will strongly affect future landscape dynamics in periglacial environments.

However, the current understanding of 'biogeomorphic feedbacks' between plants and solifluction processes and landforms is still very limited. So far, it is not well known how they influence geomorphic and ecologic properties of TBLs and their movement rates. Furthermore, while first models of TBL development were proposed by Price (1974) and Hugenholtz and Lewkowicz (2002) it is still not completely understood how TBLs initiate and develop in time and which role plants and their interactions with solifluction processes play for their evolution. A biogeomorphic approach to solifluction and TBLs can help to close this knowledge gap. Recent biogeomorphic research in fluvial and coastal environments demonstrated that plants can control the development of landforms by interacting with geomorphic processes (Balke et al., 2012; Corenblit et al., 2015; Gurnell, 2014). Through adapted traits, plants shape their immediate abiotic and biotic environment in terms of ecosystem structure and functioning. This has been called 'ecosystem engineering' (Corenblit et al., 2015; Gutiérrez and Jones, 2008; Jones et al., 1994). When this shaping affects geomorphic processes and landforms, the process has been called 'biogeomorphic ecosystem engineering' (Phillips, 2016) and resulting landforms are termed 'biogeomorphic structures' or units (Corenblit et al., 2010a, 2016). They are usually made up by different landform components that can be of abiotic, residual or functional nature (Corenblit et al., 2010a): Abiotic components are strictly created by physical processes, while residual components result from ecosystem engineering, but do not benefit the engineer. Functional landform components directly benefit either (i) the engineer or (ii) non-engineer species.

On lateral moraine slopes, Eichel et al. (2016) identified the dwarf shrub *Dryas octopetala* L. as an ecosystem engineer species that effectively influences hillslope processes through its traits. Its dense mat traps fine sediment, reduces run-off and stores moisture, while its strong roots anchor the plant in the moving soil. Thereby, *D. octopetala* can induce a change from linear erosion processes to solifluction on a slope scale and probably contribute to the development of TBLs, which would therefore represent biogeomorphic structures (Eichel et al., 2013, 2016). However, this notion needs to be tested on a landform scale by linking *D. octopetala* traits more closely to changes in solifluction processes and the resulting development of TBLs.

The aim of this paper is to understand and evaluate the role of feedbacks between vegetation and solifluction for TBL structure and development by combining detailed geomorphic and ecological investigations of a TBL with existing geomorphic and ecological knowledge and recent biogeomorphic concepts.

Our objectives are:

(1) to determine the relationship between geomorphic and ecologic patterns at a TBL,
(2) to apply the ecosystem engineering concept to develop a conceptual biogeomorphic model of TBL development that can explain observed patterns; and
(3) to evaluate if TBLs are biogeomorphic structures produced by ecosystem engineering.

6.3 Study site

The investigated TBL is located on the north-exposed, distal slope of a lateral moraine in the Turtmann glacier foreland (Switzerland) at an elevation between 2170 and 2185 m a.s.l. (Figure 6.1). Solifluction lobes are widespread landforms in the Turtmann Valley and occur on talus slopes in the hanging valleys (Otto et al., 2004) and on lateral moraines of the Turtmann glacier foreland (Eichel et al., 2013). The lateral moraine parenting the investigated TBL was formed by a smaller advance of the Turtmann glacier in the 1920s, which interrupted the dominant glacier retreat trend since the end of the Little Ice Age (Bauder and Ruegg, 2009; Tscherrig, 1965). The mean annual air temperature (MAAT) in the foreland ranges between 2.8 °C (2013) and 3.2 °C (2012) (MeteoSwiss, 2016). The glacier foreland is located 250-300 m below the lower limit of permafrost (Nyenhuis et al., 2005), which indicates no permafrost influence on solifluction lobe evolution. Moraine sediments comprise Middle Penninic marbles (Barrhorn series) and paragneiss/schist rocks (Mischabel crystalline complex), as well as Upper Penninic calcareous shales and greenstones (Tsaté nappe) and austroalpine gneiss and gabbro (Dent Blanche nappe)

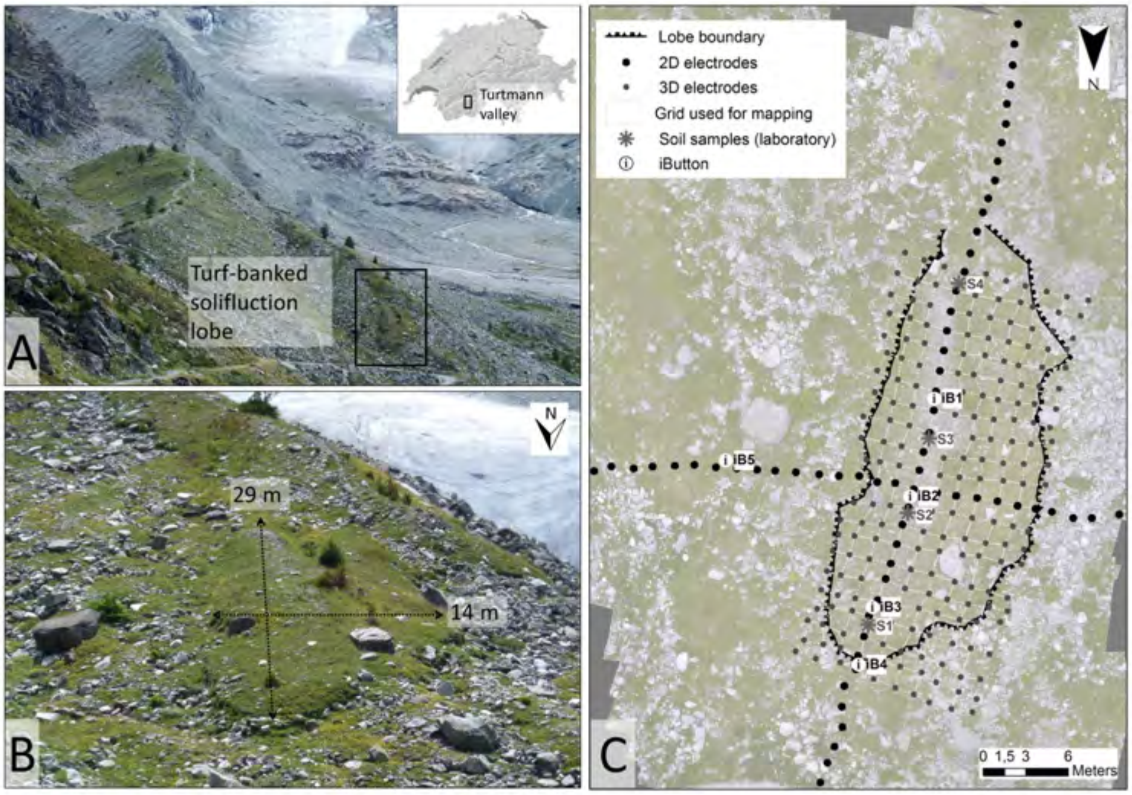

Figure 6.1: Overview of the study area and research set-up. **A** View into Turtmann glacier foreland with the 1920s lateral moraine crest, on which the TBL is located, on the left. The inset map indicates the location of Turtmann Valley in Switzerland. **B** TBL with frontal and lateral risers and tread dimensions. **C** Research set-up showing the lobe boundary, longitudinal and transverse 2 D electrical resistivity tomography (ERT) transects, as well as electrodes used for 3 D ERT. 3D electrodes also served as grid for geomorphic and vegetation mapping. Locations of soil sampling and iButton temperature loggers are shown.

(Bearth, 1980; Labhart, 2009). On these substrates, both siliceous and calcareous vegetation occurs, with alpine grassland associations (*Dryadeto-Firmetum, Elynetum*) dominating on the investigated moraine slope (Figure 6.1 C; Eichel et al., 2013, 2016).

6.4 Methods

To determine geomorphic and ecologic patterns at the lobe, its geomorphometry, material, thermal, snow and vegetation properties were assessed in July 2014 and subsequently analysed. Based on these results, the relationship between geomorphic and vegetation patterns at the lobe was assessed. By integrating our results with previous geomorphic and ecologic solifluction research results, we subsequently develop a conceptual biogeomorphic model of TBL development.

6.4.1 Geomorphic mapping, terrain survey and analysis

The TBL with its landform elements was mapped in field (1:50) using the grid layout of the 3D ERT measurements (Figure 6.1C) for orientation. Visible material distribution was classified using grain sizes according to Ad-hoc-AG Boden (2005). Mean tread slope gradient, riser height, lobe length and width were manually measured. An UAV flight provided aerial imagery to derive an orthophoto and digital surface model (DSM) for terrain analysis. The UAV, a customized Mikrokopter OktoXL Oktokopter (HiSystems GmbH), was equipped with a Panasonic Lumix GX1 (16MPixel sensor, 20mm fixed focal length lens) and manually flown at a height of roughly 15m (Eling et al., 2015). Images were taken at a rate of about 1Hz to ensure horizontal and vertical overlap for photogrammetric processing, with a total of 416 images. For georeferencing, five ground control points were measured with a Leica GPS1200 GNSS receiver operating at RTK (real time kinematic) processing mode with accuracies of about 2-3 cm. The photogrammetry software Agisoft Photoscan was used to process the images into an orthophoto mosaic and DSM using a structure from motion approach (Küng et al., 2011; Snavely et al., 2007). Resulting products possess a resolution of a few millimetres. Based on the orthophoto, the field geomorphic map was transferred to a digital map in ArcGIS. Terrain analysis was carried out in ArcGIS using a resampled lower resolution DSM (cell size 0.25 cm) to reduce small-scale topographic variability, e.g. resulting from plants. Slope gradient, incoming solar radiation, aspect and surface roughness (standard deviation of slope, Grohmann et al., 2011) were calculated.

6.4.2 2D and 3D Electrical Resistivity Tomography (ERT)

ERT provides information on material properties and soil moisture conditions (Calamita et al., 2012) and was previously used to investigate permafrost occurrence in solifluction terraces (Kneisel, 2006, 2010). If material distribution is known from mapping and texture analysis, resistivity can be interpreted as soil moisture content (Calamita et al., 2014). However, large electrode spacing in combination with inhomogeneous material enables only a qualitative interpretation. ERT measurements were conducted with an ABEM Terrameter LS, using a Wenner array and an electrode and transect spacing of 1.5 m. Across-section and longitudinal 2D ERT transect consisting of 32 to 41 electrodes (Figure 6.1 C) was used to differentiate TBL material from the surrounding slope. Furthermore, we installed a 3D ERT set-up consisting of 22 parallel transect with 220 electrodes in total (Figure 6.1 C), thereof four transects were measured in a parallel, perpendicular and horizontal way before the set-up was moved in a roll-along approach to the next four transects by overlapping two transects in each measurement step. Therefore, a true 3D data acquisition was generated which enables the TBL's internal material differentiation. For data processing, a robust least-squares inversion was performed with Res2DInv and Res3DInv to produce models with sharp boundaries (Loke and Barker, 1996, 1995). To quantify the mathematical quality of the final tomographies, the root mean square error (RMS) was calculated. Low RMS between 2.1 % and 2.5 % in the 2D ERT and 6.35 % in the 3D ERT indicate good quality.

6.4.3 Soil sampling and texture analysis

Soil samples were taken along the 2D longitudinal transect in four locations (see Figure 6.1 C) in depths from 0 to 0.75 m using a Pürckhauer drill. Soil texture was determined from the mixed air-dried and sieved (2 mm) samples for each location using a Retsch HORIBA LA-950 particle analyser (Fraunhofer Refractive Index Minerale).

6.4.4 iButton temperature loggers

Four iButton DS1922L temperature loggers were used to monitor ground surface temperatures (GST) in 3-hr increments between 01.08.2014 and 31.07.2015 (Logger 2-4) or 11.09.14 and 31.07.15 (Logger 1). The loggers were wrapped into zip-plastic bags for moisture protection and deployed in a depth of 10 cm following the set-up by Gubler et al. (2011). Species occurrence in a radius of 10 cm around the loggers was recorded. The loggers were aligned along the longitudinal ERT transect (Figure 6.1 C) to assess thermal differences along the lobe length axis. Logger programming and data read out was performed using iAssist (Keller et al., 2010), afterwards, data was processed in R. The data accuracy according to the manufacturer is ±0.5 °C and could be improved by using the zero-curtain period as 0° reference, which resulted in a temperature correction ranging from -0.13 to -0.37 °C.

To analyse the ground thermal regime, mean annual ground surface temperature (MAGST) was calculated for loggers with full year measurement records. Furthermore, mean winter ground surface temperature (MWGST, December to February) and mean summer ground surface temperature (MSGST, June to August) were calculated to analyse winter cooling or summer warming. Using the standard deviation approach by Schmid et al. (2012), snow cover conditions were identified and their duration calculated. Freeze-thaw cycles (FTCs), indicated by a temperature decrease below 0°C followed by an increase above the freezing point, were determined and distinguished according to duration into diurnal and seasonal.

6.4.5 Vegetation mapping

Individual species' occurrence was mapped per cell of the 3D ERT grid, with one symbol representing approximately 5 plant species individuals per plot. The taxonomic nomenclature of the vascular plants is according to Lauber and Wagner (2007). In addition, *D. octopetala* cover was mapped. The field map was transferred to a digital map in ArcGIS, species numbers per grid cell were calculated and species maps for individual lobe elements (risers, tread, ridge feature) were created to improve map clarity.

6.4.6 Conceptual model development

A conceptual biogeomorphic model describing TBL development through biogeomorphic feedbacks was developed based on the ecosystem engineering concept by Gutiérrez and Jones (2008) and Jones et al. (2010), which links ecosystem engineering to induced structural, abiotic and biotic changes in the environment. For model development, study results indicating these changes in terms of geomorphometry, material, thermal, snow and vegetation properties were integrated with previous geomorphic and ecologic knowledge on turf-banked solifluction lobes and ecosystem engineering in alpine and arctic environments.

6.5 Results

6.5.1 Geomorphic map and terrain properties

The geomorphic map shows that large, steep risers (< 1 m) delimit a fine material lobe tread with mostly finer material (< 63 mm) and some cobbles (63 - < 200 mm) at its sides from coarser material made up by cobbles and boulders (≥ 200 mm) of the parent slope (Figure 6.2 A). Multiple smaller risers (< 0.5 m) build up a steep, step-like lobe front with a maximum height of 1.8 m and a maximum slope gradient of 73.5° (Figure 6.2 A, B). Terrain roughness is high at the lobe front and western risers with low incoming solar radiation (Figure 6.2 C, D). At the lobe tread, terrain roughness and slope gradient are low with a mean slope gradient of 22° (Figure 6.2 A, B, C). Smaller risers (< 0.5 m) occur within the western lobe tread (Figure 6.2 A). A low-gradient, fine material dominated ridge feature at the upper tread receives the highest incoming solar radiation and divides the lobe tread into eastern (0-90°) and western aspect (Figure 6.2).

6.5.2 2D and 3D ERT results

2D ERT shows lower resistivities for the lobe tread (Figure 6.3 A, B) in comparison with the underlying parent slope material, and higher resistivities at the frontal and lateral risers. The longitudinal ERT (Figure 6.3 A) shows that the lobe front (depth of up to one m, dark blue, <0.95 kΩm, 11-19 m) and lobe centre (0.75 m-1.25 m thick, lighter blue, 0.95 – 1.69 kΩm, 11-29 m)

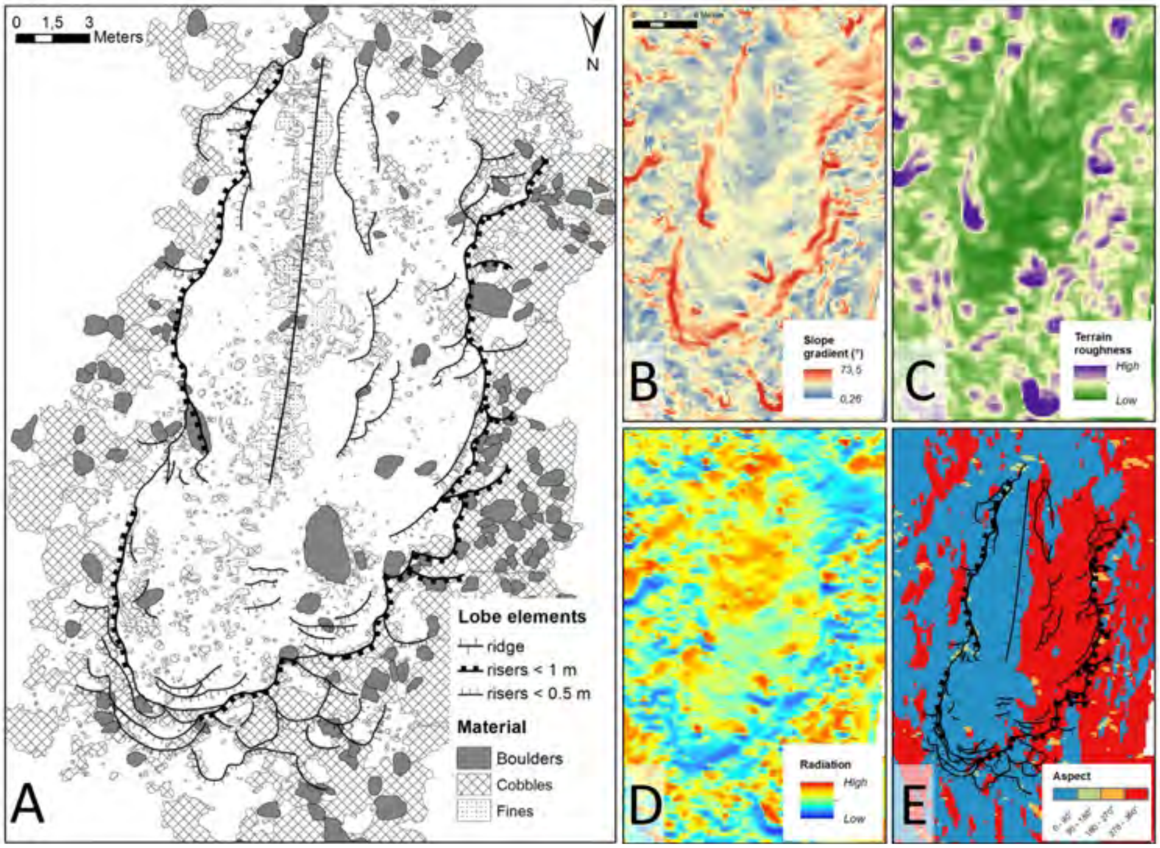

Figure 6.2: Geomorphic map and terrain parameters of the TBL. **A** Geomorphic map showing lobe elements and material distribution. **B** Slope gradient map. **C** Terrain roughness map. **D** Incoming solar radiation map. **E** Aspect map.

possess lower resistivities than the lobe rear (light green, between 1.25 and 2.25 kΩm). Resistivities are highest at the lobe root and below the frontal risers (yellow and red, 4 -16.8 kΩm). The lobe body is almost completely underlain by in a higher resistivity area of parent slope material in depth of up to 7m (dark green, 1.69 -3 kΩm). The transverse ERT transect (Figure 6.3 B) shows lowest resistivities (blue, <1.25 kΩm) at the lobe centre (22 – 27 m) in a depth of up to 3m, while resistivity is highest at the lateral lobe risers (yellow and red, 4.0 to 22.5 kΩm). High resistivities also characterize parts of the eastern parent slope (yellow and yellow-green, 1.69 to 3.0 kΩm). he 3D ERT shows a consistent spatial resistivity pattern for the lobe in all four depths (Figure 6.3 C). At the lobe surface (0 – 0.75 m), resistivity is lowest at the eastern and western tread (dark blue, 0 – 0.95 kΩm), with higher resistivities (yellow and light green, 1.69 – 5.30 kΩm) around the smaller risers (<0.5 m) within the lobe tread. At the frontal and lateral risers, resistivities are mostly higher than at the lobe tread (light green, yellow and red, >0.95 kΩm), with

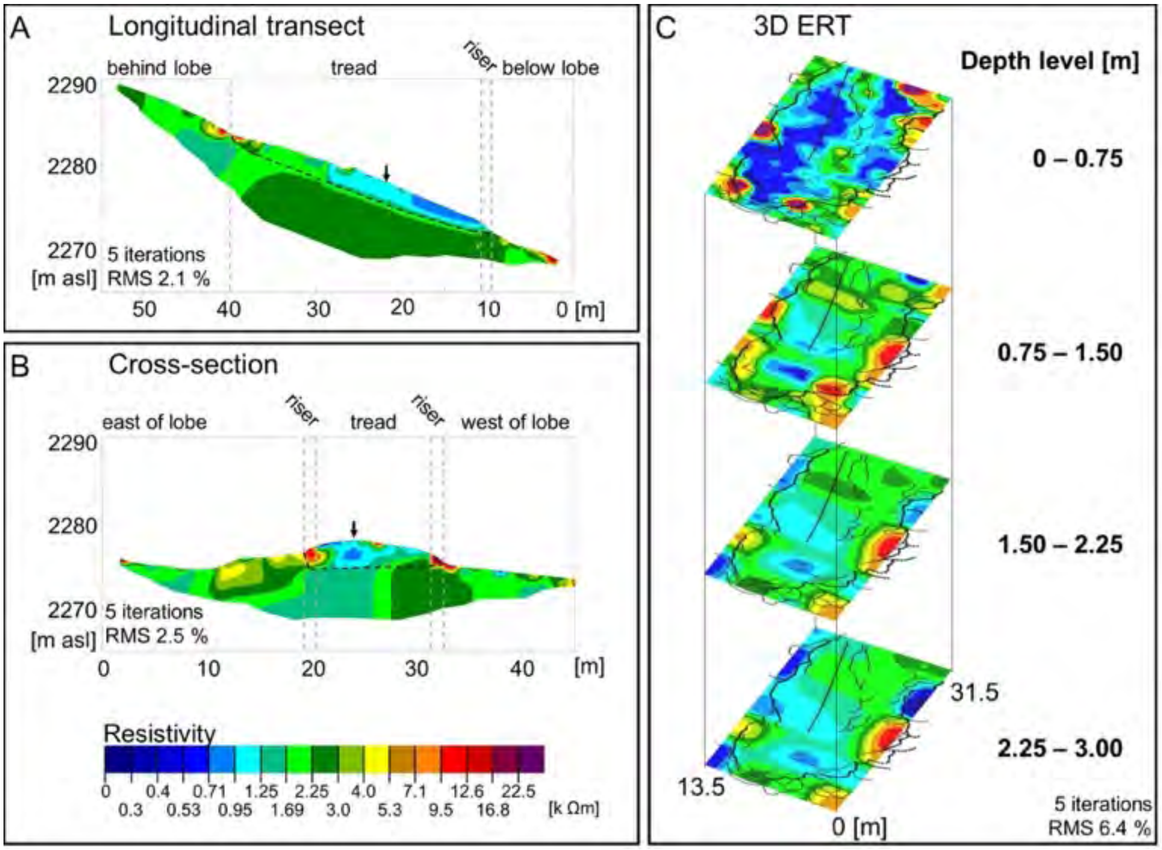

Figure 6.3: 2 and 3D Electrical Resistivity Tomographies. Blue and green colours indicate low resistivities, while yellow, red and purple colours indicate high resistivities. **A** Tomography of the longitudinal transect. **B** Tomography of the cross-section transect. **C** 3D tomographies in four depths (0 – 0.75 m, 0.75-1.5 m, 1.5 – 2.25 m, 2.25 – 3 m).

several small, but well-defined areas of very high resistivities (red and purple, > 9.5 kΩm). With increasing depth (0.75-3 m), tread resistivity generally increases (light blue and light green, > 0.95 kΩm), however, a low resistivity area (blue, 0-0.95 kΩm) in the lower tread centre persists in all depths. Riser resistivity, however, often inverses in depth: previously low resistive areas (blue, <0.95 kΩm) become highly resistive (red, >7.1 kΩm), e.g. the central western lateral riser, and vice versa (e.g. north-eastern frontal riser).

6.5.3 Soil texture

Soil texture does not substantially differ within the lobe tread, neither between different sampling depths nor between different boreholes (S1 – S4). In summary, the sand fraction of the lobe material ranged between 37.2 and 42.9 %, the silt fraction between 55.1 and 57.2 % and the clay content between 1.7 and 4.1 % for all samples (Figure 6.4). Based on Beskow's (1991) textural limits for frost susceptibility and non-frost susceptibility, this material can be assumed to be frost susceptible.

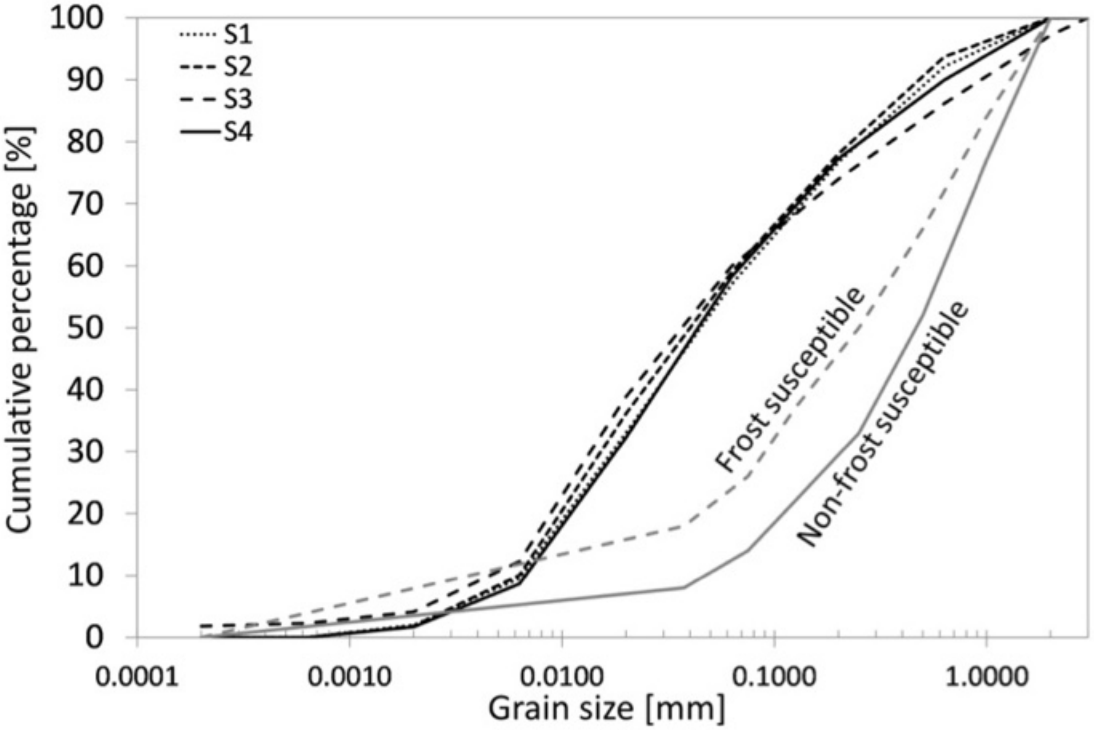

Figure 6.4: Aggregated soil texture from all depths for soil samples S1-S4 plotted with Beskow's (1991) textural limits for frost susceptibility and non-frost susceptibility.

6.5.4 Ground surface temperature data

iButton temperature data show that ground surface temperatures (GST), snow cover and freeze-thaw activity distinctly differ between different positions on the lobe (Table 6.1). At the lobe ridge (iButton 1), MWGST is lowest (-1.61 °C) with *Trifolium pallescens* and *Salix serpyllifolia* in the logger vicinity. Snow cover duration (164 days) is shortest and allows the highest number of diurnal freeze-thaw cycles (10 FTCs). Along the lobe tread towards the frontal riser (iButton 2-4), MWGST increases from -1.1 °C at iButton 2 to -0.26 °C at iButton 4 at the lobe riser, while MSGST (12.58 °C to 11.09 °C at the riser) and MAGST (4.12 °C to 3.69 °C at the riser) decrease. Snow cover duration and freeze-thaw activity vary similar to the thermal regime. At the lobe tread, snow cover last between two to three weeks longer (178 -188 days) than at the lobe ridge, while snow cover at the frontal riser is only four days longer (168 days) than at the ridge. Distinctly less FTCs occur mostly under *D. octopetala* cover at the lobe tread (2-4 FTCs) and frontal riser (2 FTCs) than at the lobe ridge (Table 6.1).

Table 6.1: Summary of results from iButton temperature loggers aligned along the central lobe axis from upslope to downslope (see Figure 6.1 C).

Temperature logger	**iButton 1 (iB1)**	**iButton 2 (iB2)**	**iButton 3 (iB3)**	**iButton 4 (iB4)**
Location	Ridge	Tread centre	Lower tread	Frontal riser
Species	*Trifolium pallescens, Salix serpyllifolia*	*Anthyllis vulneraria, Trifolium pallescens*	*D. octopetala, Poa alpina*	*D. octopetala, Salix reticulata*
Ground Surface Temperature (GST)				
MAGST [°C]	*	4.12	4.05	3.69
MWGST (DJF)[°C]	-1.61	-1.1	-0.52	-0.26
MSGST (JJA) [°C]	*	12.58	12.09	11.09
Snow cover and freeze-thaw activity				
Duration of snow cover [days]	164	178	188	168
Number of freeze-thaw cycles (diurnal)	11 (10)	4 (3)	2 (1)	2 (1)

*no data due to incomplete time series

6.5.5 Vegetation maps

Vegetation mapping shows that species fine-scale distribution and number is related to the different lobe elements, with species composition differing between risers < 0.5 m, risers < 1m, lobe tread and ridge (Figure 6.5). At the smaller lobe risers (< 0.5 m), the dwarf shrub *Salix reticulata* L. dominates, together with the herbs *Epilobium fleischeri* Hochst. at the eastern lobe front and *Trifolium badium* Schreb. at the western lobe risers (Figure 6.5 A). The shrub *Salix hastata* L. occurs mainly at the larger risers (< 1 m), together with several herb species (*Achillea nana* L.*, Campanula cochlearifolia* Lam.*, Coeloglossum viride* (L.) Hartm.) (Figure 6.5 B). The lobe tread is almost entirely covered by a *D. octopetala* mat, which is interspersed by the sedges *Carex capillaris* L. and *Elyna myosuroides* (Vill.) Fritsch (Figure 6.5 D). Several seedlings and saplings of the tree species *Larix decidua* Mill. and *Pinus cembra* L. occur along the central tread axis. The herbs *Linaria alpina* (L.) Mill. s.str. and *Silene exscapa* All. mainly occur at the lobe ridge (Figure 6.5 E). Species numbers are highest (> 10 species per grid cell) at the frontal and western lateral risers, with lowest species numbers (2-5 species per grid cell) close to the ridge (Figure 6.5 C).

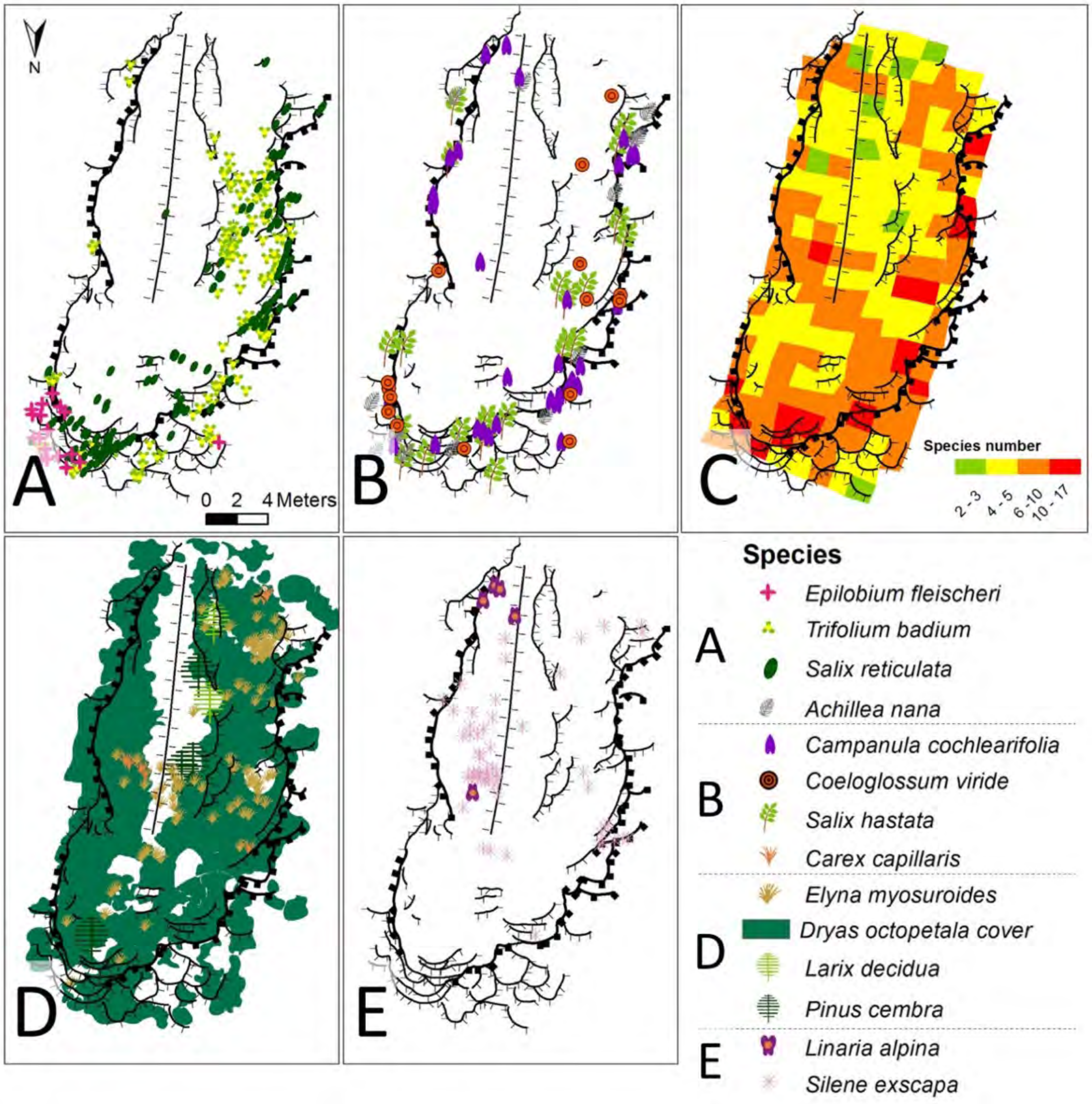

Figure 6.5: Vegetation maps based on lobe elements and map of species numbers per grid cell. **A** *E. fleischeri*, *T. badium* and *S. reticulata* occurring at frontal and lateral risers < 0.5 m. **B** *A. nana*, *C. cochlearifolia*, *C. viride* and *S. hastata* occurring at frontal and lateral risers < 1 m. **C** Species numbers per grid cell, with highest species numbers at the western lateral and at the frontal risers. **D** *C. capillaris*, *E. myosuroides* and seedlings and saplings of *L. decidua* and *P. cembra* occurring at the lobe tread, which is almost completely covered by *D. octopetala*. **E** *L. alpina* and *S. exscapa* occurring mainly at the lobe ridge.

6.5.6 Derived conceptual model of TBL development

The derived conceptual biogeomorphic model describes the development of TBLs through biomorphic feedbacks in four stages (Figure 6.6 A). It links engineer root and above-ground biomass effect traits (Figure 6.6 B, C) to induced changes in mechanical, hydrological and thermal properties of the slope (engineering mechanism, Figure 6.6 D), which affect slope processes (engineering effect, Figure 6.6 E) and the structural (geomorphometry), abiotic (material, thermal, snow distribution) and biotic (species composition) properties of the parent slope environment (Figure 6.6 F). This ecosystem engineering process can feed back to the ecosystem engineer (Figure 6.6 G) and results in the creation of different TBLs types (Figure 6.6 H). Results from our TBL investigation support the model, as discussed in the next section. In our model, we use the ecosystem engineer *D. octopetala* as an exemplary species, which can be substituted by other species with similar traits in different environments (Corenblit et al., 2015).

6.6 Discussion

6.6.1 Relationship between geomorphic and ecologic patterns at the TBL

The presented results show that the investigated TBL possesses distinct geomorphic and ecologic patterns that are closely related. Geomorphometry, material and thermal properties, as well as snow distribution and species composition differ between the lobe elements tread, risers and ridge (Figures 6.2, 6.3, 6.5). A similar close relationship between lobe elements geomorphic and ecologic patterns was found by Price (1970, 1971) in the Yukon Territories. In this area, deeply moving lobe treads are dominated by tussock communities with *Carex* sedges and *Salix* dwarf shrubs, similar to the one covering our lobe with *D. octopetala* and *Carex* and *Elyna* sedges. A late snow melt community ('front community') dominated at dryer, more slowly moving steep lobe fronts, with several species exclusively occurring there. This is similar to *S. hastata* occurring mostly at larger (< 1 m) risers at our lobe. Features comparable to our sparsely vegetated ridge feature ('Solifluktionsstrich') were found in the Swiss National Park by Gamper (1981). They were moving fastest and were dominated by *L. alpina*, which we also found at our ridge, and other pioneer species (*Saxifraga aizoides, Salix serpyllifolia*) (Zuber, 1968). Thus, although so far only very few studies jointly investigated geomorphic and ecologic patterns, their close relationship at both polar and alpine TBLs indicates that this is a re-occurring property.

6.6.2 Conceptual biogeomorphic model of turf-banked solifluction lobe development

I Initiation stage

Previous studies from Rapp (1960), Price (1974) and others suggested that solifluction lobes initiate in areas that are moving more slowly than the surrounding parent slope, either due to larger cobbles and boulders or vegetation (Figure 6.6, Stage I). To affect slope processes, plants must be able to establish on the active parent slope (Figure 6.6 F). Generally, processes reworking parent slope material, such as erosional processes (slope wash, rill erosion), solifluction processes (mainly annual frost creep and gelifluction) or landslides (debris flows, slumping), act as ecological

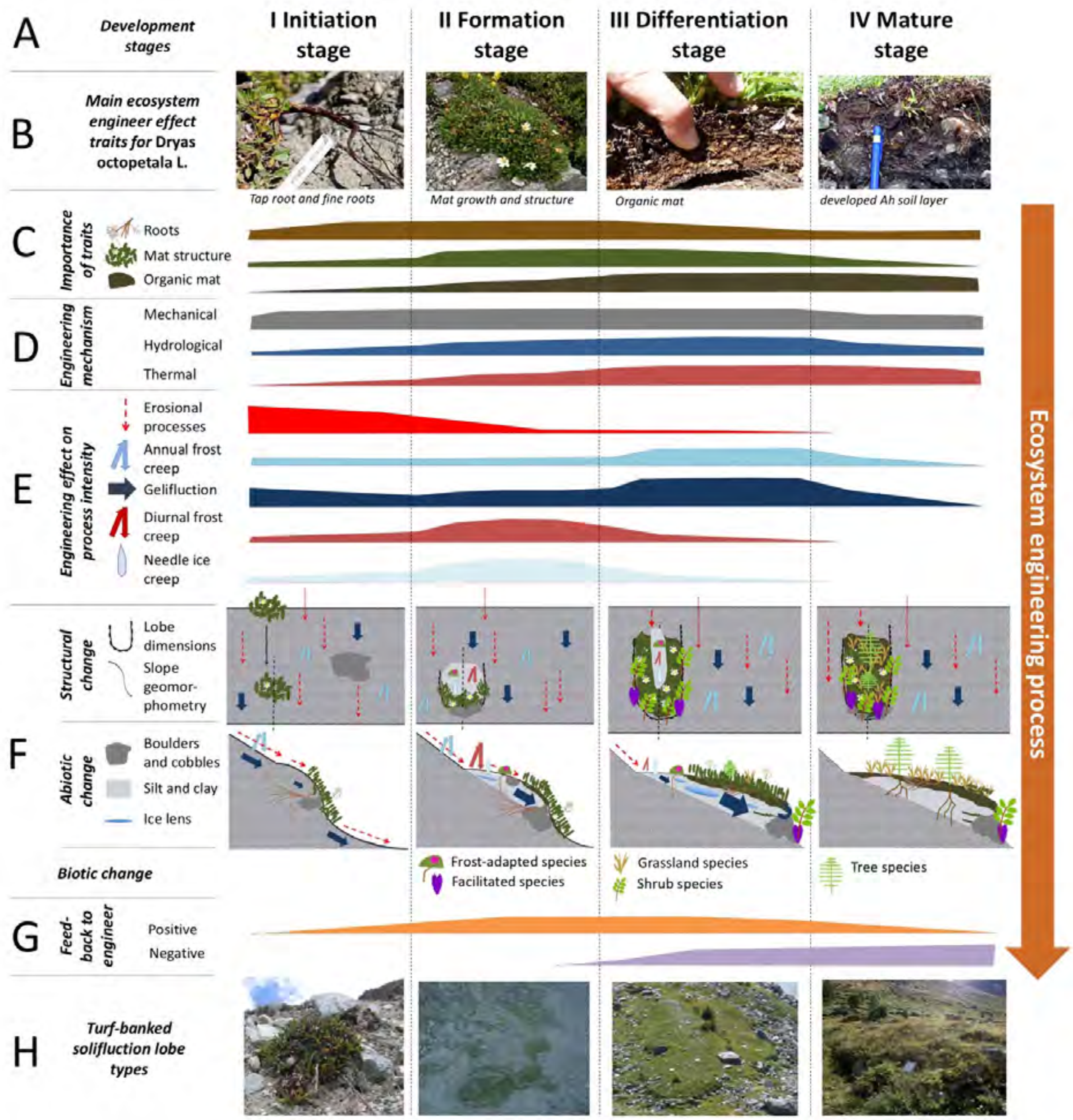

Figure 6.6: Illustration of the ecosystem engineering process by *D. octopetala* through which turf-banked solifluction lobes can be created. Line thickness in C, D, E, G indicates importance or intensity of components and processes. **A** Lobe development stages. **B** Illustration of main ecosystem engineering effect traits for *D. octopetala* in relation to development stage. **C** Changing importance of effect traits during lobe development. **D** Changing intensity of mechanical, hydrological and thermal engineering mechanisms related to the ecosystem engineer during lobe development. **E** Changes in geomorphic process intensity due to ecosystem engineering effects. **F** Structural, abiotic and biotic changes at the parent slope resulting from ecosystem engineering, showing in lobe dimensions, slope topography, material properties and species composition. Dashed black lines indicate locations of slope profiles below. **G** Changing intensity of positive and negative feedbacks to the engineer during lobe development. **H** Examples for different biogeomorphic structure configuration during lobe development. (Image of organic mat taken by Katharina Eibisch)

disturbances and limit the establishment of plants (Karsdóttir and Aradóttir, 2006; Wookey et al., 1995). However, Eichel et al. (2016) observed that ecosystem engineer species such as D. octopetala can colonize lateral moraine slopes once process magnitude and frequency of disturbances decreases, or return-periods between large-magnitude disturbances increase. In addition, *D. octopetala* can also establish from entire plants or plant fragments transported downslope by slope wash processes and landsliding (Brockmann-Jerosch, 1925; Figure 6.6 F).

Once this geomorphic 'establishment threshold' is crossed (Balke et al., 2014; Eichel et al., 2016), *D. octopetala*'s developing root system can actively reduce slope movement (Figure 6.6 B, C). Its high-tensile strength roots (Eibisch et al., 2015; Harrington and Mitchell, 2002; Kutschera et al., 1997) increase the angle of internal friction of soil (Veylon et al., 2015), while its fine lateral roots, usually terminating in coralloid root systems with ectomycorrhiza (Harrington and Mitchell, 2002), increase soil aggregate stability and thereby soil cohesion (Bast et al., 2014; Graf et al., 2009). In addition, as a result of its high phenotypic plasticity, *D. octopetala* can actively adapt its root growth to soil movement and reduce slope movement by anchoring upslope in more stable substrates (Anderson, 1906; Eibisch et al., 2015; Kutschera et al., 1997; Wookey et al., 1995). Root-induced increase in soil shear strength results in decreasing near-surface gelifluction and frost creep movement at the engineer site (Williams and Smith, 1991; Figure 6.6 D, E).

This lobe initiation process was exemplarily described by Smith (1956) on slopes on Svalbard, where isolated plants of *D. octopetala* produced a stable area behind them. As plants preferably establish in safe sites provided by more slowly moving rocks (Karsdóttir and Aradóttir, 2006), the two mechanism of lobe initiation probably often interact (Figure 6.6 F).

In time, material accumulates behind the slower moving engineer sites by erosional processes, solifluction and landsliding from upslope areas areas (Matthews et al., 1986; Zuber, 1968). A bulge or furl develops (Matthews et al., 1986; Price, 1974; Zuber, 1968; see Figure 6.6 F, H), which increases in length and width into an initial riser. We found initial *D. octopetala* risers at a lateral moraine slope in Turtmann glacier foreland (Eibisch et al., 2015; Figure 6.6 H). Due to the changed slope geomorphometry (Figure 6.6 F), these initial risers represent a structural change produced by the engineer, who benefits from more stable habitat conditions as a positive feedback (Figure 6.6 G).

II Formation stage

In the formation stage, upslope erosional and solifluction processes, summarized as 'colluviation' (Matthews et al., 1986; Strömquist, 1983), provide material which accumulates behind the initial riser. Consequently, a tread-riser sequence develops (Figure 6.6, Stage II). With its low-lying stems, branches and numerous leaves, *D. octopetala* builds up a mat structure (Figure 6.6 B), which can actively amplify material accumulation behind the initial riser. When the mat structure covers more than 35 % of a specified area, an engineering threshold is crossed (Eichel et al., 2016) and *D. octopetala* starts to interact with the occurring colluviation processes. By reducing ground surface roughness and the kinetic energy of raindrops, it decreases overland flow velocity and rainfall erosivity (Elkington, 1971; Körner, 2003; Sidle and Ochiai, 2006; Welker et al., 1997). ‚Biomat flow' replaces overland flow and increases the trapping of silt- and clay-sized sediment in the mat structure (Sidle et al., 2007; Washburn, 1979; Zuber, 1968). Therefore, the percentage of fines below *D. octopetala* increases compared to the parent slope, as observed previously by Zuber (1968) (Figure 6.6 F), while the intensity of erosional processes is strongly decreased (Figure 6.6 E). Significantly less material is transported downslope (Graf and Gerber, 1997) as it accumulates instead in the mat structure and behind the riser.

In the subsurface, the growth of *D. octopetala's* roots further decreases movement at the risers. This engineering effect can be amplified by boulders and stones, that, through frost-sorting and up-freezing, are transported quicker on the non-vegetated lobe tread than the fine matrix. They accumulate at the slower moving engineer sites (Harris, 1981; Harrison and Macklin, 1991; Huxley and Odell, 1924; Figure 6.6 F) and impede solifluction movement (Benedict, 1976). The geomorphic and terrain roughness maps show the accumulation of larger clasts at the risers of our lobe (Figure 6.2 A, C), where high resistivities in both 2 D and 3 D ERT also indicate coarser and dryer material (Figure 6.3). Together, decreasing riser movement and material accumulation enlarge lobe tread and riser length and width in time (Kinnard and Lewkowicz, 2006; Taber, 1943; Zuber, 1968). Lobe tread material is often finer than parent slope material, which shows in the geomorphic map of our lobe (Figure 6.2) and in lower resistivities in both 2D and 3D ERT at our lobe tread (Figure 6.3). In addition, our soil texture results (Figure 6.4) show that the finer silty material of the lobe tread is frost susceptible and possesses a higher permeability. Therefore, it promotes ice segregation and amplifies needle ice and diurnal frost creep (Williams and Smith, 1991) (Figure 6.6 G). High-frequent needle ice and frost creep can limit colonization by *D. octopetala* seedlings (Karsdóttir and Aradóttir, 2006; Wookey et al., 1995) and favour the occurrence of frost resistant species (Zuber, 1968) such as *S. exscapa* (Körner, 2003), which we observed at the sparsely vegetated ridge feature of the investigated TBL (Figure 6.5 E). Benedict (1970), Rose and Malanson (2012) and Sigafoos (1951) found lobes or terraces with *Dryas*-

dominated risers and nearly un-vegetated treads in alpine (Albion ridge, Colorado; Glacier National Park, Montana) and arctic environments (Seward Peninsula, Alaska) (cf. Figure 6.6 H for a similar lobe type in Turtmann valley).

The development of the tread-riser sequence significantly changes the parent slope geomorphometry and therefore represents an engineered structural change, while described material changes in the tread and risers are abiotic changes (Figure 6.6 F). Joint structural and abiotic changes of the environment result in biotic changes. At the actively-moving tread, frost-adapted species can establish, while less-adapted species take can advantage of slope stabilization and improved microclimatic habitat conditions in the *D. octopetala* mat structure at the risers (Klanderud and Totland, 2004; Reisigl and Keller, 1994; Figure 6.6 F).

III Differentiation stage

In the differentiation stage (Figure 6.6, Stage III), *D. octopetala* colonizes the frost creep dominated lobe tread by clonal growth from more stable positions at the frontal and lateral risers (Bamberg and Major, 1968; Van Vliet-Lanoe, 1993; Wookey et al., 1995). Through the accumulation of humus and dead biomass in its mat structure, an organic mat of several cm thickness can develop (Birks, 1980; Ellenberg, 1996; McGraw, 1985; Figure 6.6 B). Jointly, engineer roots, mat structure and organic mat affect the lobe tread's mechanical, hydrological and thermal soil properties (Figure 6.6 C, D).

D. octopetala can develop adventive roots at its low-lying stems and branches (Bamberg and Major, 1968), which increase soil shear strength at the surface. In addition, the organic mat increases soil organic carbon in the course of soil development (Elkington, 1971), which enhances aggregate stability and related soil cohesion (Fattet et al., 2011). Crocker and Major (1955) demonstrated that *Dryas drummondii* mats possess a more than 200 times higher organic content than bare soil and increase the soil organic content in the soil 5 cm below the mat more than 20 times. In the subsurface, however, the weight of a saturated organic mat can increase the effective normal stress and thereby decrease slope stability (Williams and Smith, 1991).

Hydrologically, the *D. octopetala* mat structure reduces moisture at the surface through transpiration and interception, while in the subsurface rooting zone, engineer roots reduce soil moisture by water extraction (Sidle and Ochiai, 2006), but also increase soil permeability and infiltration (Ghestem et al., 2011; Veylon et al., 2015). Thereby, higher pore water pressures can be promoted in the rooting zone and below (Ghestem et al., 2011, 2014).

Thermally, *D. octopetala*’s mat structure provides shading and insulation and possesses a higher albedo than bare soils. Therefore, it affects the ground surface’s energy balance (vegetation offset), while its organic mat reduces the thermal conduction into the ground (Benninghoff, 1952; Williams and Smith, 1991). Consequently, *D. octopetala* alters ground surface temperatures, attenuates ground surface temperature fluctuations and decreases the occurrence frequency of diurnal freeze-thaw cycles (Aalto et al., 2013; Cannone and Guglielmin, 2010; Ehrenfeld et al., 2005). This decrease in diurnal freeze-thaw activity was observed by the temperature loggers below *D. octopetala* cover at the lobe tread and frontal riser (iButtons 3 and 4; Table 6.1). However, the attenuation of ground surface temperatures can promote an annual freeze-thaw cycle with temperatures favouring ice segregation (Williams and Smith, 1991). Thus, in combination with higher permeability of the soil and increased moisture availability due to root effects as described above, *D. octopetala* has the potential to amplify ice segregation and increase ice lens development (Figure 6.6 F).

Collectively, these engineering mechanisms affect the intensity and vertical distribution of solifluction processes at the lobe tread (Figure 6.6 E, F). At the surface and in the upper rooting zone, increased soil shear strength, decreased pore water pressures and a reduced number of diurnal freeze-thaw cycles reduce needle ice growth, diurnal frost creep and gelifluction (Bamberg and Major, 1968; Matsuoka, 2001). In the deeper subsurface, however, the increase in effective normal stress by a saturated organic mat, amplified ice segregation and ice lens and higher pore water pressures can destabilize the slope and promote deep gelifluction during snow melt. This results in greater movement depths and a convexo-concave movement profile (Harris et al., 2008; Matsuoka, 2001) found during field investigations at well-developed, completely vegetation covered lobes (Price, 1991).

Gelifluction movement is probably most intense at the lobe front due to an increase in soil moisture as a result of downslope water flow (Benedict, 1970a; Price, 1970) which is indicated by low resistivities in a depth of up to 3 m in the 3 D ERT (Figure 6.3 C). Furthermore, the multistep front indicates the existence of episodic movement (Figure 6.2 A, Ballantyne, 2013).

In combination, the slowly moving risers and the episodic gelifluction movement produce large and thick lobes with high, often multiple step risers (Hugenholtz and Lewkowicz, 2002; Matsuoka, 2001) with characteristic geomorphic and ecologic patterns (Figure 6.6 F, H). Results from our lobe illustrates the lobe type at this stage and its characteristic patterns.

2 D ERT shows the up to 2 m thick lobe tread, which can be delimited from its parent slope by its lower resistivity (Figure 6.3 A, B), and up to 1.8 m high, steep risers (Figure 6.2 A, B). At the lobe tread, *D. octopetala* dominates, whose organic mat facilitates colonization for further species, e.g. grassland species such as E*. myosuroides* (Figure 6.5 D) typically associated with *D. octopetala* (Bamberg and Major, 1968; Ellenberg, 2009). Tread geomorphometry related to the longitudinal ridge feature divides tread aspect along its central axis (Figure 6.2 E) and could explain the occurrence of *T. badium* mostly at the west exposed lobe tread (Figure 6.5 A). The risers produced in this stage are probably not moving any more due to their high content of large clasts (Figure 6.2 A, Figure 6.3; Benedict, 1976). Species with a low root tensile strength (*T. badium*), woody roots *(S. hastata*) or rhizoms (*E. fleischeri*) can establish here, as their more fragile roots are protected from soil movement (Figure 6.6 A, B; Ellenberg, 2009; Jonasson, 1986; Pohl et al., 2012). In addition, the steep, high and rough risers (Figure 6.2 A, B, C) provide wind shelter, influence incoming solar radiation and thereby create a favourable microclimate (Price, 1970; Zuber, 1968). This shows in the low incoming solar radiation (Figure 6.2 D), lower MSGST, higher MWGST, higher MAAT and the low number of freeze-thaw cycles at the frontal riser of our lobe (iButton 4, Table 6.1), which favour species establishment (Körner, 2003) as demonstrated by highest species numbers at the lobe risers (Figure 6.5 C). In time, later succession species such as *S. hastata* can replace the less competitive engineer at the riser as a negative feedback (Eichel et al., 2016) (Figure 6.6 G). Partly differing species compositions between larger (< 1 m) and smaller risers (< 0.5 m) at our lobe (Figure 6.5 A, B) suggest that total riser height is an important property determining habitat conditions and thereby species composition (Price, 1974).

Wind-exposed areas of the tread such as the observed ridge feature, are characterized by a shorter duration of snow cover and a high incoming solar radiation, resulting in highest summer (MSGST) and lowest winter temperatures (MWGST) and a high number of freeze thaw cycles (iButton 1, Table 6.1; Figures 6.2 D, 6.6 F). Therefore, needle ice and frost creep processes occur more frequently with highest movement rates and prolong vegetation colonization (Furrer, 1954; Gamper, 1981; Matthews, 1999). Consequently, species numbers are low (Figure 6.5 C) and frost-adapted species predominantly occur (Zuber, 1968), such as *S. exscapa* (Figures 6.5 E, 6.6 C, F). This stress strategist can survive even strong frost creep movements and wind disturbance (Benedict, 1989; King and Schmitt, 1993; Körner, 2003) through its cushion growth form with highly frost-resistant shoot and leaves and its long and strong roots (Körner, 2003; Larcher et al., 2010).

As the distinct lobe geomorphometry in this stage can be attributed to biogeomorphic feedbacks induced by the ecosystem engineer, it represents a structural change (Figure 6.6 F). The differing thermal regime, snow distribution and material properties between the lobe components (Figures 6.2, 6.3; Table 6.1) are partly related to the lobe geomorphometry and represent an abiotic change, which produces the distinct vegetation patterns observed at our (Figure 6.5) and other lobes as a biotic change (Figure 6.6 F).

Mature stage (Stage IV)

In a mature stage, the engineer colonizes the entire lobe tread and promotes soil development and colonization for tree and grassland species (Figure 6.6, Stage IV). Our vegetation map (Figure 6.6 D) showed that seedlings and saplings of the tree species *L. decidua* and *P. cembra* occur along the central tread axis (Figure 6.5 D). These later successional species indicate an advanced vegetation succession (Risch et al., 2004), soil development (Figure 6.6 B, F) and lobe development. Once tree species roots perfoliate the moving soil layer, they can anchor the lobe to more stable substrates in the parent slope and thereby further decrease movement (Ghestem et al., 2014; Taber, 1943; Figure 6.6 D, E). In addition, when the organic mat reaches a certain thickness, it inhibits or slows down frost penetration. Therefore, ice lenses growth and gelifluction is reduced (Figure 6.6 E) and lobe movement is decreased or absent (Gamper, 1981; Taber, 1943, Figure 6.6 F). Increasing competition by later successional tree species, e.g. for light, further decreases the fitness of the engineer and can exclude it from the tread as a negative feedback (Figure 6.6 F, G). Relict solifluction lobes were found below pine forest cover in Glacier National Park (Montana, US) (Walsh et al., 2003), while lobes with a dense grassland and shrub cover were found on longer deglaciated moraine slopes in the Turtmann glacier foreland (Draebing and Eichel, 2016; Figure 6.6 H).

Cyclic development of solifluction lobes and lobe collapse

Previous research suggested that solifluction lobe development is cyclic and recurrent, with lobes collapsing when shear stress exerted by the thick lobe tread overcomes riser shear strength (Kinnard and Lewkowicz, 2006). This can be caused by a long-lasting snow eroding the stabilizing lobe front vegetation (Price, 1974). The lobe front collapses and tread material is transported downslope by erosional processes (Kinnard and Lewkowicz, 2006; Price, 1974). It is likely that not all lobes reach the stable mature stage described in our model but rather collapse in earlier stages, depending on lobe properties and environmental conditions. Following lobe collapse, lobes redevelop either at the same or at a downslope location where the eroded material accumulates again (Kinnard and Lewkowicz, 2006).

Model evaluation

Our model demonstrates how TBLs can develop due to biogeomorphic feedbacks between plants and solifluction processes. An ecosystem engineering process sequence can explain the close relationship between geomorphic and ecologic patterns for different stages and thereby also different configurations of TBL properties, e.g. differences in movement rates, previously observed (Ballantyne, 2013; Kinnard and Lewkowicz, 2006; Washburn, 1979; Zuber, 1968). It is a conceptual model, which relies on results from one biogeomorphic investigation of a TBL and previously published studies. A detailed biogeomorphic investigation of further TBLs to support all stages of the model with empirical data would be desirable, however, this was not applicable in this study as the multi-method biogeomorphic approach is highly time-consuming. Consequently, many interactions described in the model are only theoretically understood and partly validated by field and laboratory studies yet. To improve the model, further research needs to link plant traits with mechanical, hydrological and thermal soil properties and periglacial processes and combine geomorphic and ecologic approaches on TBLs.

As environmental conditions, individual lobe properties and species occurrence strongly affect and determine lobe development, our model is not a universal model to describe TBL development. The role plants and ecosystem engineering play in lobe initiation and development probably strongly varies between lobes, with a continuum between strongly engineered turf-banked lobes and lobes for which biogeomorphic feedbacks only play an inferior role. Nevertheless, we believe that if vegetation occurs on solifluction slopes, it will definitely affect solifluction lobe development as the influences of plants on thermal, hydrological and mechanical soil properties have been widely shown.

6.6.3 Turf-banked solifluction lobes as biogeomorphic structures produced by ecosystem engineering

Our model shows that interactions between *D. octopetala* and solifluction processes can be described in an ecosystem engineering process by which TBLs are produced. This is comparable to ecosystem engineering by *P. nigra* or *Spartina anglica* in fluvial and coastal biogeomorphic ecosystems, which produce fluvial islands or tussocks as biogeomorphic structures. These landforms clearly differ from their environment by their geomorphometry and material properties (Balke et al., 2012; Bertoldi et al., 2011; Corenblit et al., 2016; Wang and Temmerman, 2013), similar to TBLs clearly differing from their parent slope. Thus, engineered TBLs represent biogeomorphic structures.

A cyclic development of alternating landform construction and destruction, similar to cyclic TBL development, was also observed for fluvial islands (Corenblit et al., 2016), indicating that cyclicity is characteristic for biogeomorphic structures. The length of cyclic development of solifluction lobes ranges from about one century at our lobe to several centuries in other areas, depending on environmental conditions, the occurring ecosystem engineer and resulting biogeomorphic feedbacks (Hugenholtz and Lewkowicz, 2002; Kinnard and Lewkowicz, 2006; Matsuoka, 2001; Price, 1974). Therefore, the duration of the TBL development cycle is probably longer than the cycle of fluvial island development.

In addition, our model demonstrates that the role of the landform components for engineer and non-engineer species, as described by Corenblit et al. (2010), differs between TBLs types and therefore changes during the development of biogeomorphic structures. During lobe initiation (Stage I), the initial riser increases the fitness of *D. octopetala* on the active parent slope as a functional landform component. In Stage II, the stabilizing riser also becomes functional for non-engineer species, while the lobe tread is residual for the engineer, as its development is related to the ecosystem engineering process but the engineer can only partly colonize the new habitat. Instead, it is functional for non-engineer, frost-adapted species. When distinct geomorphic and ecologic patterns develop in Stage III, the lobe tread becomes functional for engineer species adapted to deep gelifluction movement and for non-engineer species facilitated by the engineer mat. The risers can become residual for the engineer once it is replaced by later successional species and become functional for these non-engineer species instead. In the mature stage (Stage IV), the lobe tread can also become residual for the engineer due to competition by later successional species, but remain functional for them.

In a wider perspective, the influences of *D. octopetala* as ecosystem engineer on solifluction processes could represent a positive niche construction *sensu* Odling-Smee et al. (2013), in which a species not only adapts to an environment but modifies and defines it. Therefore, TBLs are potentially extended phenotypes of engineers *sensu* Phillips (2016).

6.7 Conclusion

For the first time, a biogeomorphic approach was used to investigate a turf-banked solifluction lobe (TBL) and to develop a detailed biogeomorphic model of TBL development based on an ecosystem engineering process. Here we show that:

(1) **Geomorphic and ecologic patterns at turf-banked solifluction lobes are closely related and depend on the lobe elements tread, frontal and lateral risers and the occurrence of a ridge feature.** The lobe tread is characterized by fine, moist material with a dense vegetation cover by dwarf shrubs with sedges and tree seedlings and saplings, while the steep lobe frontal and lateral risers possess a different microclimate, species composition and highest species numbers. A sparsely vegetated ridge feature at the upper tread exhibits the highest freeze-thaw activity and movement with frost-adapted species.

(2) **A conceptual biogeomorphic model based on an ecosystem engineering process by *Dryas octopetala* L. can explain turf-banked solifluction lobe development and observed patterns.** In the (I) initiation stage, the ecosystem engineer *D. octopetala* initiates lobes through its stabilizing roots. Behind an initial riser, fine material accumulation is enhanced by the dense *D. octopetala* mat structure in the (II) formation stage and results in the development of a lobe tread characterized by active solifluction processes. When the engineer with its organic mat covers the lobe tread in the (III) differentiation stage, it reduces frost creep and promotes deep gelifluction. Large and thick TBLs develop with geomorphic and ecologic patterns related to the lobe elements. Lobes can stabilize in a (IV) mature stage due to colonization by tree species and a thick organic mat inhibiting solifluction processes.

(3) **Turf-banked solifluction lobes are biogeomorphic structures created by ecosystem engineering.** They are comparable to biogeomorphic structures in fluvial and coastal environments and follow a cyclic development of alternating lobe construction and destruction, during which the role of their landform components for engineer and non-engineer species changes.

Our research highlights the importance of feedbacks between plants and geomorphic processes in periglacial environments and shows that joint geomorphic and ecological, thus, biogeomorphic, investigations are strongly required to understand landscape development in a changing climate.

Acknowledgements

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7 BIOGEOMORPHIC INTERACTIONS IN THE TURTMANN GLACIER FOREFIELD, SWITZERLAND

‚Glacier retreat exposes unvegetated valley-floor deposits that undergo modification by mass movement, frost sorting, wind and running water' (Ballantyne, 2005, p. 445)

‚Nowhere can succession be studies more profitably than in the valley below the front of a large glacier' (Ellenberg, 1988, p. 440)

This chapter is based on a journal article published as:

Eichel, J., Krautblatter, M., Schmidtlein, S.and R. Dikau (2013): Biogeomorphic interactions in the Turtmann glacier forefield, Switzerland. In: Geomorphology 201, p. 98.

It addresses thesis objective 4 by providing an overview on biogeomorphic interactions in glacier forelands and showing that a biogeomorphic succession can occur here. Based on a combined vegetation and geomorphic plot survey and a geomorphic activity map from Turtmann glacier foreland, the impact of paraglacial adjustment on vegetation succession is demonstrated. The relationship between different degress of geomorphic activity and species composition is interpreted as a biogeomorphic succession. The role of biogeomorphic feedbacks for paraglacial adjustment of glacier forelands is highlighted. In addition, this chapter presents first thoughts on *D. octopetala* as ecosystem engineer (Chapters 4, 5) and turf-banked solifluction lobes as biogeomorphic structures (Chapter 6). The biogeomorphic succession proposed in this chapter is exemplified in Chapter 8.

7 BIOGEOMORPHIC INTERACTIONS IN TURTMANN GLACIER FOREFIELD

7.1 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.

7.2 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.

7.2.1 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, 2002b). 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).

7.2.2 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; Raffl et al., 2006; Whittaker, 1987). With proceeding vegetation succession, biotic processes — such as competition (Clements, 1928), facilitation, tolerance, and inhibition (Connell and Slatyer, 1977)— receive increasing importance (Matthews, 1992; Raab et al., 2012; Walker and del Moral, 2003).

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

7.2.3 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; Matthews et al., 1998; Richter, 1994).

Several studies showed that vegetation succession is regularly disturbed by geomorphic processes (Matthews, 1999; Oliver et al., 1985; Richter, 1994). 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 (Haugland, 2006; Matthews et al., 1998). 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).

7.2.4 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 (Cannone et al., 2008; Haeberli and Beniston, 1998; Heckmann et al., 2012; Moore et al., 2009). 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 (Corenblit et al., 2011; Phillips, 1999). These concepts will be illustrated in the discussion (see section 7.5).

7.2.5 Research gaps and aims of this study

Current biogeomorphic research is focused on coastal, slope, and fluvial systems (Marston, 2010; Osterkamp and Hupp, 2010; Spencer and Viles, 2002). 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 (Ballantyne, 2002a; Matthews, 1992). Because of the extreme physical conditions (Lazzaro et al., 2010), geomorphic and biotic processes probably are closely linked (Viles, 2004).

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:

(1) to assess the paraglacial impact on vegetation succession in the forefield of Turtmann glacier, Valais, Switzerland;

(2) to identify relationships and feedbacks between geomorphic activity and vegetation patterns; and

(3) 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.

7.3 Study site and methods

The approach of this study combines methods from ecology and geomorphology adapted to a biogeomorphic aim (see Figure 7.1). 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 were discussed in a third step using biogeomorphic concepts. This adds a biogeomorphic perspective to existing knowledge on glacier forefields and fosters a better understanding of biogeomorphic interactions in these environments.

7.3.1 Previous research and regional setting

The study site is located in Turtmann valley, Valais, Switzerland, a north-south oriented tributary of the Rhône valley (see Figure 7.2 A). A number of prior geomorphological and ecological studies have been performed here within the framework of the Research Training Group 437 of the German Research Foundation (Hörsch, 2003; Kleinod, 2008; Krautblatter and Hauck, 2007; Otto et al., 2009; Otto and Dikau, 2004, 2009; see also Table 7.1).

The valley is a Pleistocene glacial trough with 15 hanging valleys on both sides of the upper valley slopes (Otto and Dikau, 2004). Dry inner alpine conditions with a mean average yearly

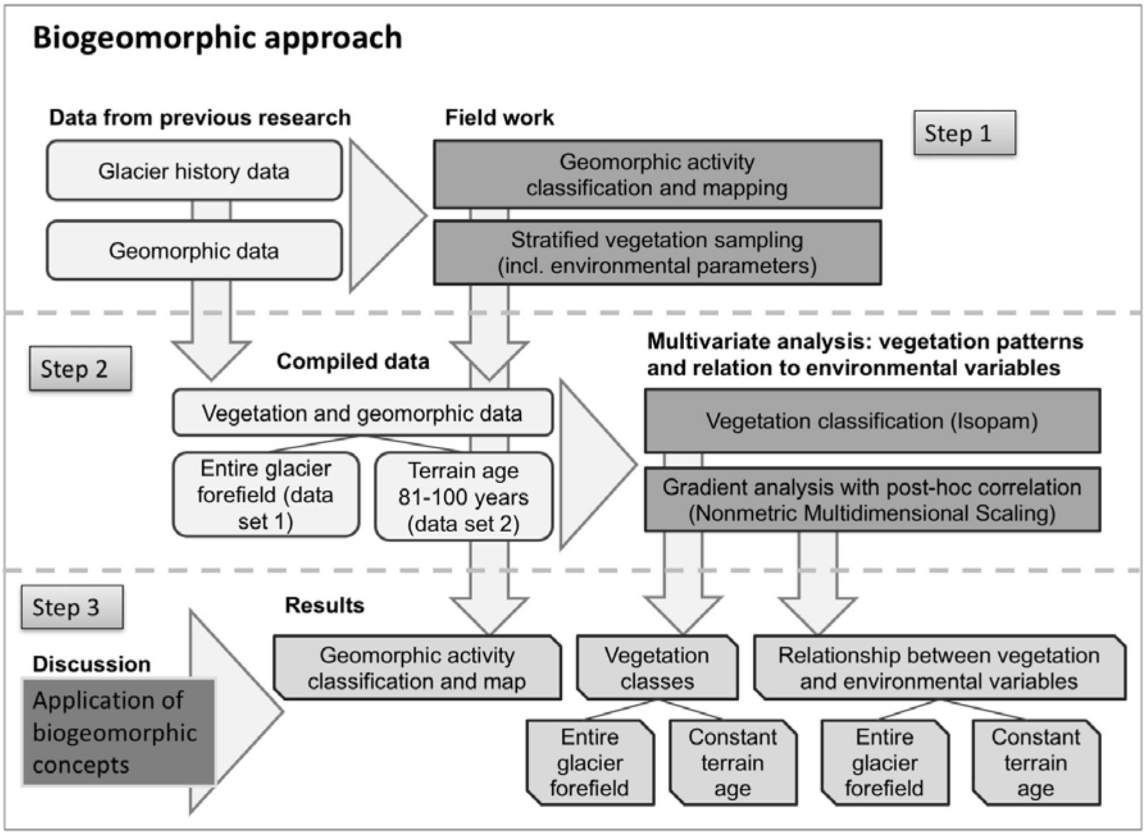

Figure 7.1: Biogeomorphic approach showing the different steps of the study with applied methods and used data.

precipitation of 496 mm (2004-2007) were recorded in the Hungerlitälli (2770 m), a tributary of the main Turtmann valley (see Figure 7.2 B) (Kleinod, 2008). Active slope processes are rock falls, rock avalanches, and rock flows, as well as debris flows, solifluction, fluvial erosion, and snow avalanches (Otto and Dikau, 2004). In the periglacial process domain, 83 rock glaciers are located in the hanging valleys (Nyenhuis et al., 2005). These main sediment storages are sedimentary decoupled from the main valley in respect to the coarse debris system (Otto et al., 2009).

The glacier forefield of this study is located at the southern end of the Turtmann valley (see Figure 7.2 B). Glacial and glaciofluvial sediments comprise middle-penninic marbles (Barrhorn series) and paragneiss/schist rocks (Mischabel crystalline complex) as well as higher penninic calcareous shales and greenstones (Tsaté nappe) and the austroalpine gneiss and gabbro (Dent Blanche nappe) (Bearth, 1980; Labhart, 2009). For the Turtmann glacier, a general recession trend was detected in the last decades, interrupted by a glacier advance in the 1980s/90s and a strong glacier recession in the twenty-first century. The glacier advance resulted in the formation of a large push moraine complex (Eybergen, 1986). In total, the Turtmann glacier retreated 1284 m from 1885 to 2005, with the strongest recession of 127 m in 2003 (Bauder and Ruegg, 2009).

Based on geomorphic maps of the study area developed in previous research projects (see Table 1), six different process domains can be distinguished in the glacier forefield: (i) glacial, (ii) glaciofluvial, (iii) glacial-denudative, (iv) glacial-cryogene, (v) landsliding, and (vi) anthropogenic. In the glacio-related domains, glacial sediment is reworked by paraglacial processes, mainly by glaciofluvial processes close to the glacier terminus and by slope processes at the 1850 lateral moraines (see Figure 7.2 C, D). The moraines are among the most important geomorphological forms of the forefield area (Otto, 2009). A hydrological power station is built on the northern end of the forefield, with a dammed sediment catch in between this and the glacier. It is regularly emptied and the sediment disposed at sediment landfills next to it (Raymond Pralong et al., 2011) (see Figure 7.2 C). These areas together with maintenance roads comprise the anthropogenic process domain.

Vegetation has been studied by a remote sensing approach encompassing the whole Turtmann valley (Hörsch, 2003). Vegetation associations found in the glacier forefield are pioneer vegetation (association *Epilobion fleischeri*), silicate debris vegetation (*Androsacion alpinae*), stands of *Salix* spp. (*Salicetum helveticae*), matgrass meadows (*Nardion)*, and dwarf shrub heaths (*Loiseleurio-vaccinion*).

7.3.2 Geomorphic activity classification and mapping

An extended geomorphic mapping approach was used, adapted to the biogeomorphic aim. In a first step, geomorphic activity was classified based on preexisting geomorphic maps of Turtmann glacier forefield (see Table 7.1). Classification criteria were time dimension (frequency) and magnitude of the involved processes (Caine, 1976; Flageollet, 1996; Otto and Dikau, 2004), clustered according to geomorphic process domains. To account for small-scale activity patterns, a subsequent geomorphic mapping was conducted in Turtmann glacier forefield. Small-scale activity patterns were mapped within the glacial-denudative process domain based on vegetation cover (see Schrott et al., 2002, 2003) and within the glaciofluvial process domain based on terrain age.

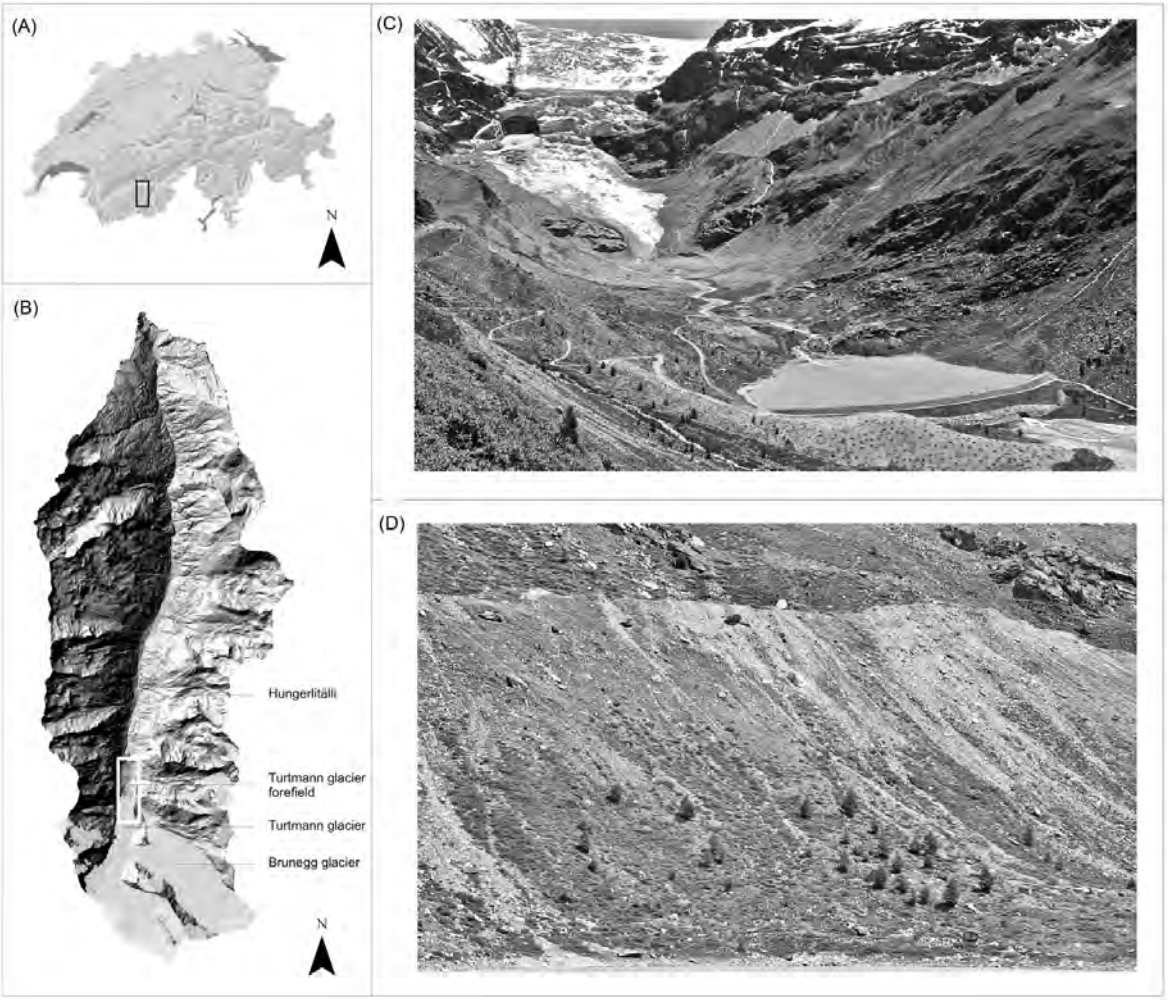

Figure 7.2: Overview of Turtmann valley and Turtmann glacier forefield. **A** Location of the Turtmann valley in Switzerland. **B** Shaded relief map of the Turtmann valley with glaciers and location of Turtmann glacier forefield (white box). **C** Turtmann glacier forefield with 1850s lateral moraines on the left, Turtmann glacier and glaciofluvial process domain in the back, and dammed sediment catch and sediment landfill in the lower middle. **D** 1850s lateral moraine of the glacial-denudative process domain, showing patterns of moderate and high activity and vegetation succession.

7.3.3 Vegetation sampling

To assess the paraglacial impact on vegetation succession, a vegetation survey was conducted using a stratified sampling design within a chronosequence approach in the area of the LIA maximum extent of Turtmann glacier. The sampling classes were constructed by combining known geomorphic process domains and landform age classes derived from glacier stages (data sources see Table 7.1). Vegetation sampling was not carried out in anthropogenically impacted areas and areas too difficult to access, such as the active steep gully moraines next to the glacier tongue.

Sample size of the plots was 2 x 2 m; the position within strata was set preferentially to account for small-scale geomorphic heterogeneity. Sampling parameters included species and cover as well as environmental (terrain age, slope gradient, elevation) and vegetation attributes (plant height of herb, shrub and tree layers, vegetation cover, species number). The taxonomic nomenclature of the vascular plants is according to (Lauber and Wagner, 2007).

7.3.4 Data sets

Two data sets including two matrixes each with species abundance and environmental attributes of plots were compiled using preexisting and mapped geomorphic data and vegetation sampling data. Plots with less than two species were excluded from this data, as well as species only occurring once.

The first data set consists of the entire remaining data (74 plots, data set 1). It is used to analyse the glacier forefield vegetation and to assess the influence of geomorphic and other environmental variables. The second data set is a subset of data set 1, consisting of 35 plots with constant terrain age (81-100 years, data set 2). This data set is used for the identification of relationships and feedbacks between geomorphic activity and vegetation, which is improved through removing the influence of different terrain ages. The 35 plots of this subset are located at the geomorphologically active lateral moraines (glacial-denudative, glacial-cryogene process domains) as well as in less active areas of the glacial process domain (see Figure 7.3 B).

The environmental and vegetation variables of the data sets are (i) terrain age (excluding data set 2), (ii) slope gradient, (iii) elevation, (iv) canopy stratification (based on plant height), (v) vegetation cover, (vi) species number, as well as (vii) geomorphic process domains and (viii) geomorphic activity classes. For simplification, all variables will be referred to as environmental.

Terrain age classes and geomorphic activity classes were coded into binary dummy variables and treated as factor variables to be used in the subsequent vegetation analysis. All other quantitative variables were treated as vector variables (cf. Leyer and Wesche, 2007).

7.3.5 Analysis of the glacier forefield vegetation and the relationships between the vegetation and environmental parameters

Two methods were used for the analysis of the species composition of the glacier forefield vegetation and its relationship to the environmental parameters: (i) vegetation classification and (ii) ordination. Vegetation classifications are employed to find patterns in floristic compositions, while multivariate ordinations analyse feedbacks between plant communities and environmental gradients (Dierschke, 1994). These feedbacks reflect in gradients of species composition, which can then be related to known environmental parameters using post-hoc correlations (Leyer and Wesche, 2007).

Table 7.1: Geomorphic and vegetation data available for Turtmann glacier forefield.

Content	Data type	Acquired by
published		
Vegetation map of the Turtmann valley	Vegetation map, 1:25,000	Hörsch (2003) (PhD Thesis, University of Bonn)
Geomorphic map of the Turtmann valley	Geomorphic map, 1:25,000	Otto and Dikau (2004)
unpublished		
Glacier history of the Turtmann glacier	Map of glacier extents (1850-1964)	Tscherrig (1965) (Oberems, Turtmann valley, Switzerland)
Geomorphic map of the Turtmann glacier forefield	Geomorphic map, 1:10,000	Bedehäsing (2007) (diploma thesis, University of Bonn)
Influence of climate change on sediment transport in the Turtmann glacier forefield	Data on sediment transport	Beer (2009) (diploma thesis, Karlsruhe Institute of Technology)
Geomorphic map of the terminus area of the Turtmann glacier	Geomorphic map, 1:10,000	Grünewald (2011) (diploma thesis, University of Bonn)

Vegetation classification

In this study, a vegetation classification served to analyse the species composition of the vegetation and to approximate successional stages. Different vegetation classes were distinguished using the classification algorithm *Isopam* (Schmidtlein et al., 2010). This algorithm is based on an ordination according to floristic similarity (distance Bray-Curtis). It creates vegetation classes with typical species, according to their frequency and significance for the particular class. It combines the Isomap-algorithm (Tenenbaum et al., 2000) for ordination with the partitioning algorithm PAM (partitioning around medoids) (Kaufman and Rousseeuw, 1990) to distinguish classes. *Isopam* is implemented in the open source R project for statistical computing (R Development Core Team, 2011).

Gradient analysis (ordination)

To examine gradients in the species composition of the glacier forefield vegetation, such as vegetation development, an unconstrained ordination was used. The non-metric multidimensional scaling (NMDS; Kruskal, 1964; distance Bray-Curtis) calculates the floristic distance between plots based on degree of cover and species co-occurrence. The calculated similarity matrix is then illustrated in an *n*-dimensional ordination space. The fitting of the illustration with the calculated similarity matrix is expressed by the measure 'stress.' Proximity of plots in the illustrated space indicates a resemblance of species composition.

The analysis was carried out with metaMDS within R vegan (version 1.17-12, J. Oksanen) using a Wisconsin double standardization and a maximum number of 100 runs to find the best solution. MetaMDS rotates the NMDS ordination space in a way that the first axis (NMDS1) can be interpreted as an expression of maximum floristic variation. Dimensions were calculated according to Kruskal (1964) with 1000 permutations for calculating coefficient of determination (r^2) and significance (p-value).

Post-hoc correlation and overlay with environmental parameters

For the analysis of the relationships between species compositions and environmental parameters, the resulting NMDS illustrations were interpreted using a post-hoc correlation with environmental parameters (R vegan: envfit, factorfit, version 1.17-12, J. Oksanen). Correlations between parameters and ordination axes with $p < 0.01$ were seen as significant, nonsignificant correlations are not displayed. To interpret the illustrated gradients in species compositions, the plots in the NMDS illustration were furthermore overlain with associated attributes. An overlay with the *Isopam* vegetation classes was used to find floristic patterns in the species composition. Terrain age classes, geomorphic process domains, and geomorphic activity classes were overlain to show their correspondence with floristic patterns.

7.4 Results

7.4.1 Geomorphic activity

Geomorphic activity was classified in three classes with low, moderate, and high activity (cf. Schrott et al., 2003). The classification according to frequency and magnitude of processes and additional classification criteria are shown in Table 7.2. The spatial distribution of these classes in Turtmann glacier forefield is shown in the geomorphic activity map (Figure 7.3 A).

The glacial process domain was classified as lowly active as no active geomorphic processes are occurring there at present. The solifluction process with high frequency but low magnitude in the glacial-cryogenic process domain was classified as moderately active.

For the glaciofluvial and glacial-denudative process domains, a spatial activity differentiation was carried out to account for small-scale activity differences. In the glaciofluvial process domain, a clear activity threshold is visible between the terrain affected by a glacier advance in the 1980s (largest extent in 1984) with a braided river system and older terrain, where glaciofluvial discharge is only transported in one channel. Thus, terrain age was used to distinguish between high activity with high frequency and magnitude near the glacier tongue (terrain age ≤ 27 years) and moderate

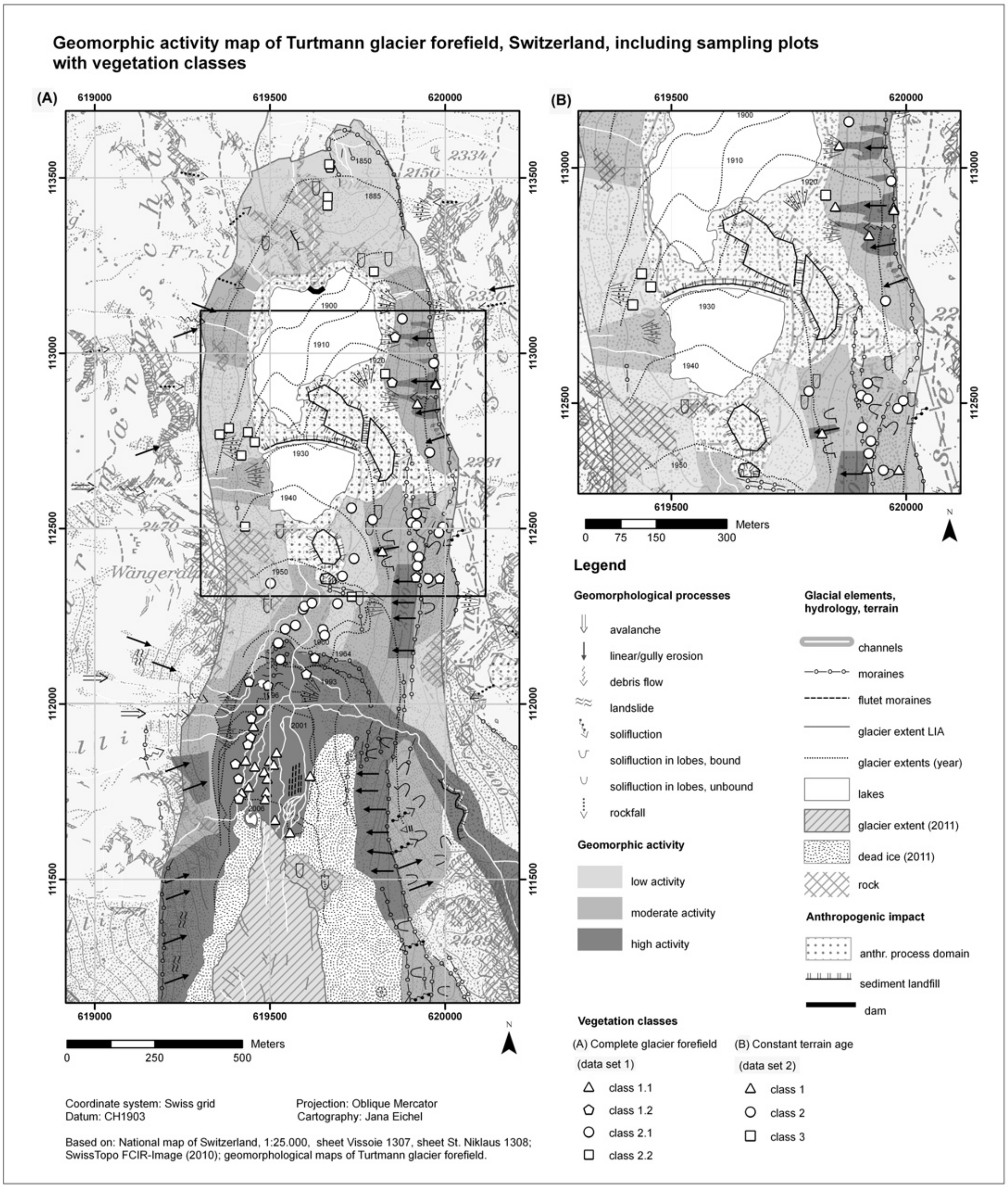

Figure 7.3: Geomorphic activity map of Turtmann glacier forefield. Sampling plots are displayed according to vegetation classes. **A** Geomorphic activity map of the glacier forefield with sampling plots according to vegetation classes. **B** Subset with vegetation classes of constant terrain age (81–100 years).

glaciofluvial activity with lower magnitude on older terrain (age > 27 years). In the glacial-denudative process domain, small-scale activity differences were indicated by large variations in vegetation cover. Areas with a vegetation cover ≤ 10% were classified as highly active due to occurring high frequency, moderate magnitude slope wash and lower frequency but higher magnitude debris flows. Areas with a vegetation cover > 10% were classified as moderately active as this indicates a lower frequency of geomorphic processes (cf. Schrott et al., 2002, 2003).

High geomorphic activity is located within the area covered by the glacier during the 1980s/90s advance with active glaciofluvial processes and at the barely vegetated erosional surfaces of the lateral moraines (Figure 7.3 A). Moderate activity was found at the other parts of the lateral moraine areas as well as at certain parts of the western valley slopes, which are affected by frequent debris flows and linear erosion. The remaining area, which was not assigned as anthropogenic process domain, possesses a low activity.

Table 7.2: Geomorphic activity classification for Turtmann glacier forefield with magnitude and frequency of process domains and additional criteria for a distinction between moderate and high activity within domains

Process domain	Criteria: magnitude and frequency	Additional criteria	Value	Activity class
glacial	No active processes			Low activity
glacial-cryogenic	Low magnitude, high frequency			Moderate activity
glacial-denudative	Moderate magnitude, moderate frequency	vegetation cover	> 10%	Moderate activity
			≤ 10%	High activity
glaciofluvial	Moderate magnitude, high frequency	terrain age	> 27 years	Moderate activity
			≤ 27 years	High activity

7.4.2 Vegetation patterns and relation to environmental parameters

Vegetation patterns in the glacier forefield (data set 1)

Vegetation patterns in the glacier forefield can be described by four hierarchical vegetation classes (class 1.1, 1.2, 2.1, 2.2) with 109 species. A typical species of class 1.1 (19 plots) is *Saxifraga aizoides*, further herb species with high frequency and significance are *Linaria alpina, Trifolium pallescens, Epilobium fleischeri,* and *Trisetum distichophyllum*. This class is mostly found close to the glacier terminus as well as on the lateral moraines (see Figure 7.3 A) in areas with high geomorphic activity. Class 1.2 (16 plots) occurs in the southwestern part of the area with highly active glaciofluvial processes and on the lateral moraines with high to moderate geomorphic activity. Typically grass *Alopecurus* species as well as the herbs *Campanula scheuchzeri* and

Trifolium badium were found in this class. In class 2.1 (27 plots) dwarf shrubs are typically occurring (*Salix reticulata, Salix serpyllifolia, Dryas octopetala*) as well as the herb *Anthyllis vulneraria*. This class was found mostly at areas with moderate activity. Class 2.2 (12 plots) contains the herbs Lotus alpinus and Pyrola minor as well as shrubs and trees (Rhododendron ferrugineum, Larix decidua). This class was mostly found on older terrain with low activity.

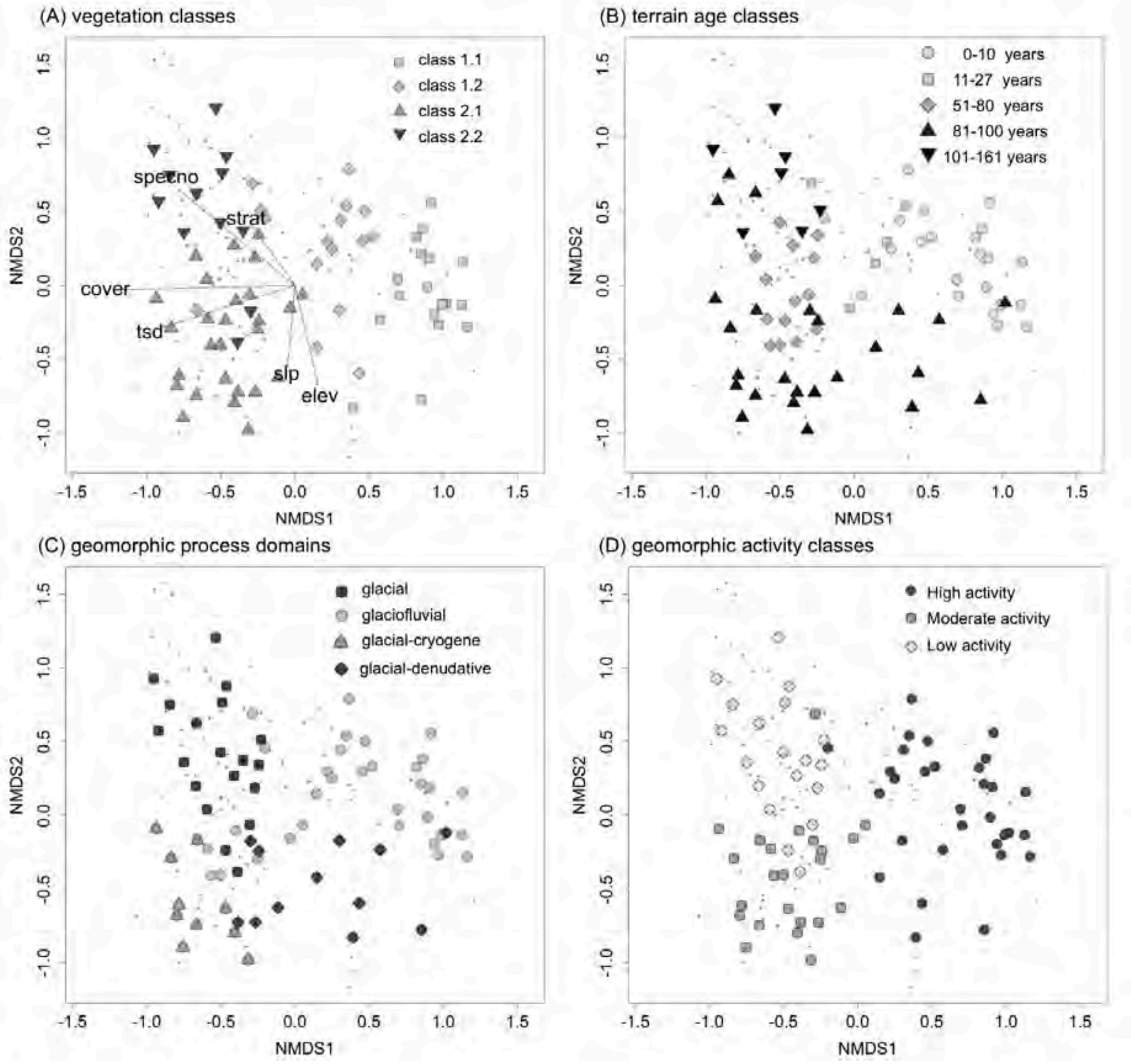

Figure 7.4: NMDS data set 1: vegetation patterns in the glacier forefield in relation to environmental parameters. **A** Overlay with vegetation classes, including environmental fit of significant ($p < 0.01$) variables. Arrows display the different vector variables with the arrow pointing in the direction of maximum change of the variable and their length depending on the size of the squared correlation coefficient. **B** Overlay with terrain age classes. **C** Overlay with geomorphic process domains. **D** Overlay with geomorphic activity. Environmental parameters: specno = species number, strat = stratification, cover = vegetation cover, terra = terrain age, slp = slope, elev = elevation. Stress = 16.35.

Relation of the glacier forefield vegetation to environmental parameters

The relation of the glacier forefield vegetation to environmental parameters shows in the main gradients in the species composition. They are illustrated in the NMDS result (three dimensions, stress 16.35) (see Figures 7.4 A-D). The main floristic gradient (NMDS1) relates to vegetation cover (cover, $r^2 > 0.6$) and time since deglaciation (terra, $r^2 > 0.6$) (see Figure 7.4 A). The second axis (NMDS2) more weakly relates to slope gradient (*slp*) and elevation (*elev*) opposed to stratification (*strat*) and species number (*specno*). Weak but significant correlations to other parameters ($p < 0.01$) exist, but are not illustrated.

For the overlain attributes vegetation classes, terrain age classes, geomorphic process domains and geomorphic activity classes, their correspondence to floristic patterns differ clearly (see Figure 7.4 A-D). Vegetation classes mostly correspond to the main gradient (NMDS1) starting with a development along the vegetation class hierarchy from class 1.1 to class 2.2 (see Figure 7.4 A). The pattern of terrain age classes shows a weak correspondence to floristic patterns (Figure 7.4 B), while the patterns of geomorphic process domains and geomorphic activity can be more clearly recognized (Figure 7.4 C, D). Along the two gradients in the NMDS illustration, glaciofluvial and glacial-denudative highly active plots can be found at the beginning of the first gradient (right section of the NMDS illustration). Glaciofluvial, glacial-denudative, and glacial-cryogene moderately active plots are located close to the end of the first and the beginning of the second gradient (lower left section) and glacial low active plots at the end of first and second gradient (upper left section).

Vegetation patterns at constant terrain age (81-100 years) (data set 2)

Vegetation patterns at constant terrain age can be described by three nonhierarchical vegetation classes (classes 1, 2, 3). Typical species with high significance and frequency in class 1 (7 plots) include the herbs *Saxifraga aizoides* and *Linaria alpina.* Class 1 is mostly occurring on lateral moraines with high geomorphic activity. Class 2 (13 plots) typically contains dwarf shrubs (*Dryas octopetala, Salix reticulata*), herbs (*Saxifraga paniculata)*, and grasses (*Carex* spp.); while shrubs (*Salix foetida*) and the herbs *Carduus defloratus*, *Lotus alpinus*, and *Sempervivum arachnoideum* typically occur in class 3 (4 plots). Class 2 was only found in moderately active areas, while class 3 mostly occurred in areas with low geomorphic activity. Species of class 3 often do not occur in other classes, while species of class 1 mostly do not occur in this class.

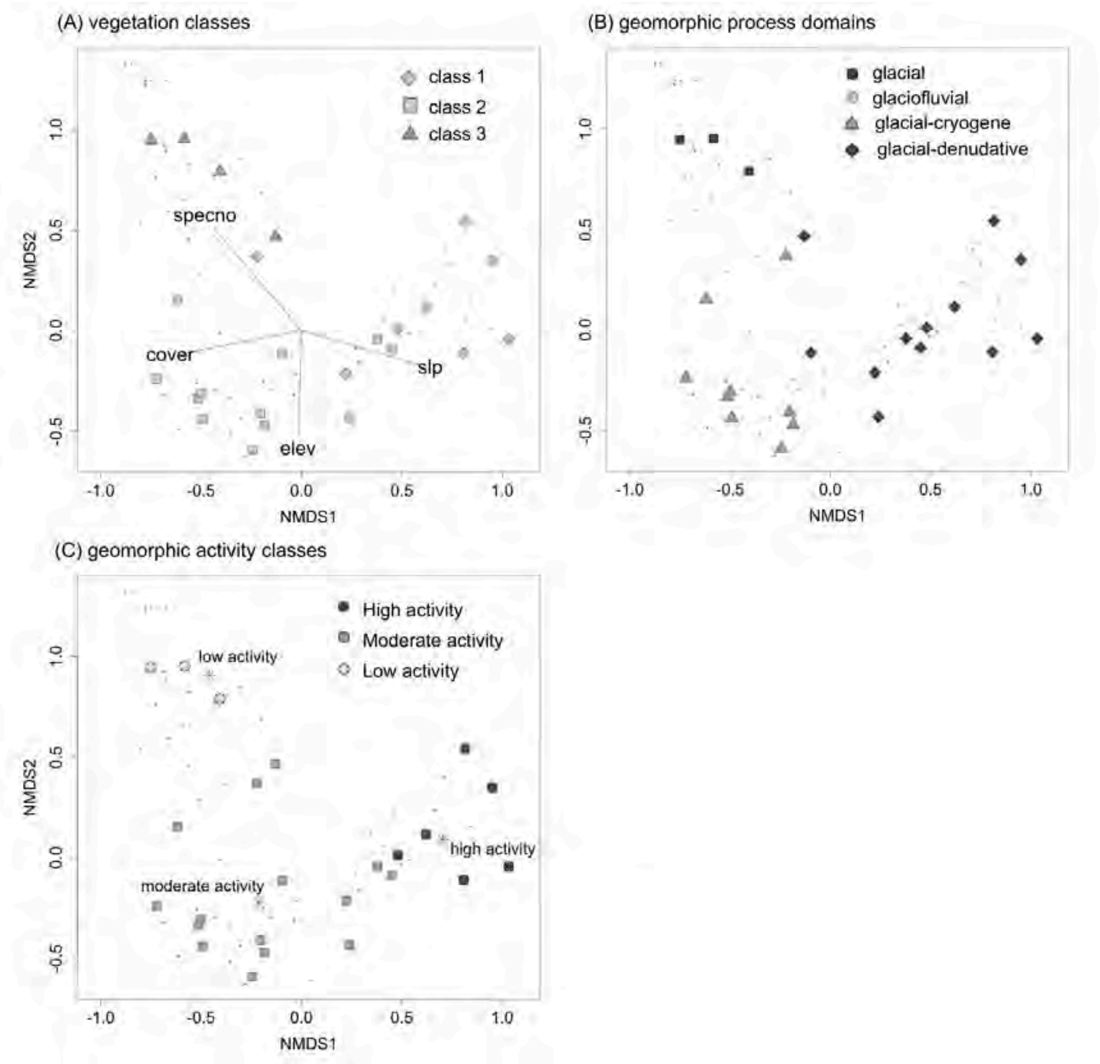

Figure 7.5: NMDS data set 2: vegetation patterns at constant terrain age (81–100 years). **A** Overlay with vegetation classes including environmental fit of significant ($p < 0.01$) vector variables. **B** Overlay with geomorphic process domains. **C** Overlay with geomorphic activity, including environmental fit with activity classes ($p < 0.01$). Asterisks represent the average ordination scores of the different activity classes. Environmental parameters: specno = species number, cover = vegetation cover, slp = slope, elev = elevation. Stress = 12.78.

Relation between vegetation of constant terrain age and environmental parameters

The relationship between vegetation of constant terrain age and environmental parameters shows in the main gradients of the species composition. They are illustrated in the NMDS result (three dimensions, stress 12.78) (see Figure 7.5 A-C). The main floristic gradient (NMDS1) strongly ($r^2 > 0.6$) relates to vegetation cover (*cover*) vs. slope gradient (*slp*). Elevation (*elev*) relates to the second axis (NMDS2), while species number (*specno*) strongly relates to both gradients. Weak correlations exist between the ordination configuration and geomorphic process domains (glacial, glacial-cryogenic, glacial-denudative) (not shown) and geomorphic activity (high, moderate, low) (Figure 7.5 C). All described correlations are significant ($p < 0.01$), correlations with the remaining environmental parameters were not significant and are not displayed.

For all overlain attributes, vegetation classes, geomorphic process domains, and geomorphic activity classes, the correspondence to floristic patterns is distinctive (see Figure 7.5). At the beginning of the first gradient, plots with high activity and slope gradient from the glacial-denudative process domain with vegetation class 1 can be found (right section, Figure 7.5 A-C). At the beginning of the second gradient, plot elevation is generally higher with high vegetation cover, moderate geomorphic activity, and vegetation class 2 (lower section). At the end of the first and second gradient, plots mostly belong to the glacial process domain with low activity, high species numbers, and vegetation class 3 (upper left section).

7.5 Discussion

7.5.1 Methods

Geomorphic activity classification and mapping

The geomorphic activity classification shows some weaknesses. As the geomorphic activity classes were based on vegetation cover for the glacial-denudative process domain, collinearity between these exists. This is disadvantageous as activity is related to vegetation in the analysis.

To classify geomorphic activity, Schrott et al. (2002, 2003) used further criteria, e.g. landform change over a time period of two years. This was, however, not possible in this study owing to a short time frame of the fieldwork. Magnitude-frequency relationships were used instead, which were criticized lately as they are believed to be valid only in equilibrium conditions (Crozier, 1999). Their use can, however, be justified here as they were used only for an approximation of geomorphic activity in a short time period and a small area (see Crozier, 1999). The advantage of this approach is furthermore its relation to ecological demands concerning an integration of frequency and magnitude of the occurring disturbances (see Matthews, 1999).

Vegetation sampling and analysis

The preferential choice of plots in this study resulted in an uneven distribution of plots within the strata (see Figure 7.3A). This influences the recognition of patterns when using vegetation classifications (Cooper et al., 2006). A preferential choice here was, however, necessary as the focus of research was purposely laid on the geomorphically more active areas. In this case, a preferential choice can be advantageous (McCune and Grace, 2002).

Both methods used for vegetation analysis were tested in previous studies and showed good performance and results. For the classification with *Isopam*, the defined vegetation classes possess a high quality of indicator species. In comparison with eight different classifications, *Isopam* achieved good results (Schmidtlein et al., 2010). The NMDS is seen as 'the most generally effective ordination method for ecological community data' (McCune and Grace, 2002, p. 125). A performance analysis in comparison with other ordination methods showed its robustness and effectiveness, especially together with the applied Bray-Curtis coefficient (Kent, 2006). The stress of the ordinations with values between 12 and 17 can be seen as normal for ecological data analysis with large samples (McCune and Grace, 2002).

7.5.2 External noise

The external noise in this study comprises further environmental variables (which were not considered) such as pedological characteristics, moisture, climate, and substrate. They are certainly important for vegetation distribution and composition, as much as anthropogenic impacts. As the development of many environmental variables with vegetation succession was already frequently studied and described (see Matthews, 1992), they were not specifically examined within this biogeomorphic approach. Anthropogenic impact on vegetation, such as activities by a hydropower company, regular hikers as well as grazing by sheep and goats could not be excluded but were impossible to quantify.

7.5.3 Paraglacial impact on vegetation succession

In previous studies, spatial discontinuities in vegetation succession in glacier forefields were related to the impact of paraglacial processes (Moreau et al., 2004, 2008). These discontinuities are also seen in the Turtmann glacier forefield. Vegetation succession here in general proceeds from pioneer stage (vegetation class 1.1) to early successional stage (class 1.2), intermediate successional stage (class 2.1), and late successional stage (class 2.2) (see Figure 7.6). It follows the main floristic gradient with typical succession trends of increasing vegetation cover, species numbers, and vegetation stratification with increasing terrain age (Matthews, 1992).

Opposing this trend, three different successional stages were, however, found on older terrain, especially terrain age 81-100 years (see Figure 7.6, bottom). Here, the pioneer stage with pioneer species (*Saxifraga aizoides)* and the early successional stage occur next to the late successional

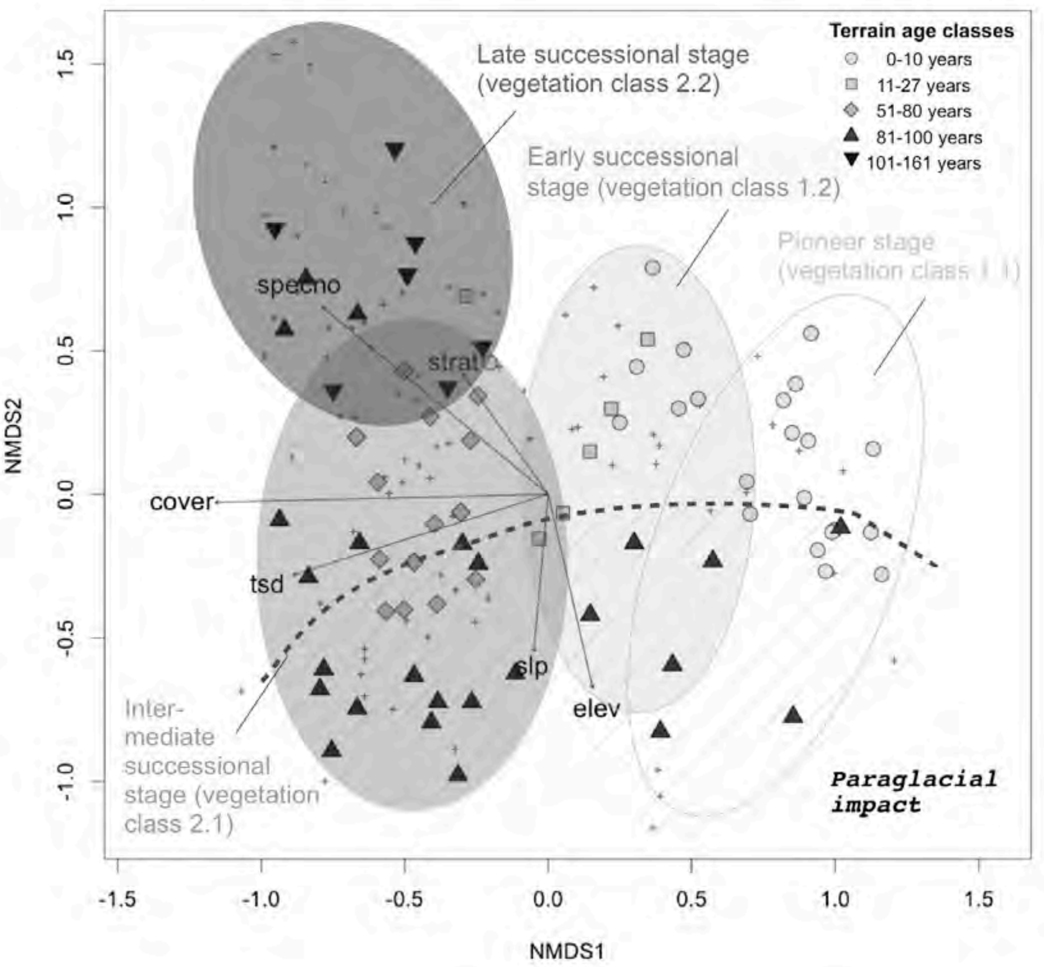

Figure 7.6: Vegetation succession and paraglacial impact in Turtmann glacier forefield based on the NMDS result from data set 1 and overlay by terrain age classes. Four successional stages can be distinguished, which were derived from vegetation classes (see Figure 7.2 A). Paraglacial impact shows in high and moderately active plots (see Figure 7.2 D) of terrain age class 81–100 years. Environmental parameters: specno = species number, strat = stratification, cover = vegetation cover, terra = terrain age, slp = slope, elev = elevation.

stage, which would be expected at this terrain age (cf. Matthews, 1992). This can be related to a paraglacial impact. At a high slope gradient (see Figure 7.6), high to moderate geomorphic activity was found at this terrain age with slope wash, gravitative processes (glacial-denudative process domain), and solifluction (glacial-cryogene process domain) (see Figure 7.3 B). These disturbances generally cause the maintenance of younger successional stages (Moreau et al., 2004) with floristic resemblance of these disturbed areas to recently deglaciated areas (Moreau et al., 2008; Richter, 1994). This is clearly showing in our results. The occurrence of these patterns especially on older terrain is, however, opposed to the results from Richter (1994), who found a decrease in geomorphic impact with increasing terrain age. A similar conclusion was reached by Matthews (1999). In Turtmann glacier forefield, paraglacial adjustment thus seems to take longer than usual.

We assume a paraglacial impact on vegetation succession exists in all glacier forefields, but with varying degrees dependent on the individual glacier forefield configuration (e.g. size, climate, initial conditions) as well as the biogeomorphic feedbacks. This highlights the importance of understanding their underlying mechanisms and influencing factors, e.g. different degrees of geomorphic activity (Matthews, 1999).

7.5.4 The relationship between geomorphic activity and species composition

The severity and spatial extent of disturbances are responsible for the starting conditions of evolving systems (Raab et al., 2012). Large-scale disturbances with high magnitude and low frequency result in the appearance of new pioneer communities; while lower magnitude, higher frequency disturbances maintain vegetation communities (Pickett et al., 1987). This suggests that a relationship exists between geomorphic activity, based on frequency and magnitude, and species composition in Turtmann glacier forefield.

Evidence for this can be provided (see Figure 7.7). At high geomorphic activity with slope wash and gravitative processes (glacial-denudative process domain; see Figure 7.3 B), pioneer vegetation of class 1 with the pioneer species *Saxifraga aizoides* and *Linaria alpina* (cf. Stöcklin and Bäumler, 1996) occurs (see Figure 7.7). Vegetation class 2 with dwarf shrubs (*Dryas octopetala, Salix reticulata*) characteristically for an intermediate successional stage (Andreis et al., 2001) relates to moderate activity of mostly solifluction processes (glacial-cryogene process domain). At low activity, vegetation class 3 with the highest species numbers is found (see Figures 7.3 B, 7.7). This pattern could, however, be partly attributed to spatial autocorrelation (cf. Legendre and Legendre, 1998) and the use of vegetation criteria for activity classification (see Section 7.3.2). Yet, differing successional developments were also found on stable, inactive or active scree (Lippert, 1966). which supports our results.

We believe that the diverse paraglacial processes have a different impact on vegetation succession depending on their frequency and magnitude and associated geomorphic activity. This impact becomes encoded in the abundance and spatial patterns of vegetation across a landscape (Corenblit et al., 2007) and shows in the described heterogeneity in vegetation succession (see Section 7.2; Moreau et al., 2004). These patterns can be explained by underlying interactions between vegetation and geomorphic processes and components as described in the concept of biogeomorphic succession (Corenblit et al., 2007).

7.5.5 Biogeomorphic succession

For sediment-mantled slopes, a lateral succession of processes and landforms was detected, which correlated to vegetation succession (Mercier et al., 2009). These simultaneous and correlated changes in landforms and vegetation were also described for the fluvial system by Corenblit et al. (2007). They termed this process 'fluvial biogeomorphic succession,' resulting from feedbacks between abiotic and biotic processes. As feedbacks change in time, four different succession phases were proposed: geomorphic phase, pioneer phase, biogeomorphic phase, and ecologic phase (Corenblit et al., 2007).

This concept, based on the results from extensive previous studies in river systems, enables a complete view of the dynamics of the complex systems and provides a link between these and the system organization (Corenblit et al., 2007). In our study, it is applied to interpret and structure the described sequence of simultaneous and codependent geomorphologic and ecologic processes in the Turtmann glacier forefield. Thereby, a holistic and systemic view on geomorphic and ecologic glacier forefield dynamics is provided and comparability of these biogeomorphic processes with similar processes in fluvial systems can be achieved.

In Turtmann glacier forefield, the different degrees of geomorphic activity with corresponding vegetation are interpreted as three biogeomorphic succession phases with a changing strength of biotic-abiotic interactions.

Pioneer phase

In the pioneer phase, plant dynamics in a fluvial system are controlled by hydrogeomorphic processes (Corenblit et al., 2007). The recurrence interval of geomorphic processes is higher than the relaxation time of the vegetation. Thus, transient physical forms prevail as described in the biogeomorphic transient form ratio (Corenblit et al., 2011; Phillips, 1999), which is an extension of the geomorphic transient form ratio described by Brunsden and Thornes (1979). This also applies for the glacier forefield in areas with high geomorphic activity. Here, only species that are adapted to strong sediment movements can occur. These are the pioneer species of vegetation class 1 with *Achillea nana* as scree-wanderer and *Linaria alpina* as scree-creeper (Schröter et al., 1926) (see Figure 7.7). Vegetation cover is low and slope wash and gravitative processes are dominant (see Figure 7.3 B).

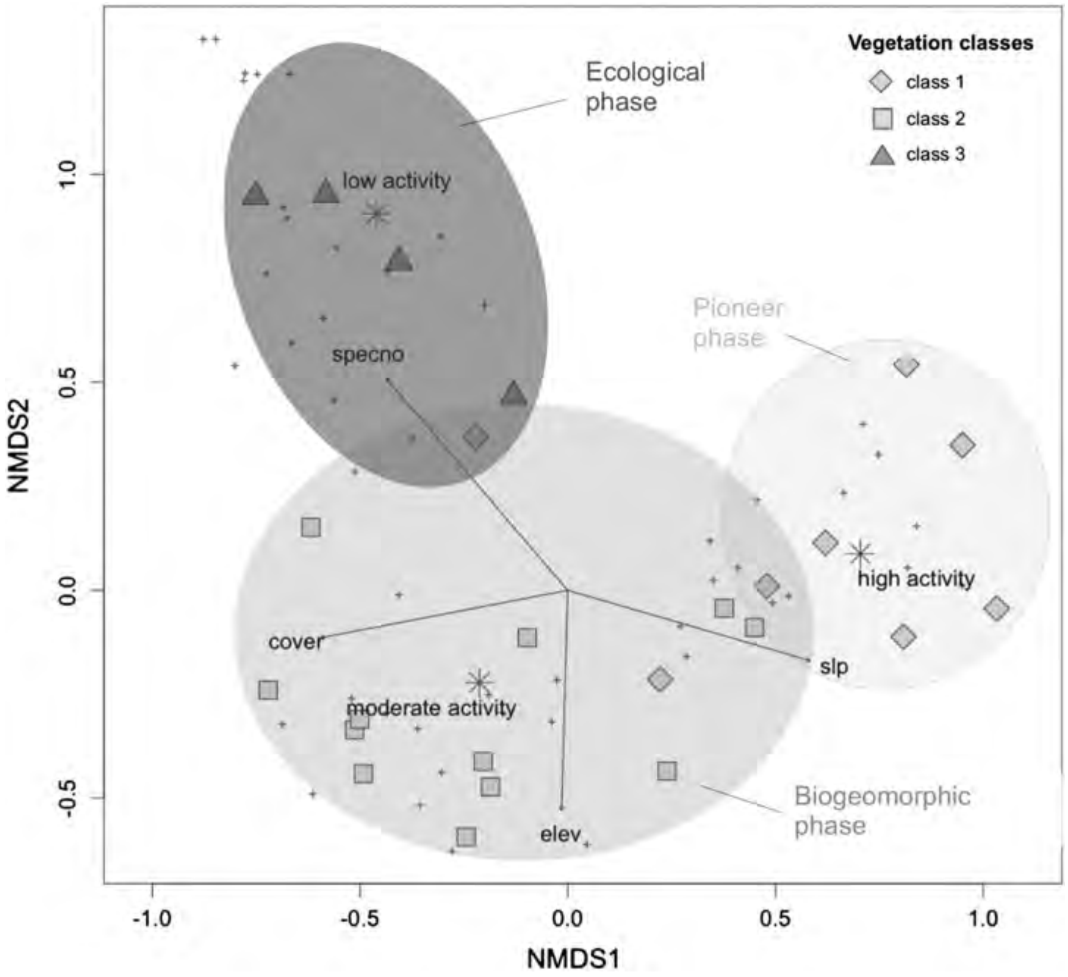

Figure 7.7: Biogeomorphic succession at constant terrain age, based on NMDS from data set 2. Overlay with vegetation classes and environmental fitting with geomorphic activity. Biogeomorphic succession phases were derived from vegetation and activity classes (Figures 3 A, C). Environmental parameters: specno = species number, cover = vegetation cover, slp = slope, elev = elevation.

Biogeomorphic phase

When the recurrence interval of the geomorphic processes becomes higher or the relaxation time of vegetation lower (Corenblit et al., 2011; Phillips, 1999), a threshold from the pioneer to the biogeomorphic phase can be crossed. Vegetation and geomorphic change become co-dependent (Phillips, 1999). This happens when the established pioneer species start to interact mechanically with the geomorphic processes (Corenblit et al., 2007). Certain plant functional traits, e.g. root characteristics, can control the recurrence interval of geomorphic processes (Corenblit et al., 2011; Lavorel et al., 2007). This was, e.g. shown for soil erosion processes, where roots increase the soil sheer strength and soil cohesion (Gyssels et al., 2005). Similar influences were also shown on moraine material (Graf et al., 2009). The species that possess these traits are called geomorphic-engineer species (Corenblit et al., 2011). In fluvial systems, these species are shrub or tree species (Corenblit et al., 2009). The emerging biogeomorphic interactions induce nonlinear behaviour that results in the building of biogeomorphic structures as biophysical attractors (Corenblit et al., 2007).

In Turtmann glacier forefield, species that can fix the moving debris occur in vegetation class 2 that was found at terrain with moderate activity, especially in the glacial-cryogene process domain with solifluction forms (see Figure 7.3 B). These are the dwarf shrubs *Salix* spp. (scree-coverer) and *Dryas octopetala* (scree dammer) (Schröter et al., 1926). For solifluction processes, it was shown that vegetation acts as a break on soil movement (Matsuoka, 2004). Lower geomorphic work correlated with the presence of herbs (Ridefelt et al., 2011). The dwarf shrubs found on terrain with moderate activity in Turtmann glacier forefield are thus most probably influencing the geomorphic activity here. (cf. Figure 7.7). Through this stabilization, they facilitate the colonization for further species, such as *Carex* spp. (Reisigl and Keller, 1994). Grassland associations can subsequently develop — such as *Dryadeto-Firmetum* with *Carex* spp., *Dryas octopetala, Salix serpyllifolia,* and *Pinguica alpina* — or *Elynetum* with *Elyna myosuroides, Saxifraga oppositifolia*, and *Saxifraga paniculata* (Reisigl and Keller, 1994) occurring in vegetation class 2 (see Section 7.4.2). The dwarf shrubs are thus potential geomorphic-engineer species whose influence possibly results in the formation of solifluction forms as biogeomorphic structures.

Ecologic phase

Geomorphic engineers often vanish in the ecologic phase of the biogeomorphic succession as with developing vegetation, they exclude themselves (Corenblit et al., 2011). In vegetation class 3 at terrain with low geomorphic activity, potential geomorphic-engineer species such as *Dryas octopetala* are missing. The dominance of autecological processes, such as competition and inhibition, here results in a different species composition, highest species numbers (see Figure 7.5), and missing pioneer species. The species composition of this phase often serves as a ‘diversity reservoir’ for a recolonization after a major disturbance (Corenblit et al., 2009).

Our results back earlier findings and can, by applying the concept of biogeomorphic succession, clearly show the codependent geomorphic and ecologic development in glacier forefields. This development is not only determined, as previously shown, by a decreasing significance of geomorphic and increasing significance of ecologic processes but is especially driven by interactions between these (cf. Corenblit et al., 2007, 2009).

The application of the biogeomorphic concepts links the different scales on which this development is happening with geomorphic-engineer mediated interactions and resulting biogeomorphic structures at a small scale and the resulting related patterns of geomorphic activity and species composition at an intermediate scale. An adaptive cycle relating to geomorphic activity and the strength of biogeomorphic interactions here seems to be embedded in the general biogeomorphic development trend of the glacier forefield (cf. Corenblit et al., 2007). Through the described biotic-abiotic interactions and their dynamics, specific biogeomorphic patterns emerge at landscape scale (Corenblit et al., 2011).

7.5.6 Biogeomorphically affected paraglacial adjustment

In Turtmann glacier forefield, the described biotic-abiotic interactions and their dynamics started with glacier retreat. Resulting patterns can thus be seen as paraglacial biogeomorphic patterns (cf. Ballantyne, 2002a). Therefore, the repeatedly detected patterns of vegetation succession and geomorphic activity in glacier forefields can be seen as the outcome of the paraglacial adjustment comprising biogeomorphic interactions. Integrating the results on the relation between geomorphic activity and vegetation into the paraglacial concept, we can say that paraglacial stabilization in relation to vegetation influence is dependent on the ratio between geomorphic activity and vegetation recovery time controlled by vegetation characteristics as described in the biogeomorphic transient form ratio and thus on biogeomorphic interactions. At moderate geomorphic activity in the biogeomorphic phase, these interactions seem to be most active.

7.6 Conclusion and perspectives

By using a biogeomorphic approach and applying biogeomorphic concepts in the Turtmann glacier forefield, new insights could be gained into geomorphic and vegetation dynamics in these environments.

A paraglacial impact on vegetation succession could be shown for the Turtmann glacier forefield. This is displayed in different successional phases at constant terrain age opposing the general succession trend.

The paraglacial impact was further differentiated according to degree of activity and related to specific species compositions at constant terrain age. At high geomorphic activity, pioneer vegetation occurs. Dwarf shrubs were mostly found at moderate geomorphic activity, while new species and highest species numbers were found at low activity.

To interpret and structure this sequence of simultaneous and codependent geomorphologic and ecologic processes, the concept of biogeomorphic succession (Corenblit et al., 2007) was applied. This sequence of three biogeomorphic phases is not only determined by a decreasing significance of geomorphic and increasing importance of ecologic processes but is especially driven by interactions between these. In the pioneer phase with high geomorphic activity, only pioneer species adapted to the dominant geomorphic processes occur. In the biogeomorphic phase with moderate activity, species composition strongly differs with a dominance of dwarf shrubs. These can fix the moving debris and facilitate the colonization for further species. They are thus potential geomorphic-engineer species. In the ecological phase with dominant autecological processes such as competition these species are missing. The application of biogeomorphic concepts developed in river systems here enables a conceptual systemic approach for understanding geomorphic-biotic interactions in a glacier forefield and a comparability of these for different environments. This strengthens the theoretical base of biogeomorphology and supports the further development of a unifying biogeomorphic terminology and concepts for different environments.

As the development of the glacier forefield is triggered by the glacier retreat since the Little Ice Age, the biogeomorphic system of the glacier forefield can be seen as paraglacially adjusting through biogeomorphic interactions. The paraglacial stabilization here depends on the strength of these interactions. This adds a biogeomorphic perspective to the paraglacial concept.

Especially with regard to accelerating dynamics in glacier forefield from climate change, biogeomorphic research in these environments should be fostered. Studies considering sediment dynamics, e.g. for glacier forefield sediment management (cf. Schleiss, 2005), could highly benefit from taking biogeomorphic interactions into account. In addition, glacier forefields offer further potentials to answer current biogeomorphic research questions such as quantification of the impact of geomorphic engineer species (Corenblit et al., 2011), a mechanical understanding of the biogeomorphic interactions and of the resulting evolution of glacier forefield systems. This especially applies to the long-term, scale-dependent evolution.

Acknowledgements

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8 BIOGEOMORPHIC SUCCESSION AND PATCH DYNAMICS: LINKING VEGETATION SUCCESSION, PARAGLACIAL ADJUSTMENT AND THEIR SPATIOTEMPORAL PATTERNS ON LATERAL MORAINE SLOPES

> *'The overarching question for biogeomorphologists becomes: how do vegetation dynamics and geomorphic flux interact with one another? [...] What types of landscape patterns emerge as a result?' (Stallins, 2006, p. 208)*

This chapter addresses thesis objective 4 relating to biogeomorphic succession and resulting spatial patterns on lateral moraine slopes. Slope-scale biogeomorphic dynamics on lateral moraines are summarized based on permanent plot data, supplemented with information on soil and material properties and snow and thermal regime. Spatial information is provided by geomorphic and vegetation mapping of lateral moraine slopes in Turtmann glacier foreland. This chapter (i) determines controls for paraglacial adjustment of lateral moraine slopes and develops a conceptual model of paraglacial process and landform succession, (ii) describes controls on vegetation succession with different successional pathways in a spatial patch mosaic, and (iii) depictstemporal and spatiotemporal biogeomorphic dynamics on lateral moraine slopes in the biogeomorphic succession concept and a biogeomorphic patch dynamics concept. Thereby, this chapter demonstrates the importance of biogeomorphic feedbacks, related to ecosystem engineering, for paraglacial adjustment and vegetation succession on lateral moraine slopes. Furthermore, it highlights the spatial variability of biogeomorphic feedbacks, related to toposequence position, moraine type, material propertied and external disturbances. Results from previous chapters on ecosystem engineering (Chapters 4, 6), turf-banked solifluction lobes (Chapters 5, 6) and biogeomorphic succession (Chapter 7) are integrated into this chapter.

Described findings and concepts were derived in cooperation with N. Meyer (soil sampling and analysis), D. Corenblit (vegetation and biogeomorphic succession), D. Draebing (paraglacial adjustment, temperature logger analysis), S. Schmidtlein (statistical analysis, vegetation mapping) and R. Dikau (geomorphic mapping, paraglacial adjustment). Based on the individual discussion sections on paraglacial dynamics (Section 8.4.2), vegetation dynamics (8.4.3) and biogeomorphic dynamics (8.4.4, 8.4.5), this chapter can provide the base for further publications addressing a geomorphologic, ecologic and biogeomorphic audience, respectively.

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8 BIOGEOMORPHIC SUCCESSION AND PATCH DYNAMICS

8.1 Introduction

Glacier forelands are highly dynamic environments in terms of both geomorphic and ecologic processes (Carrivick et al., 2013; Matthews, 1992; Rydgren et al., 2014). Due to on-going climate warming, glacier foreland areas are currently increasing in size and will continue this trend for the next centuries (Paul et al., 2004; Radić et al., 2013; Zemp et al., 2006). Their geomorphic system and ecosystem are adjusting to retreating glacier conditions with enhanced geomorphic process activity, called paraglacial adjustment, and with vegetation colonization and subsequent vegetation succession associated with changing species compositions (Ballantyne, 2002a; Matthews, 1992). In order to understand how glacier foreland landscapes will develop future, both paraglacial adjustment and vegetation succession, as well as their interactions need to be understood, as they control structure and function of the glacier foreland biogeomorphic ecosystem (Corenblit et al., 2016, Eichel et al., 2016). This is especially important for a successful sediment management and the mitigation of natural hazards in glacier forelands (Deline et al., 2015; Hauenstein, 2005; Moore et al., 2009).

Previous ecological research in glacier forelands mainly concentrated on stable valley floor areas and identified terrain age as most important factor controlling vegetation succession (Matthews, 1992; Robbins and Matthews, 2014). Once plant species establish successfully with the help of traits adapted to unfavourable initial conditions (Erschbamer et al., 2008; Makoto and Wilson, 2016; Stöcklin and Bäumler, 1996), species composition changes with terrain age. Initially, changes are triggered by improving climatic conditions (Egli et al., 2011; Kaufmann, 2002) and soil development, related to decreasing pH values, increasing nitrogen and soil organic carbon contents and developing soil horizons (D'Amico et al., 2014; Matthews, 1992; Schumann et al., 2016). Later, increasing biotic interactions either promote the establishment of other species (facilitation, Caccianiga et al., 2006; Kuen and Erschbamer, 2002; Schweingruber et al., 2007), or limit their growth and survival (inhibition, competition; Caccianiga et al., 2006; Raffl et al., 2006; Robbins and Matthews, 2014). However, the effect of disturbances on vegetation succession in unstable areas, such as lateral moraine slopes, was neglected in previous ecologic research. Disturbances, often geomorphic processes, delay vegetation succession or even reset it to pioneer stages (Eichel et al., 2013; Matthews, 1999c; Moreau et al., 2008). Thereby, they limit frequently used chronosequence approaches. Jointly, disturbances and landscape heterogeneity, e.g. material properties and local water supply, produce spatial vegetation patterns (Burga et al., 2010;Turner and Chapin, 2005), which have however been barely investigated on lateral moraine slopes and are therefore poorly understood.

Geomorphic research investigates the occurrence of geomorphic processes and related landforms following glacier retreat in the paraglacial concept. Comparable to ecologic studies, terrain age was also identified as main control for lateral moraine slopes. Immediately following glacier retreat, melting dead ice in moraines melt triggers landsliding and debris flows (Ewertowski and Tomczyk, 2015; Lukas et al., 2012; Schomacker, 2008). With increasing terrain age, these processes are replaced by gullying, associated with debris flows and water soil erosional processes (Ballantyne and Benn, 1994; Curry et al., 2006; Mercier et al., 2009). Sediment texture and moisture were identified as further important controls for lateral moraine slope modification (Feuillet and Mercier, 2012; Jäger and Winkler, 2012; Teysseire, 2006). Paraglacial adjustment is seen as completed when gullying stops (Curry et al., 2006) or vegetation stabilizes the slopes (Ballantyne, 2002b; Matthews et al., 1998). However, recent research suggested that paraglacial adjustment continues under vegetation cover through solifluction processes (see Chapter 5). Thus, for paraglacial adjustment, neither the role of vegetation colonization and succession nor of solifluction processes is completely understood. In order to improve the understanding of paraglacial adjustment, the extent of different geomorphic processes and landforms and their spatial patterns, as well as their linkage to vegetation development and patterns, need to be investigated.

So far, few studies jointly investigated vegetation succession and paraglacial adjustment dynamics in glacier forelands in a biogeomorphic approach (Cowie et al., 2014; Eichel et al., 2013, 2016; Klaar et al., 2015). Yet, for lateral moraine slopes, this research could already show that vegetation succession not only responds to geomorphic disturbances, but ecosystem engineer species actively control geomorphic process occurrence (Eichel et al., 2016). Once magnitude or frequency of geomorphic processes decreases sufficiently, the ecosystem engineer *Dryas octopetala* can establish and, once it reaches a certain cover, actively change the geomorphic process regime from water soil erosional processes to bound solifluction. In this biogeomorphic feedback window, its dense mat not limits soil erosion by water and traps fine sediments and organic matter, while its strong roots stabilize the moraine slope. Thereby, establishment is facilitated for later successional species, who can replace ecosystem engineers in time as they are more competitive. This sequence of coupled geomorphic and ecologic development, first controlled by geomorphic processes, later by biogeomorphic feedbacks, and subsequently by ecological processes, has been called biogeomorphic succession (Corenblit et al., 2007, 2009). Biogeomorphic succession dynamics have been suggested for glacier forelands by Eichel et al. (2013). However, how geomorphic processes and successional stages are exactly linked to each other, and how their linkages produce spatial geomorphic and vegetation patterns, is not yet understood.

The aim of this study is to close the stated research gaps in ecology, geomorphology and biogeomorphology by integrating biogeomorphic permanent plot data with high resolution geomorphic and vegetation maps of lateral moraine slopes in Turtmann glacier foreland, Switzerland. The objectives of this chapter are:

1) To identify controls for paraglacial adjustment of lateral moraine slopes and determine related spatial geomorphic patterns;
2) To identify controls for vegetation succession and determine related spatial vegetation patterns on lateral moraine slopes; and
3) To develop a conceptual biogeomorphic model that links vegetation succession and paraglacial adjustment on lateral moraine slopes and explains related patterns in in time and space

8.2 Methods

8.2.1 Study site

The investigated lateral moraines, with a length of about 1900 m and a mean height of 120 m, are located along the eastern valley side of Turtmann glacier foreland, Valais Alps, Switzerland (Figure 8.1 A). They can be divided into a northern lateral moraine complex (Figure 8.1 A, B), which is made up by a steep proximal lateral moraine slope formed during the Little Ice Age, and a southern lateral moraine complex (Figure 8.1 A, C), consisting of several lateral moraine ridges dating from 1850 to 1925. Both 1920 and 1925 moraines possess a distinct distal slope. An inaccessible steep medial moraine located at the southern end close to the glacier tongue was not investigated in study, neither strongly human-modified moraine slopes between the northern and southern complex (see Figure 8.1 A).

Since the end of the Little Ice Age, the Turtmann glacier has been retreating (total 1479 m from 1885 to 2015), interrupted by re-advances in the 1920s and 1980s/1990s (Figure 8 E). Strongest melt-back with around 130 m occurred in 2002/2003 and 2014/2015 (Figure 8 E, Bauder and Ruegg, 2015). The lateral moraine slopes are characterized by active geomorphic processes, with debris flows, snow avalanches, gullying, debris sliding, interrill erosion, sheet wash, and rainsplash

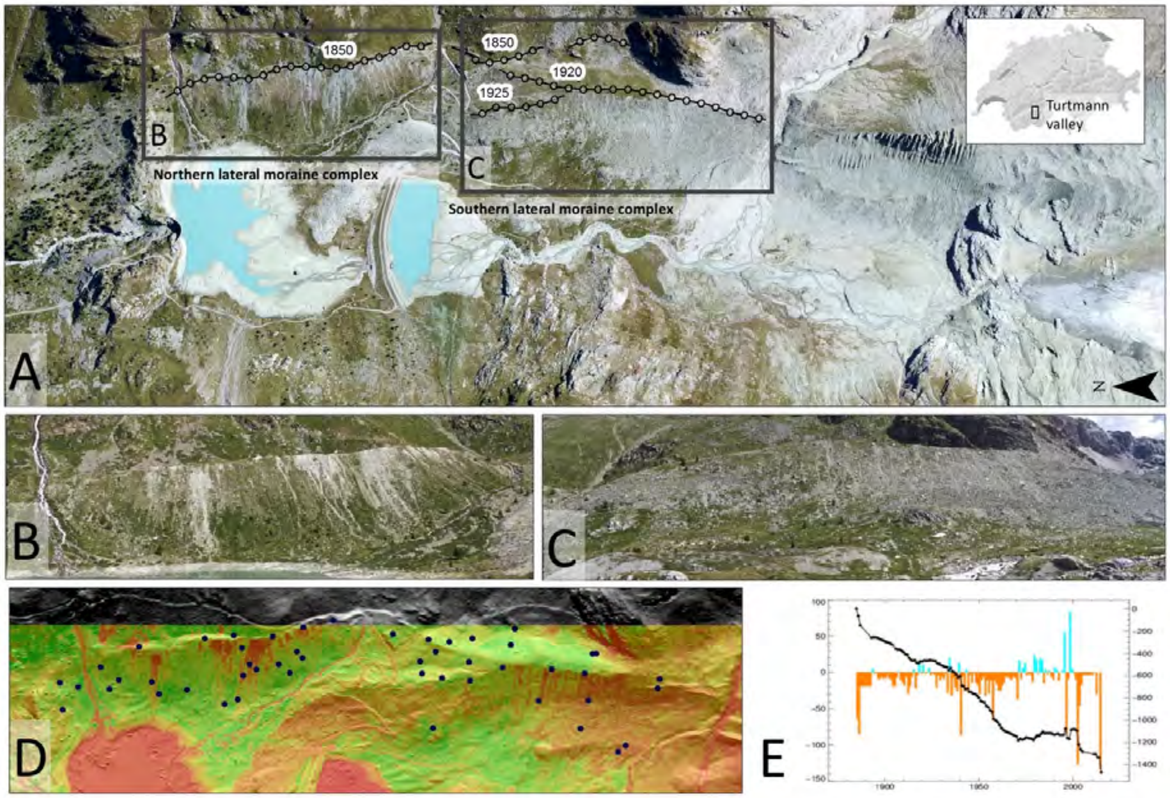

Figure 8.1: Overview of the study site. **A** Orthophoto of Turtmann glacier foreland, Valais Alps, Switzerland, taken in 2015. Area of the studied two lateral moraine complexes is marked and the age of their main moraines indicated. The inset map (right upper corner) shows the location of the Turtmann valley in Switzerland. **B** Northern lateral moraine complex, seen from opposite valley side. **C** Proximal slope of 1920/1925 lateral moraine in the southern lateral moraine complex, distal slope and 1850 lateral moraine are located behind the moraine ridge. **D** Location of permanent plots, shown on a Normalized Difference Vegetation Index (NDVI) image of the area (Swisstopo, 2011). **E** Glacier history of Turtmann glacier, showing retreating trend since 1885, interrupted by advances in 1920 and 1980 to 2000, and accelerated since 2000. Taken from Gletscherberichte, 1881–2016.

as main processes occurring in a glacial-denudative process domain and solifluction and cryoturbation in a glacial-cryogenic process domain (Eichel et al., 2013; Figures 8.1 B and C). Sediments making up the moraines comprise both siliceous and calcareous rocks, with paragneiss and schisty rocks from the Mischabel nappe, austroalpine gneiss and gabbro from the Dent Blanche nappe, Upper Penninic calcareous shales and greenstones from the Tsaté nappe and Middle Penninic marbles from the Barrhorn series (Bearth, 1980; Labhart, 2009). The latter originate mainly from the catchment of the Brunegg glacier, which was connected to the Turtmann glacier until 1934 (Gletscherberichte, 1881-2016; Otto, 2001). Accordingly, both siliceous and calcareous vegetation occurs, with pioneer vegetation characterized by *Linaria alpina*, dwarf shrub vegetation characterized by *Dryas octopetala* and dwarf willows (*Salix retusa,* *Salix reticulata, Salix serpyllifolia*) and shrub vegetation characterized by *Salix hastata* and other alpine *Salix* shrubs (Eichel et al., 2016). Human impact on the lateral moraines is

limited to hiking paths at the slopefoot of the northern and the crest of the southern lateral moraine impact. The moraine slopes are occasionally grazed by few goats and sheep.

8.2.2 Permanent plot sampling, data processing and statistical analysis

In 2013, 50 permanent plots were established on the lateral moraine slopes, and vegetation, geomorphic and further environmental properties recorded (see Eichel et al., 2016 for a detailed description). The derived basic data (see Table 4.1) was supplemented in 2015 with data on (i) material properties (including soil texture) (ii) soil properties and (iiI) thermal and snow regime of the permanent plots (see Table 8.1). The role for of these additional variables for species composition and the occurrence of geomorphic processes and landforms was assessed using a Non-metric multidimensional scaling (NMDS) with environmental fit of variables.

Soil sampling and analysis

To assess material and soil properties, soil was sampled next to each plot using 100 cm3 steel corers (sampling depth 4 cm) to gain undisturbed soil samples of identical volumes. Two replications were carried out for each plot. Overlying plant material and organic litter was sampled separately. Moist soil samples were weighed and subsequently air-dried. The soil water content was derived from the difference between moist and dry weight. Dried samples were sieved to 2mm. The proportion of material > 2mm and organic material based on their weights was noted (see Table 8.1). All further analyses refer to the fine earth (<2mm). Soil texture was determined by laser grain size analysis using a Retsch HORIBA LA-950 particle analyser (Fraunhofer Refractive Index Minerale). Organic material was removed from the sample prior to texture analysis by heating the samples to 430°C. The pH value was measured in a 0.01 M CaCl2 solution with a soil to solution ratio of 1:2.5. The C and N contents of the sieved and milled soils were determined by elemental analysis (ISO 10694, 1995). The content of CaCO3, as inorganic part of total C, was determined using a Scheibler-apparatus. The amount of organic C was derived by subtracting inorganic C from total C.

Table 8.1: Overview of additional data used for statistical analysis. The material dataset includes soil texture, while the soil dataset focuses on chemical soil properties. For a description of basic data, see Table 4.1 (from Eichel et al., 2016).

Dataset	Variable	Description
Material data	Soil moisture	Sample weight before air drying – sample weight after air drying.
	Share > 2mm	Percentage of material > 2mm in total sample, derived from weight
	Share < 2mm	Percentage of material < 2mm in total sample, derived from weight
	Clay	Percentage clay in sample material < 2 mm, derived from texture analysis (
	Silt	Percentage silt in sample material < 2 mm, derived from texture analysis
	Sand	Percentage sand in sample material < 2 mm, derived from texture analysis .
Soil data	Organic material	Share of organic material in total sample left after sieving, derived from weight
	CaCO3	Percentage of CaCO2 in sample material < 2 mm, derived from Scheibler carbonate analysis
	pH value	pH value of sample material < 2 mm
	N	Percentage of nitrogen (N) in sample material < 2 mm, derived from elemental analysis
	Organic C	Percentage of organic carbon (C) in sample material < 2 mm, derived from elemental analysis
	C/N	Ratio between organic carbon and nitrogen, derived from elemental analysis
Thermal and snow data	MAGST	Mean annual ground surface temperature (2014/2015)
	MWGST	Mean winter ground surface temperature (MWGST, December to February)
	Zero curtain	Duration of zero curtain conditions (2014/2015), calculated according to Schmid et al. (2012)
	Freeze-thaw cycles	Number of freeze-thaw cycles occurring (2014/2015)
	Snowdays	Number of days with snow cover, calculated according to Schmid et al. (2012)
Slope geomorphometry and position	Distal slope	Position on moraine slope facing away from the glacier

Thermal and snow regime

iButton miniature temperature loggers were used to assess snow and thermal properties in a depth of 5 cm from August 2014 to August 2015. Logger programming and data read out was performed using iAssist (Keller et al., 2010). Prior to data analysis in R, iButton data accuracy (given manufacturer value ±0.5 °C) was improved by using the zero-curtain period as 0° C reference. Mean annual ground surface temperature (MAGST), mean winter ground surface temperature (MWGST, December to February) and number of freeze-thaw cycles were derived. Duration of zero curtain conditions and snow cover were calculated using the standard deviation approach by Schmid et al. (2012). In addition, permanent plot location in relation to slope type (proximal vs. distal lateral moraine slope) was noted in field and added as a variable.

NMDS with environmental fitting of variables

NMDS is an ordination technique to assess how similar different objects (here: permanent plots) are in terms of certain variables, e.g. occurring species or geomorphic processes (Kruskal, 1964). It is well suited to deal with the non-normal distributed mixed data (McCune and Grace, 2002) from the permanent plots and has been applied successfully in previous biogeomorphic studies (Eichel et al., 2013, 2016). A detailed description of the NMDS technique is provided in Section 4.4.3.

In this study, two NMDS (*metaMDS*) with subsequent environmental fitting of variables (*envfit, factorfit*) were carried out with the R vegan package to assess controls on (i) occurrence of geomorphic processes and landforms and (ii) species composition. Three dimensions were calculated, using a maximum number of 100 runs to minimize stress and 1000 permutations to calculate the co-efficient of determination (r^2) and significance (p-value) (Kruskal, 1964). *MetaMDS* automatically rotates the ordination to show the main data gradient in the first axis. Prior to analysis, all species/geomorphic processes and landforms occurring less than twice in the datasets were removed.

For (i), the NMDS was performed with the dissimilarity index 'Euclidean', no standardization and no extended dissimilarities, for a geomorphic dataset (occurrence of geomorphic processes and landforms, geomorphic activity and process domains, see Table 4.1 and Eichel et al. 2016). Subsequently, environmental fitting was carried out for the datasets vegetation (reduced to cover of indicator species of vegetation classes from Eichel et al. 2016), biotic factors, terrain age (Table 4.1), material properties (Tables 4.1, 8.1), geomorphometry (Table 4.1, including distal slope variable), snow and thermal properties and soil properties (Table 8.1). For (ii), the NMDS was performed with the dissimilarity index ‘Bray-Curtis’ and Wisconsin double standardization for the vegetation dataset (species cover, see Table 4.1). Subsequently, environmental fitting was carried out for the datasets geomorphic processes and landforms, geomorphic activity, biotic factors, terrain age (Table 4.1) material properties (Tables 4.1, 8.1), geomorphometry (Table 4.1, including distal slope variable), snow and thermal properties and soil properties (Table 8.1). Only significant correlations (p-value < 0.05) are displayed in the NMDS illustration. Plot objects were overlaid with (i) geomorphic activity classes and (ii) vegetation classes from Eichel et al. (2016).

8.2.3 Geomorphic and vegetation mapping and map production

Geomorphic and vegetation mapping were carried out to identify geomorphic, material and vegetation patterns and their relationships. In field, mapping was executed in high resolution at a scale of 1:1000, using a 10 cm grid size orthophoto derived from an airplane flight in 2015 (Fulmar Sàrl, Neuchâtel, Switzerland, realized for BIMODAL project) as mapping base. This scale was chosen to record as many details as possible in field, while the resolution of the derived map is lower (Otto and Smith, 2013). Additionally, photographs were taken to illustrate mapped processes, landforms, landform elements and vegetation classes.

The purpose of the geomorphic map was to show geomorphic processes, landform and landform elements and material distribution on the lateral moraine slopes to understand their spatial occurrence and patterns. Geomorphic mapping was aided by previously produced, smaller scale geomorphic/geomorphic activity maps (Bedehäsing, 2007; Eichel et al., 2013; Grünewald, 2011). Occurrence of processes and landforms was noted, material was mapped according to the dominant grain size (fine material < 63 mm, stones > 63 – 200 mm, blocks >200 mm) in three classes, with complexes representing different grain size mixtures.

The purpose of the vegetation map was to show lateral moraine slope vegetation patterns related to vegetation succession dynamics, also including transitional stages. Vegetation mapping was based on three vegetation classes identified from permanent plot data by Eichel et al. (2016), with the indicator species *Linaria alpina* for vegetation class 1, *Dryas octopetala* for vegetation class 2 and *Salix hastata* for vegetation class 3 (see Section 4.5.1). During field mapping, vegetation classes were differentiated based on species co-occurrence and total vegetation cover into complexes to aid the subsequent identification of successional and transitional stages.

Digital maps were created in ArcGIS from the field maps in a scale of 1:2000, which is able to represent landform elements (Dramis et al., 2011) and vegetation succession patterns (Mueller-Dombois and Ellenberg, 2003). Some information, e.g. several geomorphic processes occurring in a small area, had to be generalized for integration into the smaller-scale maps (Otto and Smith, 2013). For the geomorphic map, the ArcGIS symbol set by Otto and Dikau (2004) for geomorphic mapping in high mountains was used and partly adapted. Separate maps were created for the northern and southern lateral moraine complex to improve handling of an otherwise overlong map. In addition, separate maps were produced for geomorphic processes and landforms and material to improve map clarity The material map was supplemented with glacier positions derived from a glacier stages map (1885 – 1964; Tscherrig, 1964) and orthophoto interpretation for later stages (cf. Eichel et al., 2013), while the vegetation map was supplemented with occurring trees (*Larix decidua, Pinus cembra*) mapped based on their visible shadow in the orthophoto. The accurateness of the produced maps was controlled in field in 2016 and maps were subsequently corrected where necessary.

8.3 Results

8.3.1 NMDS result for geomorphic dataset

The NMDS result shows that occurrence of geomorphic processes and landforms relates to *D. octopetala* cover along a main activity gradient (NMDS1) and to toposequence position and material properties along a second toposequence gradient (NMDS2), as described by Eichel et al. (2016) (Figure 8.2). Additional incorporated material, soil and snow and thermal variables follow these gradients. Material texture is associated to the main activity gradient (Figure 8.2 B), with high sand contents (r^2 = 0.12) relating to high geomorphic activity, while high silt (r^2 = 0.13) and clay (r^2 = 0.16) contents occur distal slopes (r2 = 0.29) with moderate to low activity of periglacial processes. Thermal properties relate to the toposequence position gradient (Figure 8.2 C), with most freeze-thaw cycles (r^2 = 0.12) occurring at crest positions, while highest number of snow days (r^2 = 0.18), and highest MWGST (r2 = 0.28) can be found in slopefoot positions. Additional incorporated soil properties relate to both gradients (Figure 8.2 D), high values of organic carbon (r^2 = 0.37), organic material (r^2 = 0.23), nitrogene (r^2 = 0.33) occur with no geomorphic activity related to both *D. octopetala* cover and slopefoot position, while high pH values (r^2 = 0.29) relate to both high geomorphic activity and crest positions. Terrain age is not significantly related to the occurrence of geomorphic processes and landforms.

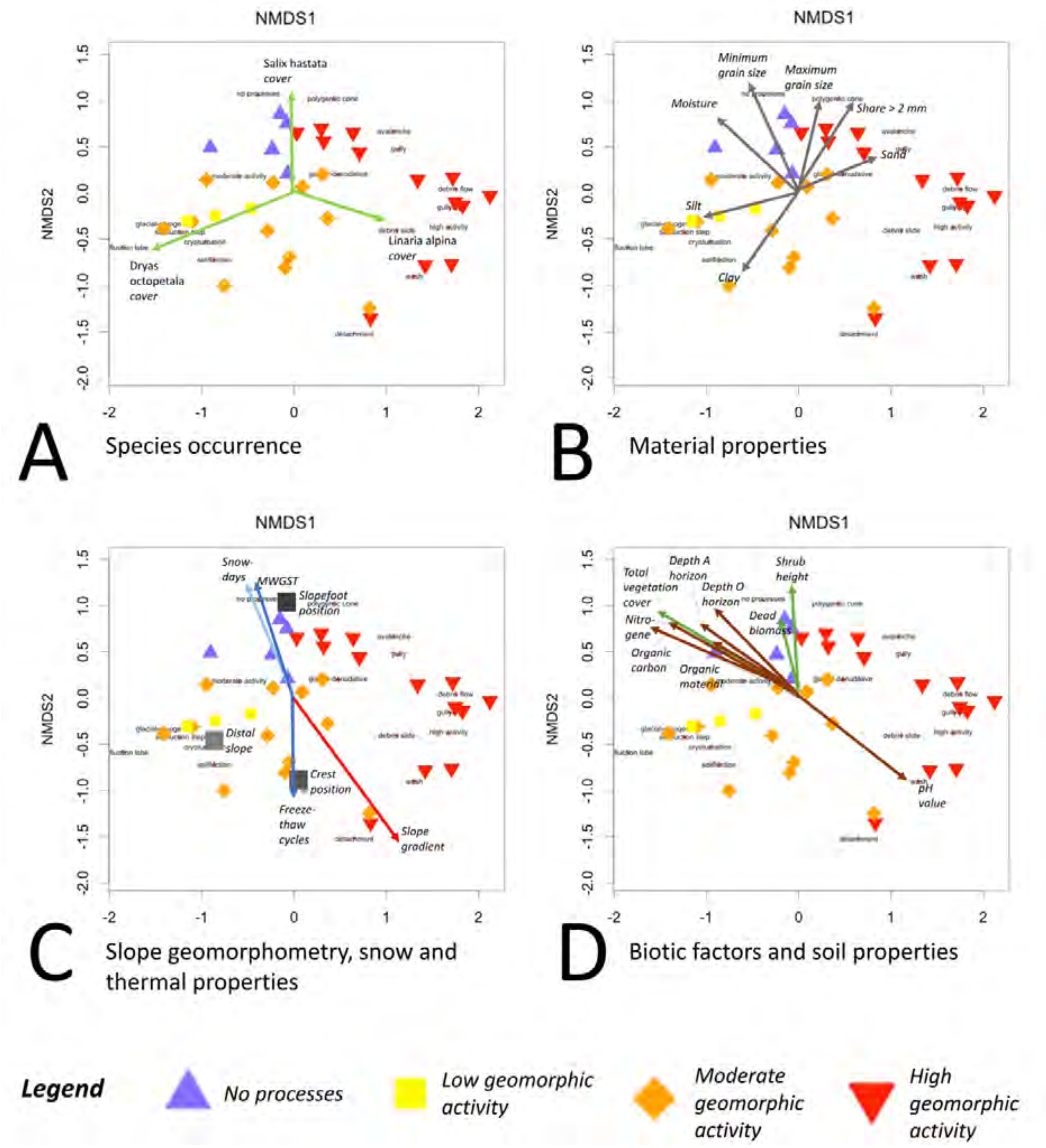

Figure 8.2: NMDS result for geomorphic dataset, showing the first two dimensions, overlay with geomorphic activity classes from Eichel et al. (2016). Arrows point in the direction of maximum variable change in the underlying geomorphic data. Only significant variables ($p < 0.05$) are displayed. **A** Environmental fitting of indicator species. **B** Environmental fitting of material properties. **C** Environmental fitting of slope geomorphometry, snow and thermal properties. **D** Environmental fitting of biotic factors and soil properties. Stress = 16.37

8.3.2 NMDS results for vegetation dataset

The NMDS result for the vegetation dataset shows that species composition is related to a geomorphic activity/ecosystem development gradient and to a second geomorphometry gradient

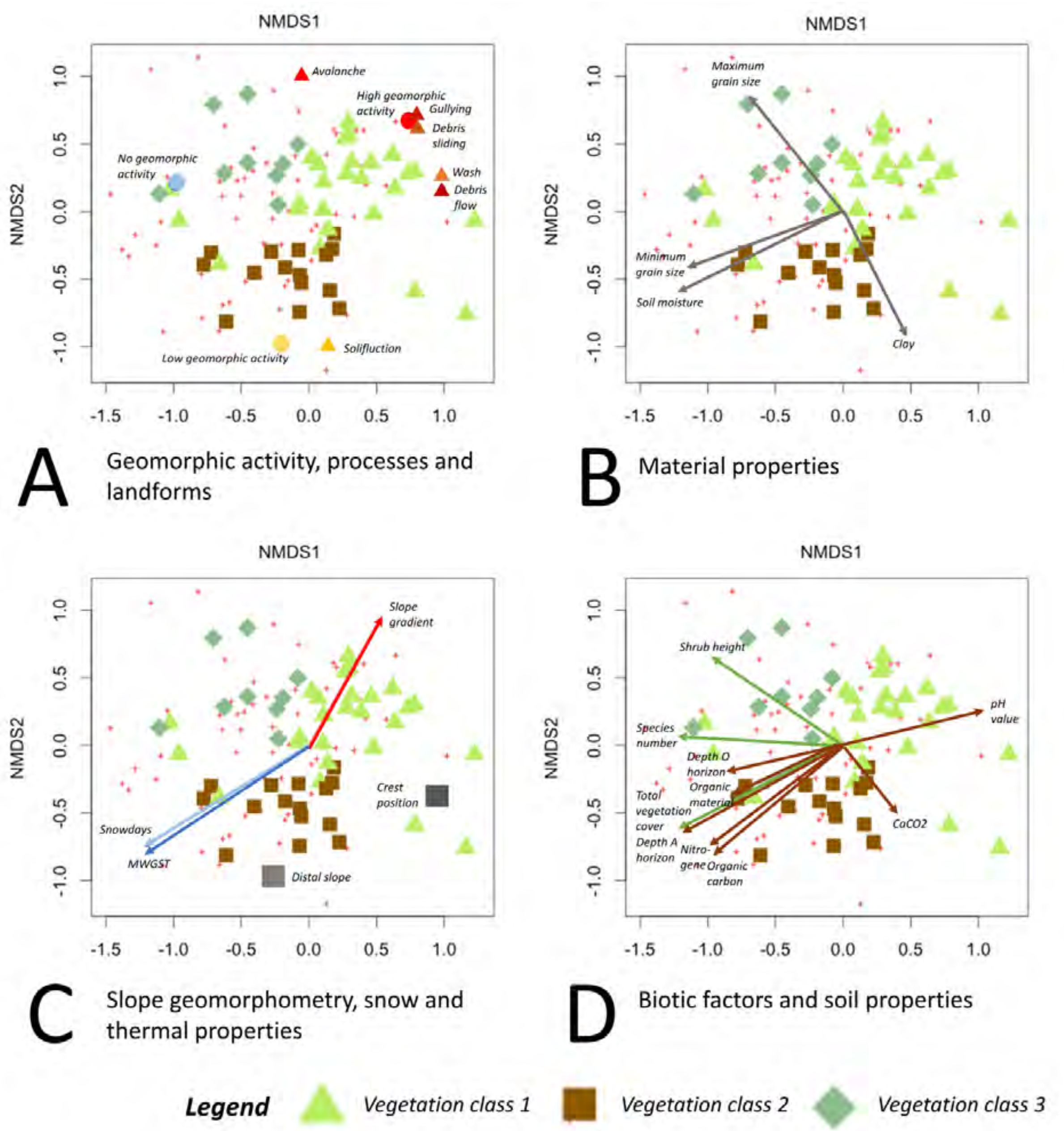

Figure 8.3: NMDS result for vegetation dataset, showing the first two dimensions, overlay with geomorphic activity classes from Eichel et al. (2016). Arrows point in the direction of maximum variable change in the underlying geomorphic data. Only significant variables ($p < 0.05$) are displayed. **A** Environmental fitting of geomorphic activity, processes and landforms. **B** Environmental fitting of material properties. **C** Environmental fitting of slope geomorphometry, snow and thermal properties. **D** Environmental fitting of biotic factors and soil properties. Stress = 3.6

(slope gradient, toposequence position, type), both relating to NMDS1 and NMDS (Figure 8.3). In addition, vegetation classes strongly relate to geomorphic activity and occurring geomorphic processes, as previously described by Eichel et al. (2016). Additional incorporated material, soil and snow and thermal variables follow the main gradients. Snow and thermal and soil properties relate to the ecosystem development gradient with high pH values (r^2 = 0.48) relating to vegetation class 1, while high nitrogen (r^2 = 0.63), organic material (r^2 = 0.36) and organic carbon (r^2 = 0.67) values, as well as longest snow cover duration (r^2 = 0.18) and highest MWGST (r^2 = 0.26) relate to both vegetation class 2 and 3 (Figure 8.3 C, D). Material properties relate to both ecosystem development and geomorphometry gradient (Figure 8.3 B), with highest $CaCO_3$ (r^2 = 0.16) and clay content (r^2 = 0.15) occurring at crest positions (r^2 = 0.22) and distal slopes (r^2=0.34) with vegetation class 1 and 2, while soil moisture (r^2 = 0.25) is related to most pronounced ecosystem development with high vegetation cover.

8.3.3 Geomorphic map

The geomorphic map shows that geomorphic patterns of process and landform occurrence are related to slope toposequence, slope type and slope length. At long proximal slopes in both northern and southern lateral moraine complex, erosion by active mass movement and water soil erosional processes dominates at at the upper moraine slope and crest, while their foot is characterized by depositional landforms (Figures 8.4, 8.5). Periglacial processes occur independently of slope position on these slopes. At distal and shorter proximal slopes of the southern lateral moraine complex, periglacial processes dominate. Rockfall and snow avalanches originating at adjacent valley slopes above of the lateral moraines influence subjacent parts of the lateral moraine slopes. A description of the mapped process domains, including mapped geomorphic processes, landforms, landform elements and criteria for their recognition, is given in Table 8.2. For location of the 1850s moraine in the northern lateral moraine complex and 1850s, 1920s and 1925s moraines in the southern lateral moraine complex, to which this section refers, see Figure 8.1A.

Long proximal slopes

Mass movement and water soil erosional process are the most important processes at upper moraine slope and crest areas of the long proximal slopes of the 1850s lateral moraine in the northern and the long 1920s and 1925s proximal slopes in the southern lateral moraine complex (Figure 8.1A, 8.4, 8.5). Dominant processes include debris flows, landsliding (slumping, debris sliding, single clast fall) and water soil erosional processes, which occur mostly in complex initiation areas along the moraine crests (Figure 8.6 C, D, E). Inter-gully walls often encompass these areas, mainly at the northern lateral moraine complex (Figure 8.4). In addition, tension cracks are an important landform element at the upper slopes (Figure 8.6 B), often occurring below vegetation visible in the orthophoto. Especially at the southern lateral moraine complex, moraine ridges are sometimes characterized by cryoturbation from the periglacial process domains, which also occurs at inter-gully walls in the northern lateral moraine complex. While mass movement and soil erosional processes often occur jointly at selective areas of the northern upper lateral moraine slope (Figure 8.4), they occur along the the entire upper proximal 1920s lateral moraine slope (Figure 8.5). Here, a complex step, created by water soil erosional and mass movement processes, marks the transition from a flatter crest area to a steep upper slope. Debris flows dominate in the central part of the upper slope, while landsliding, mostly debris sliding, dominates in its southern part. The northern proximal 1925 lateral moraine slope is dominated in its upper part by unbound and bound solifluction between several smaller moraine ridges (Figure 8.5). An intermittently active fluvial channel separates the 1920s distal and 1850s proximal slope, which formed an erosional step at the eastern slopefoot of the 1850s proximal slope. At the northern lateral moraine complex, bound solifluction dominates between complex initiation areas at upslope positions and produces interwoven turf-banked terraces, mostly south of an artificial active fluvial channel (Figure 8.4).

Complex channels, formed by both debris flows and water soil erosional processes (Figure 8.6 F), link upslope geomorphic processes with downslope depositional areas. At the northern lateral moraine, these are often lined by debris flow levees (Figure 8.4). Here, some debris flow heads reworked by solifluction (Figure 8.6 H) can also be found in midslope positions in the central part, together with solifluction processes, turf-banked terraces and ploughing boulders (Figure 8.6 G). A sequence of smaller moraine ridges characterizes the northernmost midslope and lower slope of the northern lateral moraine complex (Figure 8.4), as well as the northernmost proximal slope of the 1920s lateral moraine in the southern lateral moraine complex (Figure 8.5). Between these, unbound solifluction with occasional turf-banked terraces occurs.

At both northern and southern lateral moraine complex, the slopefoot is characterized by complex cones, often made up by debris flow heads. At the northern lateral moraine complex, these are often reworked by solifluction processes, which is indicated by overhanging fronts or lobate bulges of the front (Figure 8.4). Several lobate forms occurring at the slopefoot of the northern lateral moraine complex show distinct features of turf-banked solifluction lobes (cf. Table 8.2). Additionally, turf-banked terraces occur here and a recent fine material dominated debris flow deposit dating from 2015. At the southern lateral moraine, debris flow heads and debris flow fine material deposits (Figure 8.6 K, L) occur at the foot of the central, debris flow dominated 1920s.

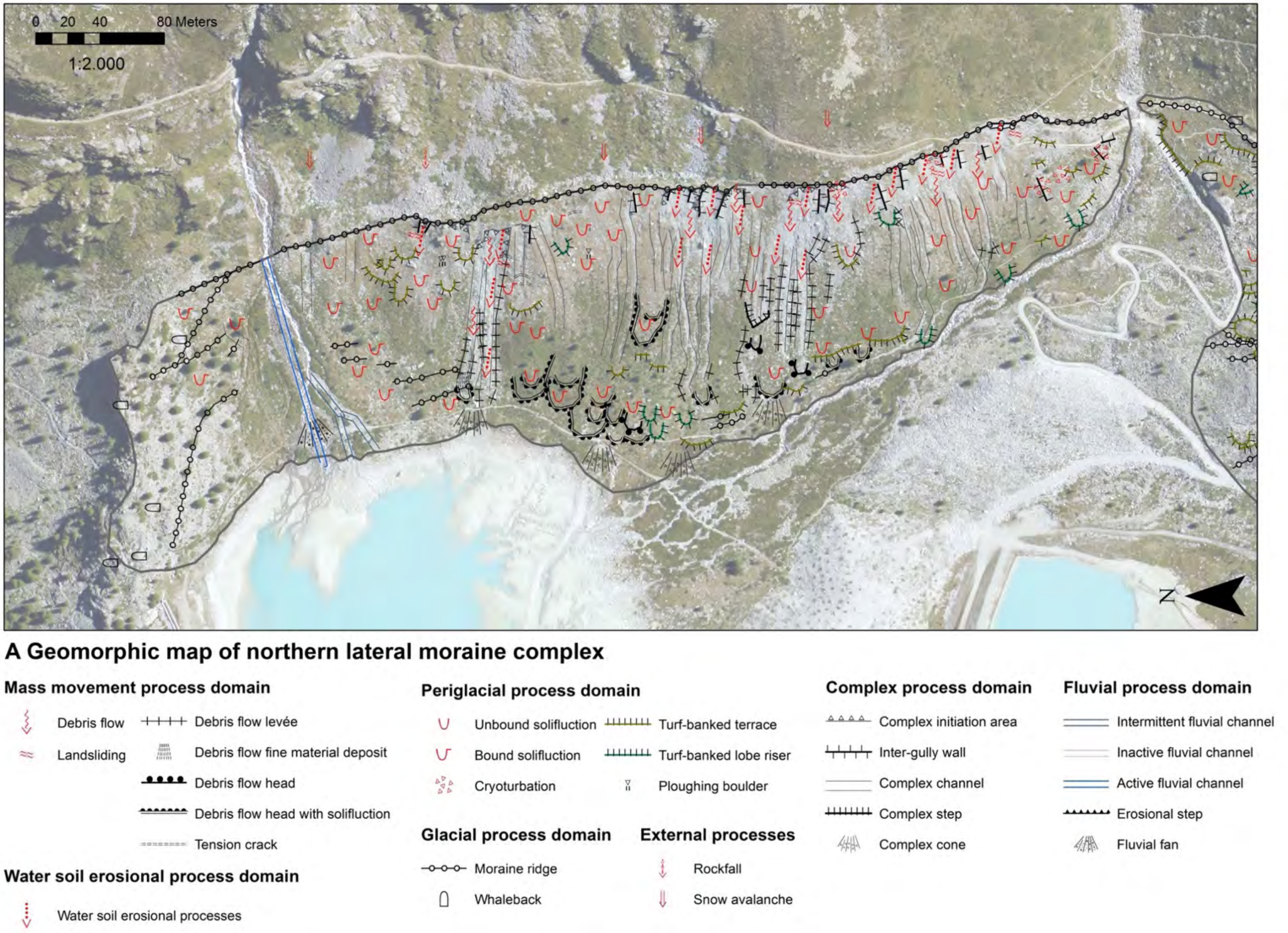

Figure 8.4: Geomorphic map of northern lateral moraine complex. A larger version of this map in the indicated scale can be found in the attachment.

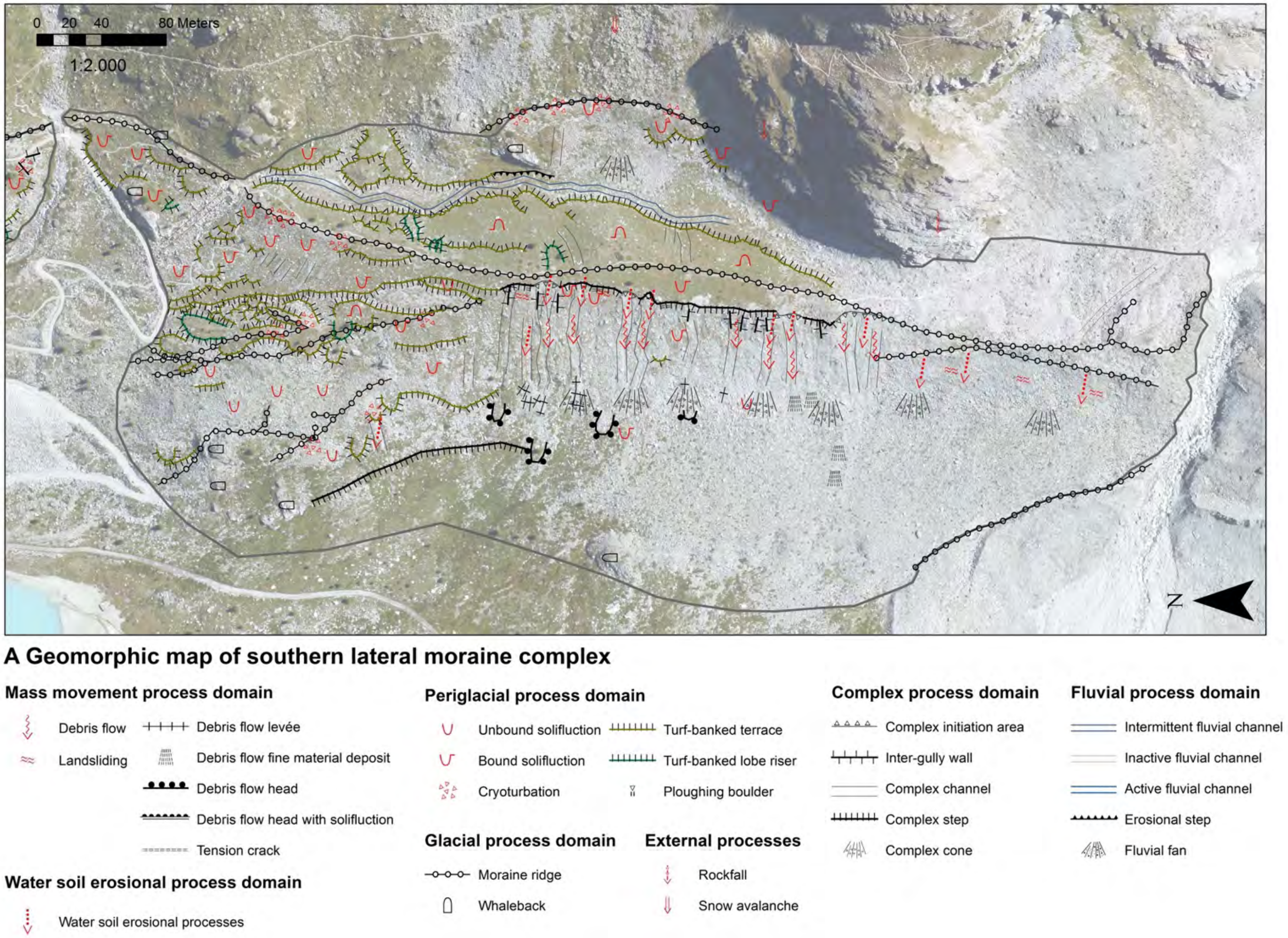

Figure 8.5: Geomorphic map of southern lateral moraine complex. A larger version of this map in the indicated scale can be found in the attachment.

Table 8.2: Description of mapped geomorphic process domains with associated processes, landforms and landform elements.

Process domain	Process	Landform/landform element	Description
Mass movement	Debris flow		Mixture of fines, larger sediment and water moving downslope in a Bingham flow, triggered by intensive rainfall or rapid snowmelt (Dikau, 2004; Hungr, 2005; Iverson, 2005)
		Debris flow levée	Linear deposition of debris along the side of a debris flow track
		Debris flow fine material deposit	Deposition of solely fine material, either due to overtaking of boulder front or initial fine material composition, mostly at slopefoot but can occur in all slope positions (Figure 8.6 L)
		Debris flow head	Debris flow deposition consisting of a boulder front with finer material behind it, often in a lobate shape, occurring mostly at slopefoot but can occur in all slope positions (Figure 8.6 K)
		Debris flow head with solifluction	Debris flow head with indications of reworking by solifluction, e.g. lobate bulges modifying the original shape or an overhanging front (Figure 8.6 H)
	Landsliding		Downward movement of slope material resulting from a failure along a well-defined shear plane (Dikau, 2003), includes fall or slide of individual clasts (Figure 8.6 D), translational debris sliding and rotational slides (slumps)
	Debris flow/landsliding	Tension crack	Cracks developing at landslide and debris flow initiation areas from unloading by previous material removal, indicate new potential shear planes (Figure 8.6 B)
Periglacial	Cryoturbation		Soil movement due to frost action (Prick, 2004)
	Bound solifluction		Slow downslope movement of soil mass due to diurnal and annual frost creep and gelifluction under vegetation cover
		Turf-banked lobe riser	Vegetation-covered riser of an isolated, tongue-shaped solifluction lobe (Van Everdingen, 2005). In this study, the existence of a distinct lobe front and at least one lateral riser served to distinguish solifluction lobes from solifluction terraces and debris flow heads (Figure 8.6 H)
		Turf-banked terrace	Vegetation-covered, straight or lobate step or bench, indicating differences in solifluction movement rates (Van Everdingen, 2005) (Figure 8.6 I)
	Unbound solifluction		Slow downslope movement of soil mass resulting from freeze-thaw processes (needle-ice creep, diurnal and annual frost creep and gelifluction) (Matsuoka, 2001)
	Ploughing boulder		Boulder moving faster than surrounding material transported by solifluction, pushing up a mound at their downslope site (Ballantyne, 2001; Berthling et al., 2001) (Figure 8.6 G)

Table 8.2 (continued): Description of mapped geomorphic process domains with associated processes, landforms and landform elements.

Process domain	Process	Landform/landform element	Description
Water soil erosional	Water soil erosional processes		Processes eroding slope material by running water, including rain splash, sheet wash, interrill erosion, rill erosion and gully erosion, excluding fluvial processes (Fullen and Catt, 2004) (Figure 8.6 E)
Complex			Polygenetic landforms and landforms elements created or modified by multiple processes and their interplay
		Complex initiation area	Steep, concave upslope area where mass movement and water soil erosional processes initiate (Figure 8.6 C)
		Complex channel	Channel produced by debris flows and soil erosional processes (Figure 8.6 F)
		Complex cone	Polygenetic depositional cone formed by mass movement and soil erosional processes, can be affected by periglacial processes
		Complex step	Steep feature at a slope created by mass movement and water soil erosional processes
		Inter-gully wall	Ridge-like landforms produced by a combination of debris flows and soil erosional processes (‚gullying') between gully channels
Fluvial			Processes and landforms associated with running water in a river bed/channel (Gregory, 2003)
		Active fluvial channel	River channel continuously active
		Intermittent fl. channel	River channel intermittently active
		Inactive fl. channel	River channel not active during observational period
Glacial			Landforms created or shaped by glacier ice
		Moraine ridge	Uppermost linear feature of a glacier ice sediment deposition (moraine)
		Roche moutonnée (whaleback)	Bedrock outcrops shaped by glacier ice with a steep side away from the ice movement direction
External processes			Processes originating outside the lateral moraine area
		Rockfall	Fall of rock debris from rock faces
		Snow avalanche	Downslope movement of snow mass, depositing sediments and organic material in avalanche cones at slopefoots. Mapped based on visible snow avalanche deposits and occurrence of avalanche sediments on larger boulders (Luckman, 1977)

Figure 8.6: Illustration of geomorphic processes and landforms on the lateral moraine slopes. **A** Location of process/landform. **B** Tension crack with *Salix serpyllifolia* root. **C** Complex initiation area. **D** Initiation of individual clast fall at moraine crest. **E** Interrill erosion in complex initiation area. **F** Complex channels. **G** Ploughing boulder. **H** Debris flow head reworked by solifluction. **I** Turf-banked solifluction terrace. **J** Turf-banked solifluction lobe. **K** Debris flow head. **L** Debris flow fine material deposit.

proximal lateral moraine slope. Debris heads are occurring less frequently than at the northern lateral moraine complex and indications for reworking by solifluction could not be seen.

Distal and short proximal slopes

Bound solifluction dominates at the distal and short proximal 1920s, 1925s and 1850s moraine slopes in the southern lateral moraine complex (Figures 8.4, 8.5). Large and distinct turf-banked terraces characterize these slopes (Figure 8.6 I), partly interwoven or overlaid by turf-banked solifluction lobes (Figure 8.6 J; see Chapter 5).

External processes

At the northern lateral moraine complex, snow avalanches originating at the adjacent eastern valley slopes above the moraine contribute to the development of complex slopefoot cones, while external rockfall created a complex cone at the proximal 1850s moraine slope in the southern lateral moraine complex

8.3.4 Material and glacier history map

The material and glacier history map shows that material distribution is patchy on the lateral moraine slopes, with smaller patches and a higher proportion of fine material at the northern lateral moraine complex, while blocky and stony material dominated at the southern lateral moraine complex in large patches (Figures 8.7, 8.8). A description of the mapped material classes is given in Table 8.3.

Material distribution at the northern lateral moraine complex

At the northern lateral moraine complex, material distribution is linked to toposequence position, with fine material (F2, with stones and blocks) dominating at the moraine crest, upper slope and moraine foot and along longitudinal pathways (Figure 8.7). Stony material occurs in all slope positions, with stony material with fines and stones (S3) dominating at the northern and central part, while stones with fines (S1) dominate at the southern part. Blocky material (mostly B2 with fines and stones) occurs in midslope position and in the northern bedrock bar area (B1 with stones) of the lateral moraine complex. Material distribution represents a patchy material mosaic, with very small fine material patches (F1) occurring especially in the southern part.

Material distribution at the southern lateral moraine complex

At the southern lateral moraine complex, fine material mostly occurs at the southern proximal 1920s moraine slope, also showing a patchy distribution at the central moraine slope area (F2), while fines with stones dominate (F1) at the southernmost upper slope (Figure 8.8). Very small fine material patches (F1) also occur at some crest positions and at a hilly feature (F2) between

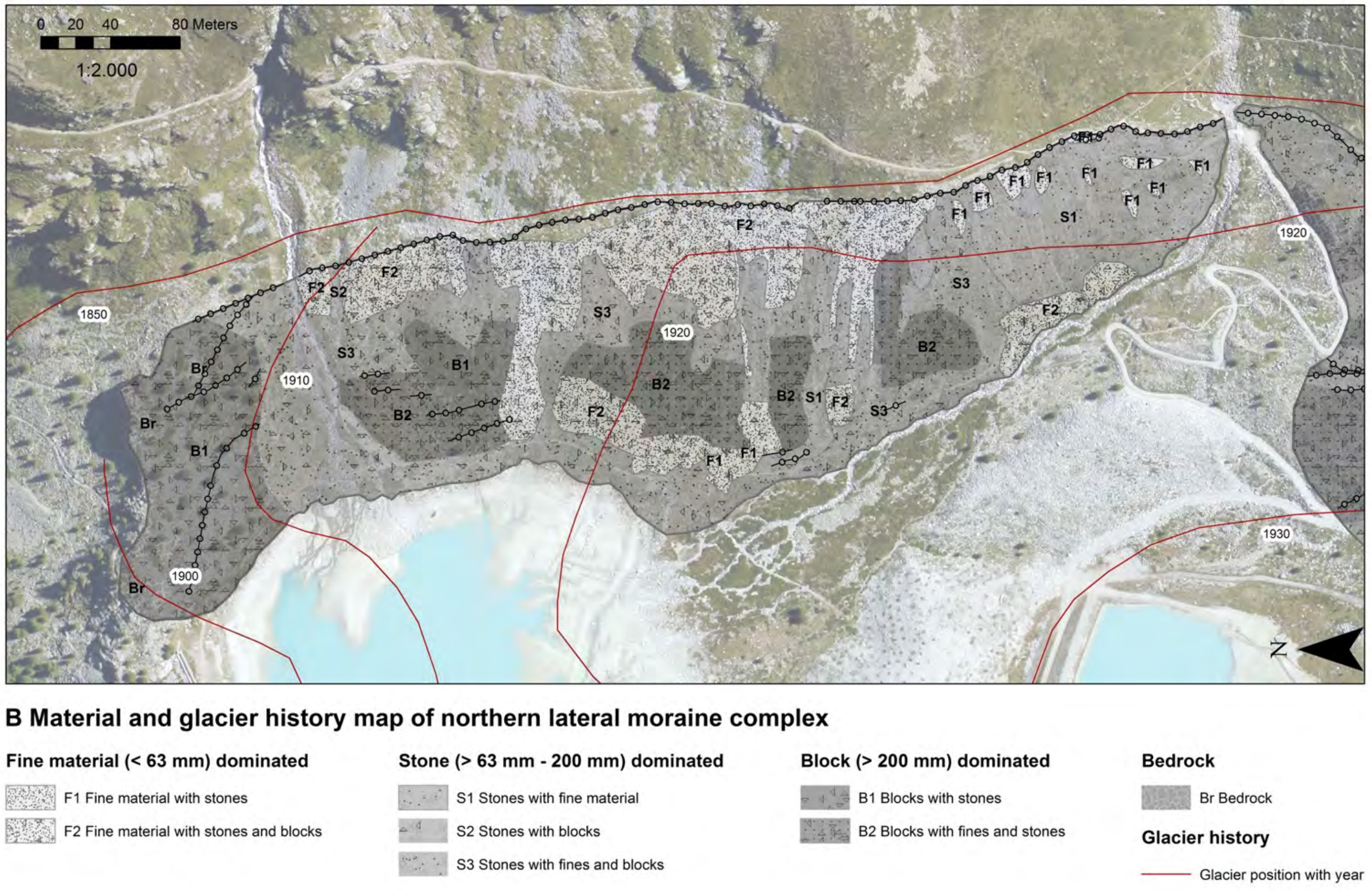

Figure 8.7: Material and glacier history map ot the northern lateral moraine complex. A larger version of this map in the indicated scale can be found in the attachment.

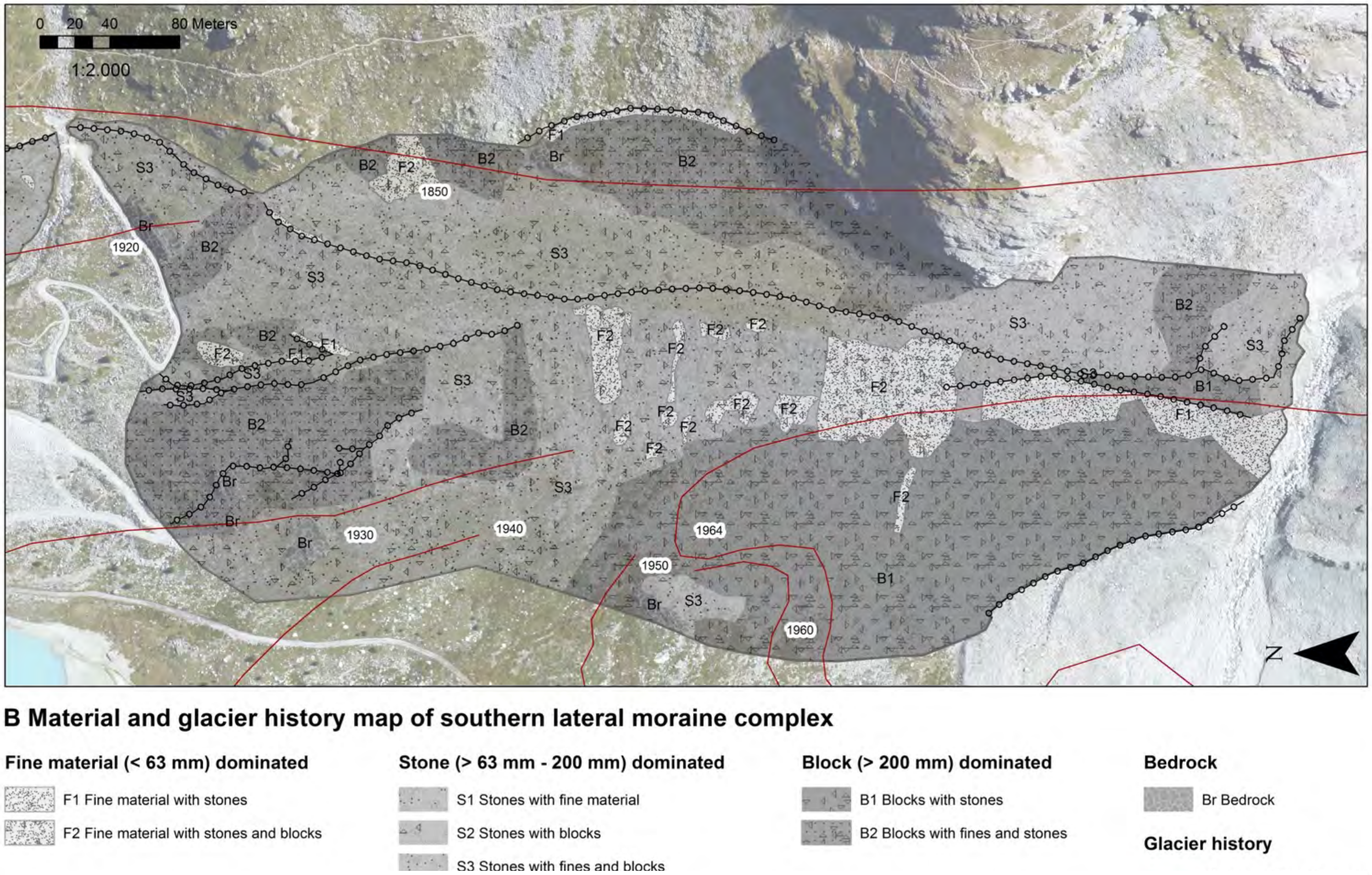

Figure 8.8: Material and glacier history map ot the southern lateral moraine complex. A larger version of this map in the indicated scale can be found in the attachment.

Table 8.3: Description of mapped material classes.

Dominant grain size	Material class	Complex	Description
Fines (≤ 63 mm)	F1	Fine material with stones	Mainly fine material interspersed with stones, very few blocks
	F2	Fine material with stones and blocks	Mainly fine material with interspersed stones and blocks
Stones (>63 – 200 mm)	S1	Stones with fine material	Stony material interspersed with fine material, very few blocks
	S2	Stones with blocks	Stony material interspersed with blocks, very few fines
	S3	Stones with fine material and blocks	Stony material interspersed with fine material and blocks
Blocks (> 200 mm)	B1	Blocks with stones	Blocky material interspersed with stones, very few fine material
	B2	Blocks with stones and fines	Blocky material interspersed with stones and fine material

the 1850s and 1920s moraine ridges. Blocky material dominates at the long, flat slopefoot of the southern proximal 1920s moraine slope (B1), the crest and midslope areas of the northern 1925s proximal and distal moraine slope (B2) and the proximal slope of the 1850s moraine (B2). In additional, two elongate blocky material patches (B2) exist at the northern proximal slope of the1920s moraine and at the most southern area of the complex. Stony material (mostly S3) dominates at the southern lateral moraine complex and occurs in all slope positions, especially to both sides of the 1920s moraine ridge.

Displayed glacier positions show that the ice retreated both downslope from east to west and along the lateral moraine length from north to south. No obvious relationship between material patterns and glacier history can be seen.

8.3.5 Vegetation map

The vegetation map shows a patchy mosaic of vegetation classes at both northern and southern lateral moraine complex, with smaller patch sizes and a higher heterogeneity at the northern lateral moraine complex and larger patches at the southern lateral moraine complex. Table 8.4 gives an overview and description of the mapped vegetation classes and complexes, while Figure 8.11 provides exemplary images for each of them.

Vegetation patterns at the northern lateral moraine complex

Vegetation patterns at the northern lateral moraine complex show a very fine-patterned mosaic of all vegetation classes, which is related to toposequence position (Figure 8.9).

Vegetation class 1 (with *Linaria alpina*, Figure 8.11 A) mainly occurs at upper and midslope positions and in elongated patches following the slope gradient. While vegetation class 1.1 with *Saxifraga aizoides* dominantly occurs at crest positions, vegetation class 1.2 with dwarf shrubs occurs at both crest and midslope positions, often bordering class 1.1 patches. Vegetation class 1.4 with Salix shrubs occurs in midslope and slopefoot positions. Vegetation class 1.3 with *Hernaria alpina* occurs in very small patches at the southern slope.

Vegetation class 2 (with *Dryas octopetala*, Figure 8.11 B), especially class 2.6 with *Festuca* spp. grassland, is dominating the slope. Class 2.6 occurs in all slope positions, often in larger patches separating vegetation class 1 patches. Class 2.5 with *Elyna myosuroides* mainly occurs in slopefoot positions and once at the northern crest, while vegetation class 2.7 with Salix shrubs occurs only in one patch at a midslope position. Classes 2.1 to 2.4 also occur sparsely, with vegetation class 2.4 with *Salix* dwarf shrubs occurring in midslope positions, while classes 2.1 and 2.2 with *Bartsia alpina* occur in small patches at crest and slopefoot positions.

Vegetation class 3 (with *Salix hastata*, Figure 8.11 C) dominates at the northern slope part and in midslope positions. Class 3.1 with *Salix* shrubs (cover < 50%) occurs in a single larger patch at the northernmost part of the slope, while class 3.2 with *Salix* shrubs (cover > 50%) occurs in midslope positions and along the artificial creek at the northern slope part. Classes 3.3. and 3.4 with dwarf shrubs and 3.5 with *Festuca* spp. grassland often border class 3.1and 3.2 patches in midslope positions or occur at the slopefoot.

Trees (*Larix decidua, Pinus cembra*; Figure 8.11 D) occur dominantly at slopefoot and midslope positions in class 2.5, 2.6 and 3.4 patches, and at the northern slope part with vegetation class 3.

Vegetation patterns at the southern lateral moraine complex

At the southern lateral moraine complex, patch sizes are larger and with vegetation class occurrence mainly differs between distal and proximal slopes (Figure 8.10).

Vegetation class 1 occurs almost exclusively at the southern 1920s proximal moraine slope, where class 1.4 with Salix shrubs makes up a large patch at it southernmost part, while a mosaic of class 1.1 and 1.2 patches makes up the more northern part. In addition, a small patch of class 1.2 occurs at the southern proximal 1925s moraine slope. Very small patches of class 1.3 occur at the 1850s, 1920s and 1925s moraine ridges.

Vegetation class 2 dominates the distal 1920s, 1925s, northern proximal 1920s and 1850s slope and occurs also in some parts of the 1925s proximal slope. Vegetation class 2.1 occurs in larger

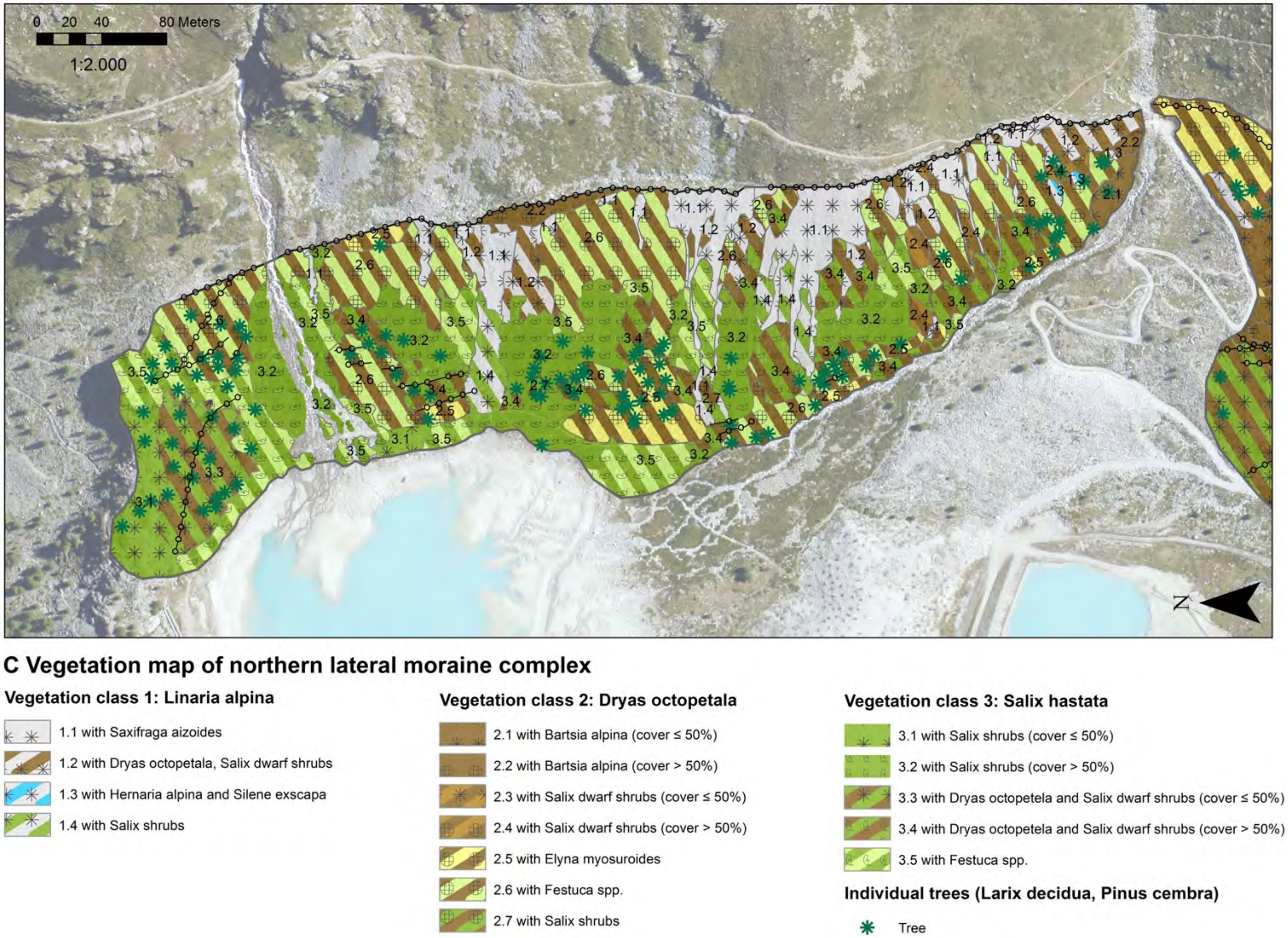

Figure 8.9: Vegetation map of the northern lateral moraine complex. A larger version of this map in the indicated scale can be found in the attachment.

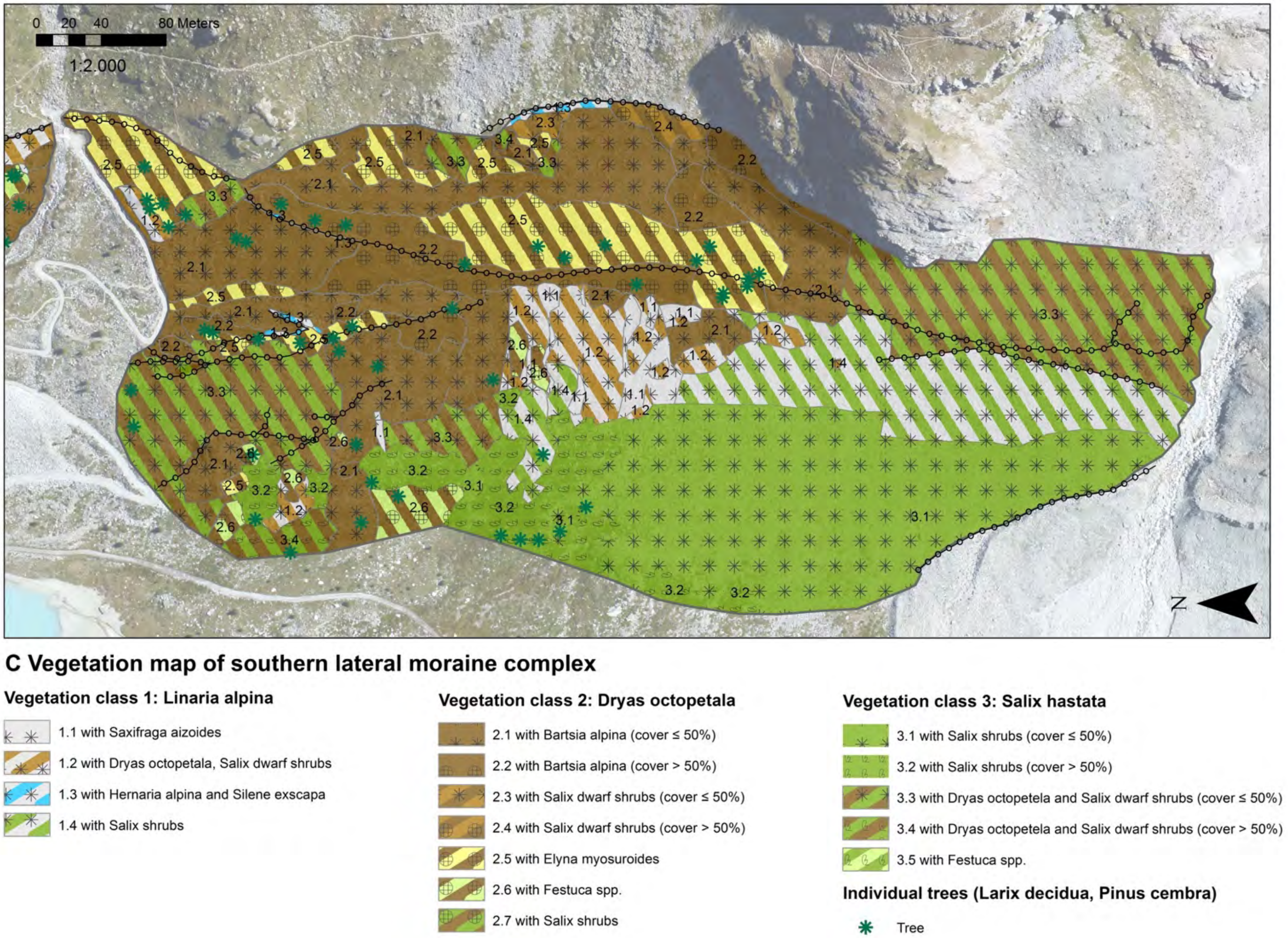

Figure 8.10: Vegetation map of the southern lateral moraine complex. A larger version of this map in the indicated scale can be found in the attachment.

Table 8.4: Overview and description of mapped vegetation classes and associated complexes.

Vegetation class	Dominant species	Complex		Description
Vegetation class 1 Indicator species: *Linaria alpina*	*Linaria alpina*	1.1	with *Saxifraga aizoides*	Dominant species *L. alpina* occurring together with *Saxifraga aizoides* with a very low cover
		1.2	with *D. octopetala, S. retusa, Salix serpyllifolia, Salix reticulata*	Dominant species *L. alpina* occurring together with dwarf shrub species seedlings with a low cover
		1.3	with *Hernaria alpina, Silene exscapa*	Dominant species *L. alpina* occurring together with *Hernaria alpina* and *Silene exscapa* with a very low cover
		1.4	with *Salix spp. (Shrubs)*	Dominant species *L. alpina* occurring together with shrub *Salix* spp. seedlings
Vegetation class 2 Indicator species: *Dryas octopetala, Bartsia alpina, Salix retusa, Pinus cembra*	*Dryas octopetala*	2.1	with *B. alpina (cover ≤ 50%)*	Patchy *D. octopetala* mat with *B. alpina* covering less than 50% of the area
		2.2	with *B. alpina (cover > 50%)*	Dense *D. octopetala* mat with *B. alpina* covering often nearly 100% of the area
		2.3	with *S. retusa, S. serpyllifolia, S. reticulata (cover ≤ 50%)*	Patchy *D. octopetala* and *Salix* dwarf shrub occurrence, covering less than 50% of the area
		2.4	with *S. retusa, S. serpyllifolia, S. reticulata (cover > 50%)*	Dense *D. octopetala* mat interspersed with *Salix* dwarf shrubs, covering more than 50% of the area
		2.5	with *Elyna myosuroides*	*D. octopetala* mat mixed with *E. myosuroides* grassland, very high cover
		2.6	with *Festuca* spp.	*D. octopetala* mat mixed with *Festuca* spp. grassland, very high cover
		2.7	with *Salix spp. (shrubs)*	*D. octopetala* mat interspersed with *Salix* spp. shrubs, very high cover
Vegetation class 3 Indicator species: *Salix hastata*	*Salix hastata*	3.1	with *Salix foetida, Salix helvetica (cover ≤ 50%)*	*Salix* shrub vegetation, covering less than 50% of the area
		3.2	with *S. foetida, S. helvetica (cover > 50%)*	*Salix* shrub vegetation covering more than 50% of the area with sparse understorey
		3.3	with *D. octopetala*, *S. retusa, S. serpyllifolia, S. reticulata (cover ≤ 50%)*	*Salix* shrub vegetation with interspersed with dwarf shrubs, covering less than 50% of the area
		3.4	with *D. octopetala*, *S. retusa, S. serpyllifolia, S. reticulata (cover > 50%)*	*Salix* shrub vegetation with dwarf shrubs in understory, very high cover
		3.5	with *Festuca* spp.	*Salix* shrub vegetation with interspersed with *Festuca* spp. grassland, very high cover

Figure 8.11: Illustration of vegetation classes with dominant species and associated complexes. **A** Vegetation class 1 with *Linaria alpina* as dominant species and complexes 1.1, 1.2, 1.3, 1.4. **B** Vegetation class 2 with *Dryas octopetala* as dominant species and complexes 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7. **C** Vegetation class 3 with *Salix hastata* and complexes 2.1, 2.2, 2.3, 2.4, 2.5. **D** Mapped individual trees of species *Larix decidua* and *Pinus cembra*.

patches at the 1925s proximal slope, as well as at the 1850s and 1920s proximal moraine slopes and in a depression between the 1920s and 1850s moraine ridges. Class 2.2 dominates the remaining slopes covered by vegetation class 2, mixed with class 2.5 in a large patch at the 1920s distal and several smaller patches along the 1925s and 1850s moraine ridges. Class 2.3, 2.4 and 2.6 occur sparsely, with small patches of 2.3 and 2.4 at the 1850s moraine slope, while some smaller patches of class 2.6 occur at foot and midslope positions of the 1925s moraine slope. Class 2.7 does not occur.

Vegetation class 3 dominates at the proximal 1925s and 1920s slope, especially at the southern part of the moraine complex. A large patch and some smaller patches of class 3.1 cover the flatter slopefoot of the 1920s and slopefoot of the 1925s moraine, bordering patches of class 3.2. Class 3.3 makes up large patches at the southernmost and northernmost moraine slopes and several smaller patches at the 1850s and northern 1920s proximal slopes. Class 3.4 occurs in small patches at the 1850s moraine and the slopefoot of the 1925s proximal slope, while class 3.5 is absent.

Trees mostly occur either at crest or slopefoot positions, especially in patches of classes 2.5, but also with class 2.1, 2.2, 3.1 and 3.3.

8.4 Discussion

8.4.1 Methods

The time series of the iButton temperature data used to derive snow and thermal data is relatively short with only one year. However, it gives first useful indication on snow and thermal regime in the permanent plots. NMDS ordinations showed good results for previous biogeomorphic studies (Eichel et al., 2013, 2016). Stress of the two ordinations with values ranging between 3 and 17 can be seen as normal for data analyses with large sample sizes (McCune and Grace, 2002).

Field mapping is generally subjective (Otto and Smith, 2013), which needs to be kept in mind when interpreting the derived maps. Concerning the geomorphic map, an important field mapping difficulty arose from form convergence (Schumm, 2006). As different geomorphic processes can produce similar landforms, it was sometimes difficult to attribute detected landforms to the creating geomorphic processes. Examples are step-like features on slopes, which can be created by solifluction processes (turf-banked terraces) or fluvial or soil erosional processes, or their interactions (complex steps), and lobate landforms created by both solifluction (turf-banked solifluction lobes) or debris flows (debris flow heads). Criteria defined during field mapping (Table 8.2) helped to distinguish the different landforms, as well as the use of a complex process domain to account for polygenetic landforms created and/or modified by several processes. For the material map, material was differentiated visually in field which was difficult below dense vegetation cover. Local removal of vegetation for soil sampling in small spots next to permanent plots helped to get a general impression of the underlying material in different locations. Material was only mapped based on three main material classes, which were visually assessed, therefore, the described material complexe are the most detailed possible material differentiation. As stated by Otto and Smith (2013), the goal of material mapping should anyway be to identify material patterns instead of sedimentological analyses. Concerning vegetation mapping, difficulties arose from the delimitation of vegetation classes, which often coalesce instead of showing distinct boundaries (Mueller-Dombois and Ellenberg, 2003). This problem could partly be solved by mapping complexes with mixed species compositions from two vegetation classes. In addition, the orthophoto helped to determine boundaries of vegetation class patches.

8.4.2 Controls for paraglacial adjustment of lateral moraine slopes and related geomorphic patterns

Controls on paraglacial adjustment

The NMDS result showed that slope toposequence and gradient, material properties, occurring plant species and slope type (distal vs. proximal slopes) control the occurrence of geomorphic processes and landforms on lateral moraines slopes (Figure 8.2), and therefore their paraglacial adjustment. In contrast to previous studies (Ballantyne, 2002a; Curry et al., 2006), terrain age could not be identified as a controlling factor, high geomorphic activity also occurs on older terrain (cf. Eichel et al., 2013, 2016),

Slope gradient and toposequence position controls for paraglacial adjustment have been suggested by Ballantyne (2005), Curry et al. (2006) and others and are demonstrated quantitatively in the data of this study (Figures 8.2, 8.12 A). At slopefoot positions, paraglacial adjustment is first completed, as indicated by the absence of geomorphic processes, *Salix hastata* shrub cover and increasing shrub height, related to vegetation stratification. In addition, most developed soils occur at slopefoot positions, indicated by the development of pronounced soil horizons, and comparatively high contents organic material, nitrogen and organic carbon (Egli et al., 2010; Kabala and Zapart, 2012; Matthews, 1992). High activity often persists at crest positions with a high number of freeze-thaw cycles and lowest snow cover due to exposition to winds (Matthews, 1992). Thus, paraglacial adjustment is strongly delayed here and active mass movement and water soil erosional and periglacial processes can persist (Figure 8.2).

Material control on paraglacial adjustment shows in the linkage between the occurrence of no processes and larger grain sizes (Figures 8.2, 8.12 A). This confirms the importance of sediment texture for paraglacial reworking (Jäger and Winkler, 2012), as debris flows and water soil erosional processes can only occur with finer material (Ballantyne, 2002b; Curry et al., 2006; Mercier et al., 2009; Rose, 1991). Thus, material properties, often linked to the glacier depositional mechanism and source of glacial sediment (e.g. blocky material from supraglacial rockfall debris) also importantly control sediment reworking and paraglacial adjustment (Lukas et al., 2012). Results from this study show that larger clasts are occurring more often in slopefoot positions, which indicates material sorting following the slope toposequence, e.g. by erosion of fine material containing larger blocks, which are subsequently transported downslope by fall or slide of individual clasts (Ballantyne and Benn, 1994; Jäger and Winkler, 2012; Small, 1983) (see Figure 8.6 D).

The importance of *Dryas octopetala* cover for the occurrence of geomorphic processes and landforms has been previously discussed by Eichel et al. (2016) in terms of ecosystem engineering., which changes the dominant process regime from water soil erosional processes to solifluction. In addition, the results show that *D. octopetala* cover and solifluction are linked to the occurrence of fine-grained material (Figure 8.2). This supports that fine material accumulates in the dense engineer mat and thereby promotes solifluction (Chapter 6). Furthermore, solifluction and ecosystem engineering are related to distal slopes (Figures 8.2, 8.12), which usually possess a lower initial slope gradient and lower geomorphic activity (Curry et al., 2006; Jäger and Winkler, 2012). This could promote engineer establishment on distal slopes, which accelerates their paraglacial adjustment.

Paraglacial process and landform succession on lateral moraine slopes

Based on the NMDS results, three stages of paraglacial adjustment, linked to occurring processes and landforms, can be identified (Stage II: Gullying, Stage III: Solifluction, Stage IV: Stabilization; Figure 8.12 A). They are related to the sequence of process and landform succession described by Mercier et al. (2009). Due to the limitation of this study to the stable, accessible lateral moraines in Turtmann glacier foreland (see Figure 8.1), a dead-ice related phase (Stage I) described by previous studies (Curry et al. 2006, Mercier et al. 2009 and others) cannot be identified in data from this study. Stage II is characterized by gullying through debris flows and water soil erosional processes with a high geomorphic activity. It relates to the highest slope gradient and least soil development, indicated by high pH-values and opposed high values of organic material, nitrogen

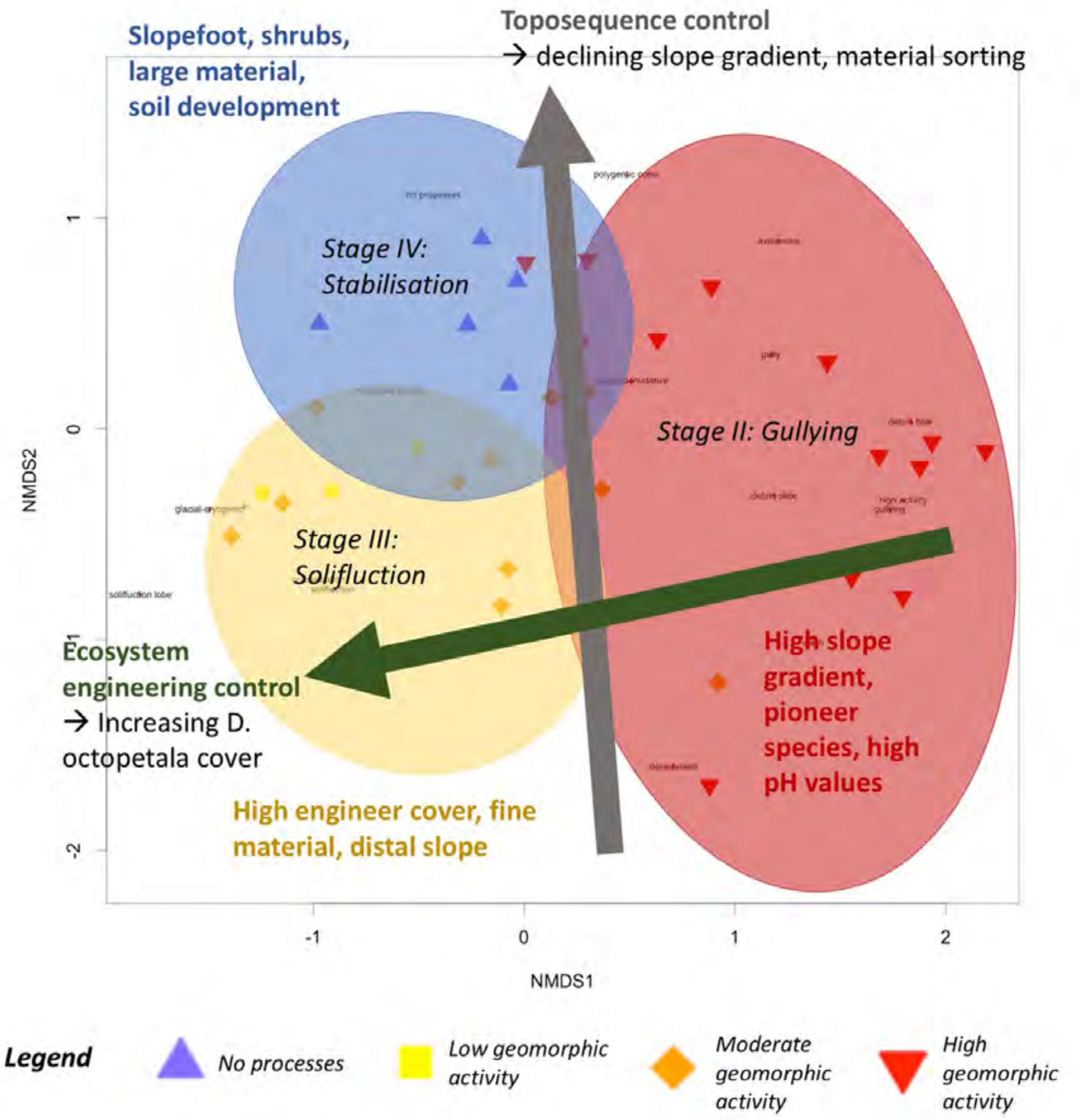

Figure 8.12: Interpretation of NMDS result for occurrence of geomorphic processes and landforms, showing toposequence and ecosystem engineering gradient as main controls. Occurrence of geomorphic processes and landforms is attributed to three stages of paraglacial process and landform succession with specific properties.

and organic carbon (Figure 8.2 D; Egli et al., 2010; Matthews, 1992). *Linaria alpina* pioneer vegetation, adapted to active geomorphic processes (Ellenberg, 2009; Schröter et al., 1926; Stöcklin and Bäumler, 1996), dominates with low cover (<3%) in this stage. The dominance of solifluction processes and landforms with moderate to low activity can be identified as a third stage (Stage III) of paraglacial adjustment as described in Chapter 5. It can occur in all slope positions and is controlled by a high cover of the ecosystem engineer *Dryas octopetala* (Eichel et al., 2016). It has been suggested that *D. octopetala* can establish with decreasing geomorphic activity and actively limit water soil erosional processes and promote solifluction. Thus*, D. octopetala* cover is probably a main control for a change from Stage II to Stage III. A stable stage (Stage IV) with absent geomorphic processes, often on polygenetic cones or with large material sizes, indicates completed paraglacial adjustment. Its relationship to most pronounced soil development and vegetation stratification, which are indicating advanced ecosystem

development (Matthews, 1992), suggests that these are potential valuable indicators to identify completed paraglacial adjustment. This can be useful in the the presence of high cover ecosystem engineer species (cover values up to 85% in permanent plots; cf. Eichel et al., 2016) such as *Dryas octopetala*, under which solifluction processes still occur and are even promoted (see Chapters 5, 6).

Geomorphic and material patterns

Geomorphic and material patterns show that paraglacial adjustment on lateral moraine slopes can be spatially variable, with patterns related to the identified controlling factors slope toposequence and type, material properties and ecosystem engineering, but also to glacial sediment source and deposition and to terrain age (Figures 8.4, 8.5, 8.6, 8.7, 8.9, 8.10).

The geomorphic maps demonstrate that toposequence position strongly influences geomorphic patterns related to occurring processes and landforms (Figures 8.4, 8.5). At crest positions, mass movement and water soil erosional process dominate, often associated with complex initiation niche (Figures 8.4, 8.5), which are probably the remains of previous inter-gully walls and channels (Curry et al., 2006). The existence of inter-gully walls on the northern lateral moraine complex indicates that paraglacial adjustment is on-going here, comparable to lateral moraine slopes in Norway, where gullies also have a long preservation potential (Curry et al., 2006). In crest positions, tension cracks probably developed due to unloading of the slope following sediment removal by mass movement processes (Dikau, 2003). They reduce slope stability and induce new mass movements, such as slumping or debris flows (Bracken, 2004; Dikau, 2004). Thus, their occurrence at the moraine crest indicates that debris flows material is not only supplied by water soil erosional processes from inter-gully walls (Ballantyne and Benn, 1994). The demonstrated linkage between a certain vegetation cover, often vegetation class 2, and the occurrence of tension cracks (Figures 8.4, 8.5, 8.9, 8.10) suggests that a certain slope stability, e.g. through plant roots (Ghestem et al., 2014; Veylon et al., 2015), first needs to be attained for tension crack development, while continuous sediment removal by soil erosional processes limits tension crack development in more active complex initiation niches. The occurrence of cryoturbation at moraine ridges (Figures 8.4, 8.5) is probably favoured by their strong exposure to winds, which limit snow cover and vegetation establishment (Matthews, 1992) but promote high numbers of freeze thaw cycles, as showing in the NMDS result (Figure 8.2). In midslope positions, complex channels link upslope geomorphic processes with their downslope depositional areas and serve as transport path for sediments (Figures 8.4, 8.5). Debris heads occurring in midslope positions indicate that debris flow range can be limited, e.g. due to decreasing slope angle or obstacles, which decrease movement velocity and result in sediment deposition (Hungr, 2005). This can result in the convex midslopes of lateral moraines previously observed by Ballantyne and Benn (1994) in Norway. In slopefoot positions, debris cones dominate (Figures 8.4, 8.5), which are typical features of lateral moraine slopefoots and indicate completed paraglacial adjustment (Ballantyne and Benn, 1994). They are often made up by piled up or interlocked debris flows heads (Figure 8.4), but also by avalanche deposits. Debris flow heads often show signs of reworking by solifluction, which indicates the importance of fine material re-deposition by debris flows for the occurrence of solifluction processes and landforms. This linkage between the two processes can explain the distinct turf-banked solifluction lobes found in footslope positions at the northern lateral moraine complex (Figure 8.4) and highlights the palimpsestic nature of lateral moraine slopes (Dikau et al., 2004; Knight et al., 2011; Schmidt and Dikau, 1999). Landform palimpsests also show in interlocked turf-banked terraces, indicating the existence of several episodes of solifluction movement with different layers, and in all polygenetic landforms from the complex process domain.

The relation of geomorphic patterns to slope type (distal vs. proximal) shows in the dominance of mass movement and water soil erosional processes on proximal moraine slopes, while distal moraine slopes in the southern lateral moraine complex are often dominated by solifluction processes under a dense vegetation cover (Figures 8.5, 8.10). This lower geomorphic activity and quicker vegetation colonization was attributed to gentler initial distal slope gradients (Curry et al., 2006; Jäger and Winkler, 2012). Shorter proximal moraine slopes show a similar pattern (Figures 8.5, 8.10). Due to their shorter length, material deposition by mass movement and water soil erosional processes probably more quickly decreases their slope gradient in comparison to longer proximal slopes. Resulting decreasing geomorphic activity then facilitates engineer colonization.

Linkages between geomorphic patterns and material distribution show in associations between material properties and occurring geomorphic processes (Figures 8.4, 8.5, 8.7, 8.8). Mass movement and water soil erosional processes are limited to finer material (Curry et al., 2006; Jäger and Winkler, 2012; Mercier et al., 2009), while blockier material is either reworked by unbound solifluction (Figure 8.5) or shows no sign of geomorphic processes. Blocky material distribution could be linked to the origin of glacial sediments. Larger areas of blocky material dominate at the southern lateral moraine complex, whose material was dominantly derived and deposited from the Turtmann glacier with a mainly siliceous catchment geology. In contrast, the Brunegg glacier probably contributed finer, calcareous material to the northern lateral moraine complex during its linkage with the Turtmann glacier (until 1934; Otto, 2001). In addition, large blocky material patches, often made up by smaller moraine ridges, indicate that blocky material was deposited along the retreating glacier front during sequential years (northern ends of northern and southern lateral moraine complexes; Figure 8.4, 8.5). This blocky material could have been derived from supraglacial rockfall material. In turn, the hilly fine material feature between the 1850s and 1920s moraine ridges at the southern lateral moraine complex could be attributed to dumping of fine material from the glacier front or side, e.g. by debris flows. These material distribution patterns, linked to process occurrence and activity, highlight the importance of glacial sediment sources and deposition for paraglacial adjustment (Lukas et al., 2002).

Ecosystem engineering by *D. octopetala* can explain the close linkage of solifluction processes with with vegetation class 2 on all material types and in all toposequence positions (Figures 8.4, 8.5). Eichel et al. (2016) suggested that *D. octopetala* actively changes the process regime from gullying to bound solifluction through its adapted traits once geomorphic activity sufficiently decreases. Thus, ecosystem engineering strongly controls process occurrence and related geomorphic patterns on lateral moraine slopes, which has not been accounted for in previous studies (cf Ballantyne, 2002; Curry et al., 2006). Geomorphic and vegetation maps furthermore show that several large solifluction landforms, such as turf-banked solifluction lobes and interlocked turf-banked terraces occur on young lateral moraine slope terrain (< 100 years) with high *D. octopetala* cover in vegetation class 2 (Figures 8.4, 8.5). The comparably quick development of these landforms with large dimensions has also been attributed to ecosystem engineering (see Chapters 5, 6). As engineer-promoted solifluction processes occur in all toposequence positions, is seems that ecosystem engineering can override toposequence control on geomorphic process occurrence determining paraglacial adjustment (cf. Chapter 5). The large moraine slope areas affected by solifluction processes indicate that solifluction need to be acknowledge as a main process contributing to paraglacial adjustment of lateral moraine slopes (see Chapter 5).

Finally, the geomorphic maps demonstrate that geomorphic patterns at the lateral moraine slopes are mostly independent from terrain age (Figures 8.4, 8.5, 8.7, 8.8), which is usually seen as a key control for paraglacial adjustment (Ballantyne, 2002; Curry et al., 2006). At youngest slopes in the southern lateral moraine complex, mass movement and soil erosional processes dominate (Figure 8.5), however, these processes also occur on high terrain age (> 100 years) at the northern lateral moraine complex (Figure 8.4). Yet, a lower number of debris heads, together with the existence of a complex step along the moraine crest of the 1920s moraine in the southern lateral moraine complex (Figure 8.5), indicate that paraglacial adjustment is less advanced here. In contrast, the high number of debris flow heads at the central part of the northern lateral moraine complex, below a very thin moraine ridge and vegetated upper moraine slopes (Figure 8.4), suggests that sediment reworking is nearly finished here. It has to be noted that lowering of the moraine crest by backward erosion could increase the impact of external processes such as snow avalanches and rockfall, on the moraine slope. In the current state, the existing moraine crest at the northern lateral moraine complex acts as a buffer *sensu* Fryirs et al. (2007) that prevents rockfall and probably smaller snow avalanches from entering the moraine slope system. However, as soon as this buffer is removed, connectivity between the lateral moraine slope and the adjacent valley slope is established. As a result, snow avalanches could more frequently affect the moraine slopes and permanently remove vegetation at the moraine crests, thereby reinitiating sediment reworking (Cossart, 2008).

Conceptual model of paraglacial process and landform succession on lateral moraine slopes

Based on the identified controls and described patterns, a conceptual model of paraglacial process and landform succession on lateral moraine slopes can be formulated (Figure 8.13) with the three stages identified in the NMDS result (Stage II, Stage III, Stage IV) and the initial dead ice melting stage (Stage I) described by Mercier et al. (2009). During this paraglacial succession, process importance changes, geomorphic activity decreases and landforms develop. This is linked to a set of controls, whose importance changes during paraglacial succession. While terrain age influences the occurrence of Stage I and Stage II, associated with dead ice melting and gullying, the importance of terrain age significantly decreases during paraglacial succession. Instead, ecosystem engineering and toposequence position become important (Figure 8.13). Ecosystem engineering changes the process regime to solifluction processes, while toposequence position affects rates of paraglacial succession. Lateral moraine slope stabilization starts at footslope positions, while gullying is favoured at crest positions even with high terrain age. The detected patchy geomorphic patterns develop. Material properties and distribution, changing during paraglacial adjustment, represent an additional control on process occurrence in all stages.

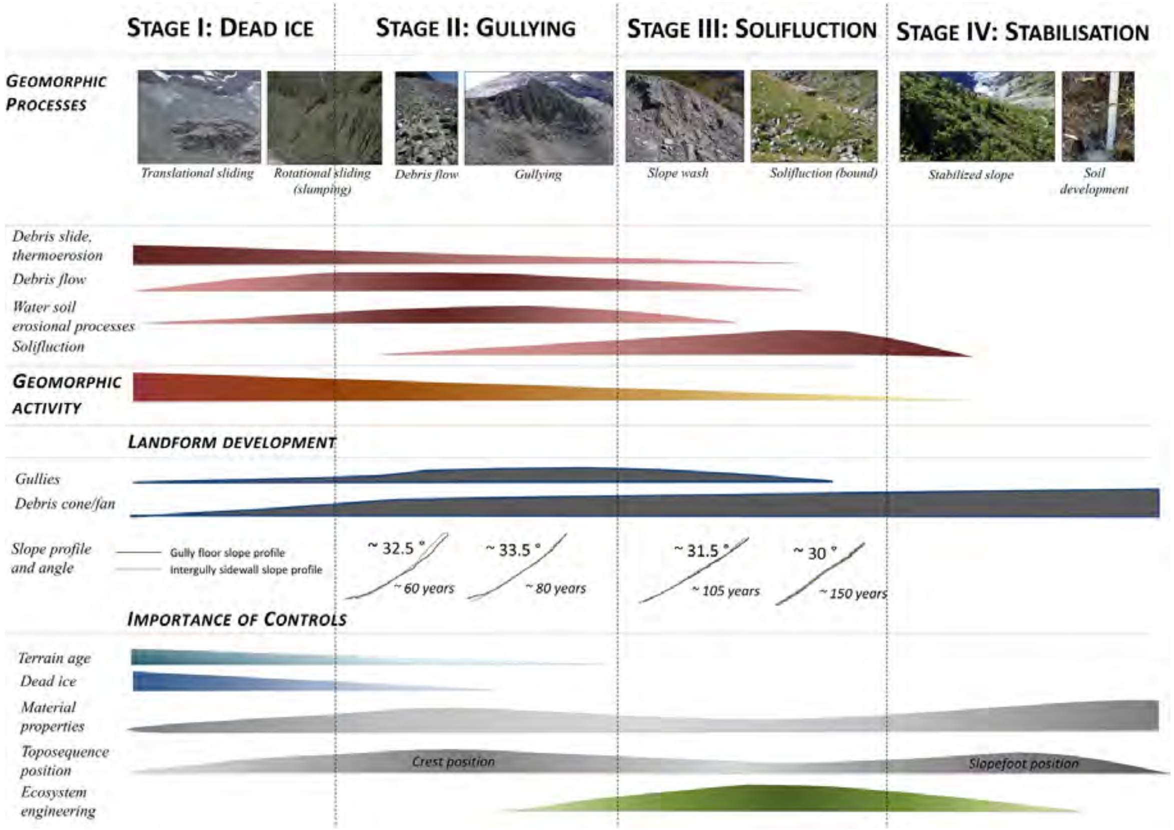

Figure 8.13: Illustration of paraglacial process and landform succession on lateral moraine slopes with four stages. Geomorphic processes, their importance and landform development along the successional sequence is shown, as well as the changing importance of different controls for paraglacial adjustment. Slope profiles and angles are taken from Curry et al., 2006.

Stage I: Dead ice melting. Following glacier retreat, dead ice melting strongly controls paraglacial adjustment of lateral moraine slopes by causing translational and rotational slides and supplying moisture for debris flows (Figure 8.13, Stage I, Bennett et al., 2000; Lukas et al., 2012). Thereby, the slope angle of lateral moraine slopes usually quickly decreases within the first 10 years following deglaciation (Welch, 1970). Material distribution, initially defined by glacial sediment source and deposition, is modified in this stage. This stage was not detected at the investigated lateral moraine slopes, however, it can be found at lateral moraine slopes in the southern part of the glacier foreland, bordering the glacier tongue.

Stage II: Gullying. Gullying processes start to dominate some decades following glacier retreat at slopes with angles larger than 30° (Ballantyne, 2005; Curry, 2000; Mercier et al., 2009). However, gullying processes can persist for a longer time, especially at crest positions (Figure 8.4). Within the first decades, gullies rapidly attain their maximum size and density (Curry et al., 2006; Mercier et al., 2009; Figure 8.13, Stage II). Material properties are important in this stage, as they determine the occurrence of gulling processes (Curry et al., 2006; Jäger and Winkler, 2012; Mercier et al., 2009), which in turn influence material distribution. Debris cones build up at the slopefoot beneath active gullies, resulting in a decreasing slope angle (Ballantyne, 2005; Curry et al., 2006; Figure 8.13, Stage II).

Stage III: Solifluction. Either with decreasing slope angle, needed for solifluction processes (Figure 2.13, Stage III; Ballantyne, 2002; Benedict, 1976) or with the establishment of ecosystem engineer species, solifluction starts to dominate on lateral moraine slopes (Figure 8.13, Stage III). The results suggest that ecosystem engineering can play a key role for this switch between Stage II and Stage III, as bound solifluction below ecosystem engineer cover occurs also on high slope gradients and in all toposequence positions (Figure 8.2). Thus, a neither a low slope gradient, nor toposequence position are important in this stage. Material control also slightly decreases, as bound solifluction occurs also on stony material, probably aided by fine material accumulation in the *D. octopetala* mat (Chapters 5, 6).

Stage IV: Stabilization. Stabilization of lateral moraine slopes is often linked to blocky material and starts at slopefoots (Figure 8.13, Stage III). In addition, ecosystem engineering can also contribute to slope stabilization by decreasing solifluction processes under high engineer cover and facilitating establishment of more deeply rooting species (Chapter 6). The results suggest that associated pronounced soil development and vegetation stratification, linked to the occurrence of shrubs, are helpful indicators to identify slope stabilization and thereby the completion of paraglacial adjustment.

The presented conceptual model of paraglacial process and landform succession sees paraglacial adjustment to be completed when glacial sediments are stabilized and no more geomorphic process occur. This definition is in line with Ballantyne (2002 a, b), but prefers from the initial definition by Church and Ryder (1972), who considered paraglacial adjustment as completed when geological norm of primary denudation is attained in the system. For the investigated lateral moraine slope systems, this is an important point. Solifluction could well represent the geological norm of denudation for the Turtmann valley, as solifluction processes are present on many slopes of the main and hanging valleys (Otto and Dikau, 2004). They also occur on the main valley slope adjacent to the lateral moraine slopes. However, the occurrence of solifluction processes is also related to forest limits. Treeline ecotones have been found to interact with solifluction, with no solifluction occurring below forest vegetation (Walsh et al., 2013). This indicates that region-specific treeline elevation also determines the occurrence of solifluction processes and thereby the geological norm of the region. This needs to be taken into account when defining paraglacial adjustment of lateral moraine slopes as completed.

The geomorphic map shows that paraglacial adjustment of lateral moraine slopes does not follow a terrain age gradient but can be patchy and spatially variable. At the investigated lateral moraine slope, a mosaic of different process domains *sensu* Montgomery (1999), linked to different paraglacial successional stages, shows. Its spatial configuration probably strongly controls sediment transport on lateral moraine slopes.

Process mosaic and and landform palimpsest demonstrate the limitations of space for time substitution approaches to understand paraglacial adjustment. Instead, they highlight the importance of geomorphic mapping, but also vegetation mapping, as a tool to understand paraglacial adjustment of lateral moraine slopes. Recently used laser scanning approaches to derive digital elevation models of difference enable the quantification of lateral moraine slope sediment dynamics in terms of erosion and deposition (Hilger et al., 2013). However, laser scanning alone cannot provide information on occurring processes or processes chains, as they only show that sediments have been transported, but not by which processes(s). In future approaches, the combination of laser scanning with a detailed geomorphic mapping would provide valuable information on the contribution of different processes to paraglacial adjustment and their spatiotemporal dynamics.

8.4.3 Controls for vegetation succession on lateral moraine slopes and related spatial vegetation patterns

Controls on vegetation succession

The NMDS shows that (i) material properties and (ii) decreasing geomorphic activity, linked to slope gradient, control species composition and associated vegetation succession on lateral moraine slopes (Figures 8.3, 8.14). Soil, snow and thermal properties are connected to the geomorphic activity gradient and provide no independent control. Species composition is not related to terrain age.

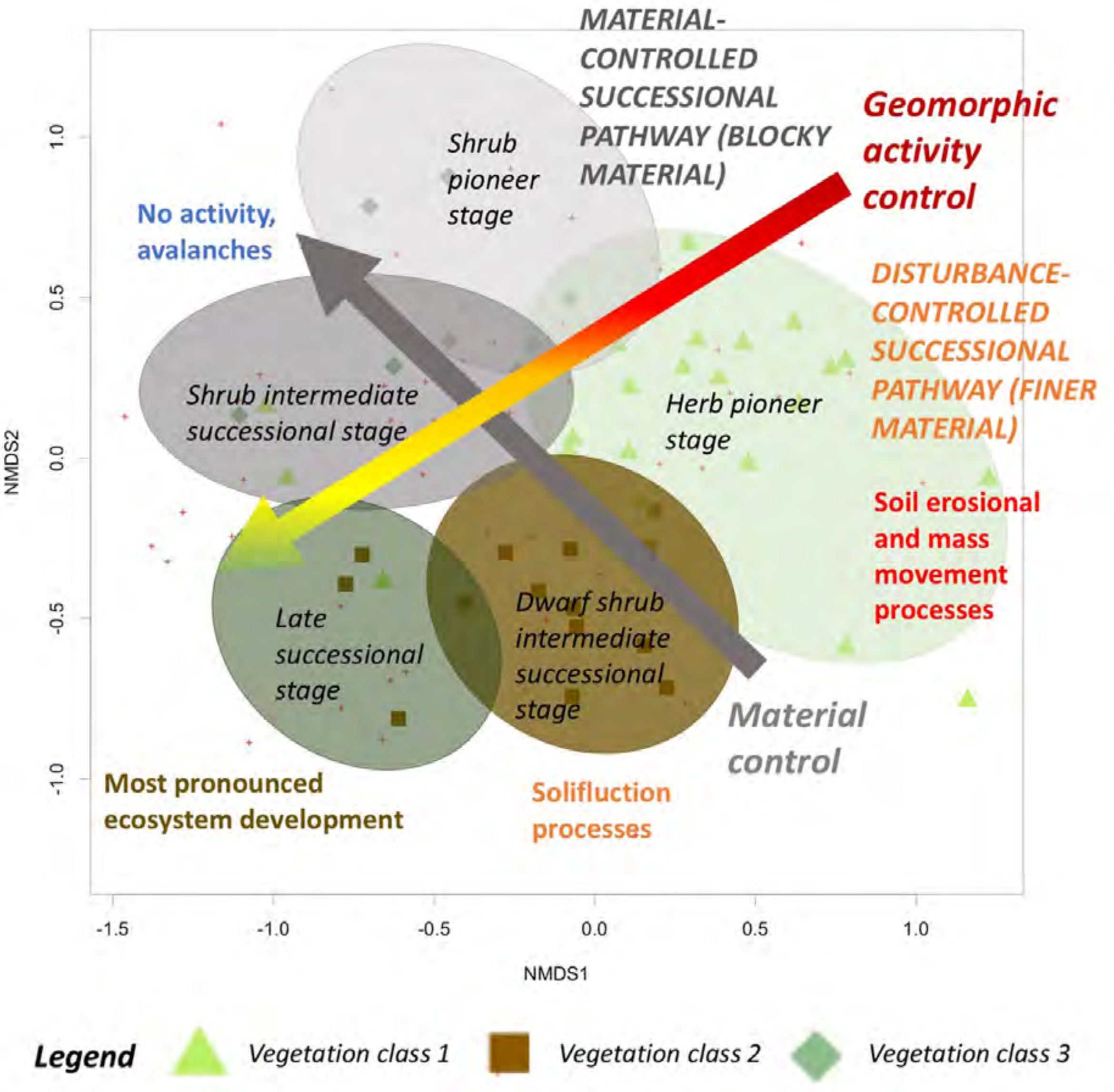

Figure 8.14: Interpretation of NMDS result for species composition, showing main controls related to geomorphic activity and material properties. Two successional pathways, dependent on material properties and disturbance-intensity, are shown.

The role of material properties for species composition shows in the linkage between grain sizes and occurring species. Vegetation class 3 with shrub species (*Salix hastata*) dominantly occurs with largest grain sizes, while vegetation classes 1 and 2 with pioneer (*Linaria alpina*) and dwarf shrub (*Dryas octopetala*) species mostly occur with finer material (Figure 8.3). The role of substrate properties for different starting points and pathways of vegetation succession has been highlighted by Burga et al. (2010). The dominance of later successional shrub species on larger material found in this study could be explained by the higher angle of friction of blocky material. This makes slopes with blocky material more stable, less geomorphic disturbances occur. In addition, the establishment of shrub species is potentially favoured by more available moisture, as coarse substrates shade underlying fined material and thereby prevent moisture loss (Körner, 2003).

In contrast, the (ii) strong linkage between vegetation succession and geomorphic activity on lateral moraine slopes has only sparsely been found in previous studies (cf. Eichel et al., 2016).

This probably results either from the focus of previous studies on undisturbed terrain (Matthews, 1999), often stable areas of the valley floor (Matthews and Vater, 2015), or a negligence of geomorphic processes even in studies with a thorough investigation of environmental parameters (Rydgren et al., 2014). Interestingly, the geomorphic activity gradient also influences soil development, indicated by the most pronounced organic and A soil horizons and highest nitrogen and organic C contents (Kabala and Zapart, 2012; Matthews, 1992) and snow and thermal regime. Usually, snow cover is seen as an important independent control on vegetation succession (Robbins and Matthews, 2014). However, at the investigated lateral moraine slopes, it is strongly linked to slope toposequence. As demonstrated in studies by Blöschl and Kirnbauer (1992) and Elder et al. (1991), topographical attributes, such as slope gradient and curvature changing along the toposequence, exert a strong roll on alpine snow distribution. Soil development is considered to depend on terrain age (Chapin et al., 1994; Matthews, 1992; Schumann et al., 2016). Yet, at the investigated lateral moraine slopes, terrain age control on soil development seems to be replaced by geomorphic activity control. Similar results highlighting the role of geomorphic activity for soil development in glacier forelands were presented by Temme and Lange (2014). A clear toposequence gradient, as suggested by Bridge and Johnson (2000), cannot be found in the NMDS result (Figure 8.3), as pioneer vegetation class 1 also occurs at slopefoot positions. This could be attributed to the occurring geomorphic processes, such as debris flows, which usually initiate in crest positions, transport material along the midslope and accumulate this material at slopefoot positions. Thereby, they can also create new areas for pioneer colonization at slopefoot positions.

Vegetation succession pathways

Based on the identified two main controls, two successional pathways can be distinguished for the investigated lateral moraine slopes. The first successional pathway is controlled by (i) the occurrence of larger material sizes (material-controlled successional pathway), while the second successional pathway is controlled by (ii) decreasing geomorphic activity on finer material (disturbance-controlled successional pathway) (Figure 8.14). Both can lead to most pronounced ecosystem development indicated by advanced soil development and highest vegetation cover and species numbers.

The (i) material-controlled pathway occurs on material with large grain sizes and no or low geomorphic activity. It is characterized by the occurrence of shrubs (vegetation class 3, *Salix hastata* and others) and linked to increasing total vegetation cover and ecosystem development in an intermediate/later successional stage.

The (ii) disturbance-controlled successional pathway occurs on finer material, where high geomorphic activity, associated with mass movement and water soil erosional processes on steep slopes, limit vegetation colonization to vegetation class 1 with the pioneer species *Linaria alpina* (Figure 8.14; Eichel et al., 2016). With decreasing geomorphic activity, dwarf shrubs of vegetation class 2 with *Dryas octopetala* can occur. This species change cannot only be attributed to the decreasing magnitude and frequency of the geomorphic disturbances, but also to ecosystem engineering by *Dryas octopetala,* which actively decreases geomorphic activity by favouring solifluction processes (Figure 8.12 B; Eichel et al., 2016, Chapter 6). In addition, *D. octopetala* also strongly contributes to soil development through humus accumulation, trapping of organic matter and nitrogen fixation (Eichel et al., 2016; Elkington, 1971). The linkage of vegetation class 2 to distal slopes indicates that an intermediate successional dwarf shrub stage with advanced soil development is attained more quickly here than on proximal slopes (Vetaas, 1997), probably due to initially lower slope gradients and geomorphic activity on distal slopes (Curry et al., 2006; Jäger and Winkler, 2012).

Vegetation pattern and, successional pathways

The vegetation maps show that patches of different vegetation classes occur in a mosaic-like pattern (Figures 8.9, 8.10). This pattern is strongly linked to occurring geomorphic processes and landforms, material distribution and toposequence position (Figures 8.4, 8.5, 8.7, 8.8). Patches of vegetation class 1 with *Linaria alpina* mostly occur on fine material at crest positions with water soil erosional and mass movement processes and landforms and cryoturbation. Patches of vegetation class 3 with *Salix hastata* occur nearly exclusively on blocky material (B1, B2) in slopefoot and midslope positions where no geomorphic processes occur, except for occasional solifluction. Patches of vegetation class 2 with *Dryas octopetala* occur on all material types and in

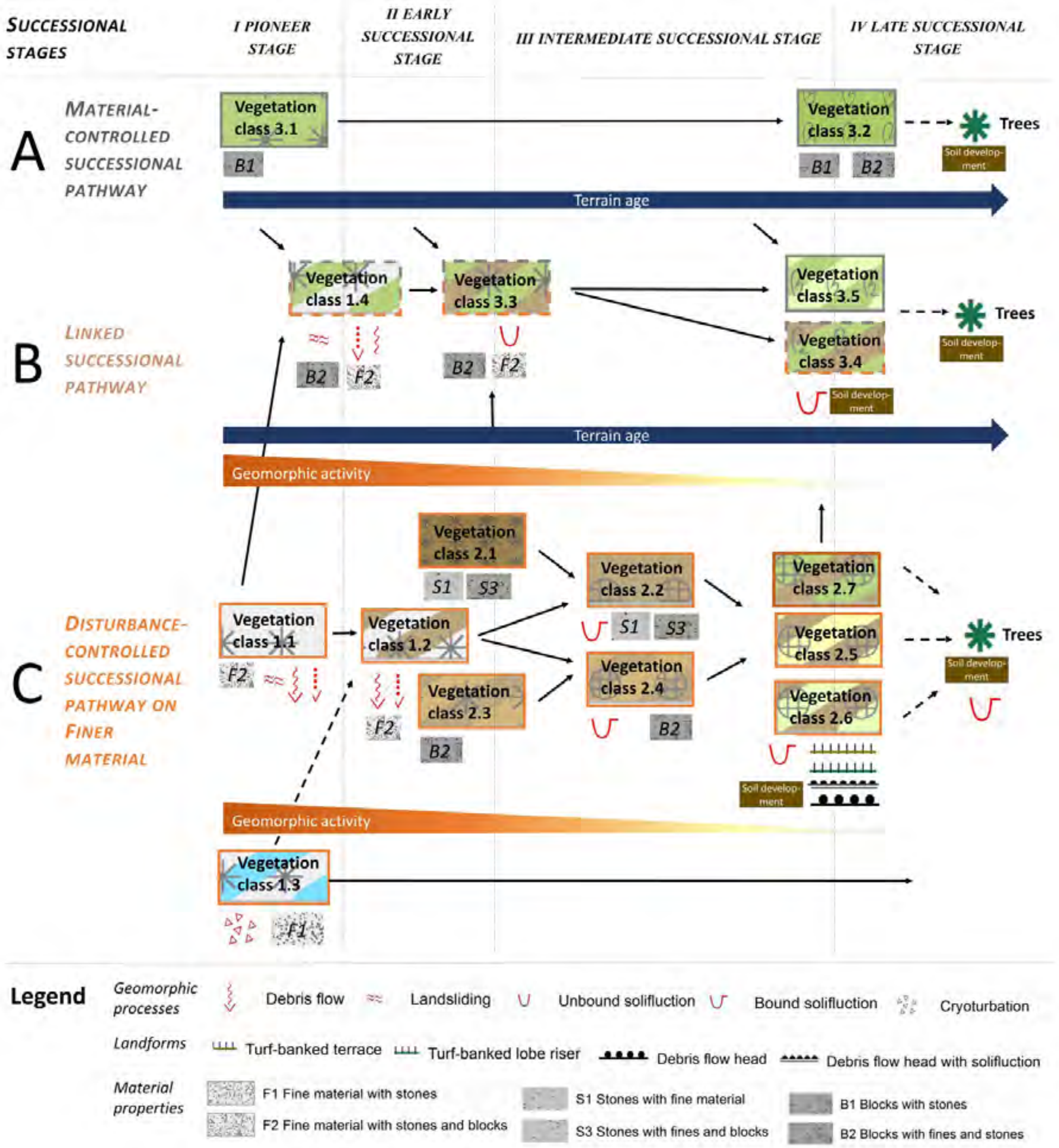

Figure 8.15: Vegetation successional stages and successional pathways for vegetation class patches on lateral moraine slopes. **A** Material-controlled successional pathway on blocky material. **B** Linked successional pathway. **C** Disturbance-controlled successional pathway on finer material.

all toposequence positions, but are always linked to solifluction processes and associated landforms.

According to the patch dynamics concept, patches with different species compositions and habitat properties can represent different successional stages (Lovett et al., 2007; Watt, 1947; Wu, 1999). Thus, based on their species composition, occurring geomorphic processes and material properties, vegetation class patches can be attributed to different successional stages of the material-and the disturbance-controlled pathway. In addition, a linked pathway, depending on both material properties and disturbances, can be identified (Figure 8.15).

Material-controlled successional pathway: The material-controlled successional pathway occurs on mostly stable, blocky material patches (B1, B2). These are colonized by *Salix* shrubs (class 3.1) as pioneer species, indicated by low shrub cover, in a *pioneer stage* (Figure 8.15 A, Stage I). *Salix hastata*, which prefers moist environments such as floodplains (Lauber and Wagner), is probably favoured by higher available moisture under the blocky material and a low disturbance intensity (Körner, 2003). Vegetation succession along this pathway is dominantly controlled by terrain age, which shows in a dominance of class 3.1 patches at youngest terrain (Figure 8.10), while patches with high *Salix* shrub spp. cover (class 3.2) dominate at older terrain (Figure 8.9). Vegetation maps indicate that late successional tree species can occur in vegetation class 3.2, which is probably enabled by advanced soil development (see Figure 8.12 B). In comparison to (hypothetically undisturbed) finer material patches, patches of the material-controlled successional pathway will probably take longer to reach a *later successional stage*, as blocky material delays vegetation succession (Ellenberg, 2009; Lüdi, 1958). In addition, it is likely that the material-controlled successional pathway is strongly linked to glacial sediment source and deposition responsible for large blocky material patches, as discussed in Section 8.4.2. Thus, the patch mosaic location of patches following this pathway is strongly determined by initial material distribution.

Disturbance-controlled successional pathway: Patches of the disturbance-controlled pathway occur mostly on fine and stony material. This pathway is controlled by a decreasing geomorphic activity, related to geomorphic process magnitude and frequency (cf. Eichel et al., 2016) and toposequence position (Figure 8.15 C). Patches are often created by geomorphic processes. A *pioneer stage* (Figure 8.15 C, Stage I) of class 1.1 with *Linaria alpina* and *Saxifraga aizoides* occurs with high geomorphic activity by active mass movement and soil erosional processes on fine material patches (F2), mostly in crest positions (Figures 8.4, 8.5, 8.7, 8.8, 8.9, 8.10). *L. alpina* and *S. aizoides* are both pioneer species that can establish under cold, moist and disturbed conditions through adapted traits. These include high seed numbers, a high longevity of seed, vegetative colonization and adaption of their roots and stems to moving debris (Kutschera and Lichtenegger, 2013; Schröter et al., 1926; Schwienbacher et al., 2012; Stöcklin and Bäumler, 1996). An additional pioneer stage is represented by patches of vegetation class 1.3 with *Linaria alpina* and *Hernaria alpina.* This pioneer stage is linked to high cryoturbation activity in fine material-dominated (F1) crest positions (Figure 8.15 C, Stage I). As these are highly exposed to winds, protective snow cover is quickly blown off (Matthews, 1992). This promotes cryoturbation in the fine material (French, 2007), which damages plant roots, dries up the soil and delays soil development (Haugland, 2006; Haugland and Beatty, 2005; Matthews, 1999c). Thus, vegetation colonization is limited in exposed crest positions to this pioneer stage. Through vegetative colonization from less disturbed areas, a transition to early successional stages is possible (cf. Chapter 6). However, this can take several decades or will not occur at all (Haugland, 2006). A decreasing magnitude or frequency of mass movement or water soil erosional processes enables the the transition of class 1.1 pioneer patches to an *early successional stage* (Figure 8.15 C, Stage II; Eichel et al., 2016). Dwarf shrubs species of vegetation class 2, such as the ecosystem engineer *D. octopetala* can establish with decreasing geomorphic activity and facilitate soil development and colonization for further species (Eichel et al., 2016; Matthews and Vater, 2015). This transition from pioneer to early successional stage shows in the vegetation maps, where class 1.2 patches are often neighbouring more active class 1.1 patches (Figures 8.9, 8.10). In addition, patches of vegetation classes 2.1 and 2.3 with a low cover of *D. octopetala* or dwarf shrub species are also situated in an early successional stage, linked to larger material sizes. While class 2.1 patches occur mostly on stony material (S1, S3), class 2.3 patches also occur on blockier material (B2). Both patch types are linked to bound solifluction, which is promoted by the ecosystem engineer *D. octopetala* (Eichel et al., 2016). Increasing solifluction activity favours adapted dwarf shrubs species (Chapter 6) and therefore induces a transition towards an *intermediate successional stage* (Figure 8.15 C, Stage III). In patches of this successional stage, either *D. octopetala* with *Bartsia alpina* (class 2.2) dominates on stony material, or dwarf shrubs (class 2.3) on blockier material. With increasing engineer cover and engineer mat depth, ground temperature fluctuations are dampened and solifluction activity decreases (Chapter 6). In addition, *D. octopetala* favours the establishment of later successional species by advancing soil development (Andreis et al., 2001; Reisigl and Keller, 1994). Situated in typical transitional stages towards a later successional stage are patches of the dwarf shrub classes 2.5 and 2.6. They are associated with grassland species (*Elyna myosuroides, Festuca* spp.), which further contribute to soil development (Reisigl and Keller, 1994) and thereby promote vegetation succession. In addition, *Salix* shrub species (class 2.7) can also establish in the dwarf shrub mat under improved, less disturbed conditions (Chapter 6) and initiate vegetation stratification (Andreis et al., 2001; Nagl and Erschbamer, 2010; Raffl et al., 2006). Patches of these transitional stages often occur on solifluction landforms or debris flow heads reworked by solifluction in slopefoot positions (Figures 8.4, 8.9). A *late successional stage* is characterized by the establishment of tree species (*Larix decidua, Pinus cembra*) in patches with advanced soil development and improving climatic conditions (Figure 8.15 C, Stage IV). Both *Larix decidua* and *Pinus cembra* need developed soils and a moderated temperature regime, as their root growth stops at temperatures below 4°C and 0°C, respectively (Ellenberg, 2009; Körner, 2003). The occurrence of mature successional stages with tree species is often limited in high altitudes (Robbins and Matthews, 2014). However, this seems not to be a limiting factor at the investigated lateral moraine slopes, as trees also occur on highest altitudes at the southern lateral moraine complex (Figure 8.10).

Linked successional pathway: Vegetation class patches with a mixture of pioneer and shrub species, or shrub and dwarf shrub species, indicate that the material- and the disturbance controlled pathway can be linked (Figure 8.15 B). Linkages can be created by geomorphic processes, which change the material composition or reset succession to earlier stages (cf. Matthews, 1999). Class 1.4 (*L. alpina* with *Salix* shrub spp.) could develop either from blocky material deposition by debris sliding or individual clast fall/slide to finer material patches, or from fine material deposition by debris flows and water soil erosional processes on blocky material patches. This results in mixed material properties (B2, F2) and links the pioneer stage of the disturbance-controlled pathway to the material controlled pathway with blocky material (Figure 8.15 B, Stage I/II). A further link between the pathways is provided by class 3.3 (*Salix* shrub spp. with dwarf shrubs, low cover). This class could develop by (i) time-dependent succession from class 1.4, by (ii) starting unbound solifluction disturbances, which favour dwarf shrubs, or by (iii) shrub colonization of early successional dwarf shrub stages (Figure 8.15 B, Stage II/III). The intermediate/late successional stage of the linked pathways consists of Class 3.5 (*Salix* shrub spp. with dwarf shrubs, high cover) and class 3.4 (*Salix* shrub spp. with *Festuca* spp.). These can develop (i) through time-dependent successional development from class 3.3, (i) by colonization of blocky material with shrub species through dwarf shrubs and grassland species or by (iii) the increasing dominance of shrub species on solifluction-dominated finer material (Figure 8.15 B, Stage III/IV). With advancing soil development, a later successional stage with trees can also start to develop in this linked successional pathway (Figures 8.9, 8.10).

This linked pathway explains decreasing patch sizes with increasing terrain age. At the southern lateral moraine complex, large patches of the material-controlled pathway occur, while smaller patch sizes linked to geomorphic processes (e.g. debris flow cones) dominate at the northern lateral moraine complex. By redistributing fine material, debris flows can change the material-properties at midslope and downslope positions (Figures 8.4, 8.5, 8.7, 8.8) and create new, disturbance-related patches that follow the linked pathway. At the northern lateral moraine complex, this shows in complex channels often colonized by vegetation class 1.4 and while complex cones and debris flow heads are often colonized by class 3.4 (Figures 8.9, 8.10). Decreasing patch sizes in time point to increasing spatial heterogeneity and contradict classical succession models frequently used in glacier forelands (Cutler et al., 2008). However, they offer a suitable explanation for the limited control of terrain age detected in this and other studies (Eichel et al., 2013; Rydgren et al., 2014). In summary, these finding suggests that time-dependent primary vegetation succession on lateral moraine slopes can switch in time to patch dynamics (Matthews, 1999).

8.4.4 Biogeomorphic succession

Both disturbance-controlled pathway and paraglacial process and landform succession demonstrate that geomorphic processes and species composition are closely related. This indicates that vegetation succession and paraglacial adjustment are connected through biogeomorphic feedbacks. Their coupled development can be described as a biogeomorphic succession *sensu* Corenblit et al. (2007). A model of this biogeomorphic succession on lateral moraine slopes is developed in this section by combining stages from the model of paraglacial succession (Figures 8.13, 8.16 B) with stages from the disturbance-controlled succession pathway (Figures 8.15, 8.16 C). Four phases of biogeomorphic succession on lateral moraine slopes are described: geomorphic phase, pioneer phase, biogeomorphic phase and ecologic phase (Figure 8.16 A). Previous geomorphic and ecologic knowledge on paraglacial adjustment and primary succession on lateral moraine slopes is used to describe ecosystem structure and function in each phase (cf. Corenblit et al., 2015). Stages from the conceptual biogeomorphic model of turf-banked solifluction lobe development (Chapter 6) are linked to the biogeomorphic successional phases (Figure 8.16 D).

Geomorphic phase: The geomorphic phase is characterized by purely abiotic interactions between processes, landform properties (geomorphometry) and material properties affecting slope stability (Figure 8.16, I Geomorphic phase). It corresponds to Stage I of the paraglacial succession, which is characterized by a high geomorphic process activity (Figure 8.16 B). Dead ice melt delays surface stabilization and promotes debris sliding, thermoerosion and debris flows. These processes are dominantly occurring with high frequencies and influence material distribution and slope geomorphometry. Together with unfavourable climatic conditions, dead ice melt and associated geomorphic processes inhibit vegetation colonization (Kaufmann, 2002; Matthews, 1992). In comparison to biogeomorphic succession in fluvial and coastal environments, processes from the the geomorphic phase are not responsible for species dispersal on lateral moraine slopes. Usually, they usually originate within the glacier foreland area and therefore transport bare sediments without diaspores. Hence, seeds are dispersed by other processes during this phase, commonly through wind (Caccianiga et al., 2006; Nagl and Erschbamer, 2010). As the geomorphic phase assumes a complete prior destruction of vegetation (Corenblit et al., 2007), it probably only occurs immediately following glacier retreat on young terrain age free of diaspores (Matthews, 1992). Thus, it lasts for years to decades, depending on ice core occurrence (Lukas et al., 2012).

Pioneer phase: The pioneer phase is characterized by the colonization and recruitment of pioneer species on the lateral moraine slopes, controlled by active geomorphic processes (Figure 8.16, II Pioneer phase; cf. Corenblit et al., 2015). It corresponds to Stage II of the paraglacial succession model (Gullying) and to both pioneer and early successional stage of the disturbance-controlled successional pathway (Figure 8.16 B, C). Geomorphic processes with high magnitude (debris flows) or high frequencies (water soil erosional processes) are dominating. Colonizing pioneer species can endure this high geomorphic activity either through adapted response traits (Figure 8.16 D) or the preference of safe sites, or a combination of both. Favourable response traits are often related to life-history traits, including high seed numbers, quick germination and growth and a tolerance of moist and cold conditions (Marcante et al., 2009; Stöcklin and Bäumler, 1996). They can also be related to plant morphology, including flexible roots and stems of debris vegetation (Schröter et al., 1926). Safe sites, such as depressions or larger rocks, can facilitate colonization by provide more stable and favourable microclimatic conditions (Cooper et al., 2004; Mori et al., 2013; Raffl et al., 2006). Vegetation cover is still very low in the pioneer stage (< 10%) (Figure 8.16 C; Nagl and Erschbamer, 2010), which corresponds to classes 1.1 and 1.3 at the investigated lateral moraine slopes. When the first ecosystem engineer dwarf shrub species manage to establish between high magnitude geomorphic processes or once process frequency has decreased sufficiently (establishment threshold, Figure 8.16 D; Eichel et al., 2016), vegetation succession proceeds to an early successional stage. It has been suggested that safe sites also facilitate the establishment of the ecosystem engineer *D. octopetala* on active slopes. In addition, *D. octopetala*'s can colonize vegetatively from more stable sites in this phase (Chapter 6). Small *D. octopetala* mats can already facilitate colonization for other species by trapping seeds and

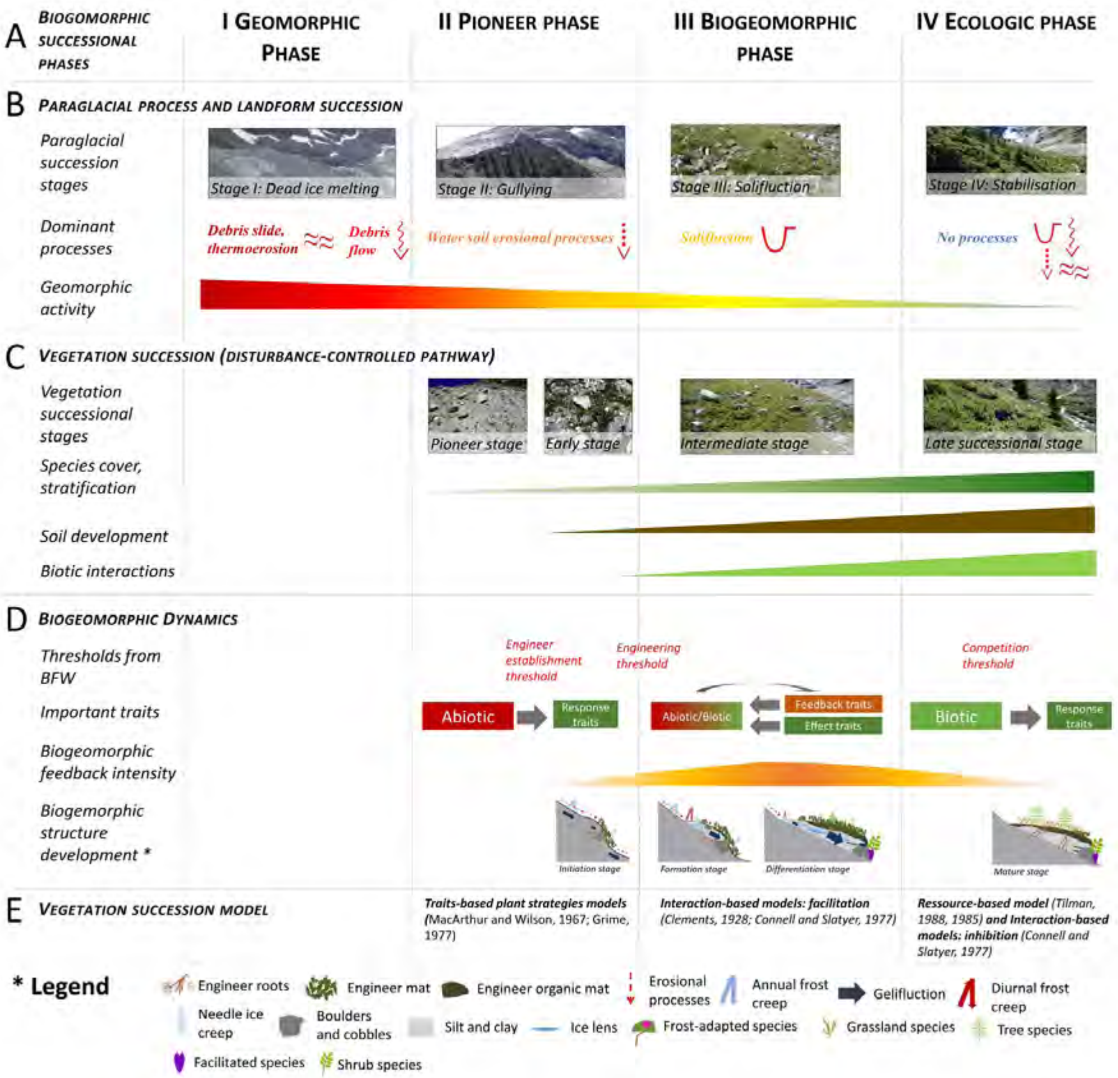

Figure 8.16: Biogeomorphic succession on lateral moraine slopes. **A** Biogeomorphic successional phases. **B** Corresponding paraglacial process and landfom successional stages with dominant geomorphic processes and changing geomorphic activity. **C** Corresponding vegetation successional stages of the disturbance-controlled pathway. Changing species cover, stratification and soil development are indicated. **D** Biogeomorphic dynamics during biogeomorphic succession, including biogeomorphic feedback thresholds identified in the biogeomorphic feedback window (BFW), important traits, biogeomotphic feedback intensity and linked development of turf-banked solifluction lobes as biogeomorphic structures. **E** Suitable vegetation succession models explaining vegetation development during the biogeomorphic successional phases.

providing safe sites themselves (Birks, 1980; Cutler et al., 2008; Elkington, 1971). Thus, species numbers increase at the end of the pioneer phase (Matthews, 1992; Raffl et al., 2006), biotic interactions start (Figure 8.16 C). The initial position of ecosystem engineer species on the slope, set in this stage, can strongly control subsequent slope development (Corenblit et al., 2007) e.g. the development of turf-banked solifluction lobes (Figure 8.16 D; Chapter 6). At the investigated lateral moraine slopes, the pioneer phase is characterized by vegetation classes 1.2, 2.1 and 2.3.

It usually lasts some years to decades, depending on geomorphic process magnitude and frequency and toposequence position. However, it can also be continuous at a local scale (Corenblit et al., 2015), e.g. in complex initiation areas and at cryoturbated moraine ridges. Here, pioneer vegetation (class 1.1 with gullying, class 1.3 with cryoturbation) persists for over a century (Figures 8.4, 8.9). On a larger scale, pioneer phase occurrence is punctual (Corenblit et al., 2015), as it necessitates high magnitude disturbances, such as debris flows, which strongly destroy vegetation through a large mechanical stress (Lamberti et al., 1991; Stoffel, 2010). A switch from the pioneer to the biogeomorphic phase occurs once engineer cover crosses an engineering threshold (around 35%, Figure 8.16 D; Eichel et al., 2016) and starts to actively influence occurring geomorphic processes, as described in the biogeomorphic feedback window (Chapter 4).

Biogeomorphic phase: In the biogeomorphic phase, feedbacks between geomorphic processes and plants are most intense and control paraglacial succession and ecosystem development, as well as the development of biogeomorphic structures (Figure 8.16; III Biogeomorphic phase). The biogeomorphic phase corresponds to Stage III of the paraglacial succession model (Solifluction) and the intermediate stage of the disturbance-controlled successional pathway (Figure 8.16 B, C). Biogeomorphic feedbacks are controlled by engineer effect and response traits this (Figure 8.16 D). Engineer effect traits, such as *D. octopetala*'s dense mat, induce a change from mass movement and water soil erosional processes to bound solifluction (see Chapter 4). Feedback traits, such as D. octopetala's flexible root system, provide a response to this change and enhances *D. octopetala*'s survival (Figure 8.16; Chapters 4, 6). Turf-banked solifluction lobes with distinct geomorphometry, material properties and species distribution can be produced feedbacks between *D. octopetala* and solifluction processes (formation and differentiation stage of turf-banked solifluction lobe development, Figure 8.16 D; Chapter 6). In addition, *D. octopetala* contributes to soil development by organic matter accumulation and nitrogen fixation (Figure 8.16 C; Elkington, 1971; Reisigl and Keller, 1994). This is an important control for biogeomorphic succession (Bätz et al., 2015b), as it facilitates the establishment of further species (classes 2.5, 2.6, 2.7). With increasing thickness of *D. octopetala*'s organic map, gelifluction movement decreases (Eichel et al., 2016), while soil temperatures increase (Egli et al., 2011). Later successional shrub and tress species (*Larix decidua, Pinus cembra*) can establish, biotic interactions increase and vegetation stratification commences (Figure 8.16 D; Andreis et al., 2001; Nagl and Erschbamer, 2010; Raffl et al., 2006).

Ecologic phase: The ecologic phase is characterized by a stabilization of both geomorphic system and ecosystem and the dominance of biotic interactions (Figure 8.16, IV Ecologic phase; cf. Corenblit et al., 2015). It corresponds to Stage IV of the paraglacial succession (Stabilization) and the late successional stage of the disturbance-controlled successional pathway (Figure 8.16 B, C) This phase is characterized by increasing stratification and advanced soil development, therefore, response traits to these changed biotic conditions become important, e.g. shade tolerance (Figure 8.16 D; Raffl et al., 2006; Robbins and Matthews, 2014; Schweingruber et al., 2007). Competition, e.g. for light increases and *D. octopetala* can become excluded by later successional species, which can grow more quickly and survive despite competition (Caccianiga et al., 2006; Marcante et al., 2009; Stöcklin and Bäumler, 1996). Biotic interactions, start to dominate and control ecosystem structure and function, which is partly or totally disconnected from geomorphic disturbances (Corenblit et al., 2015). This dominance of biotic interactions also applies for turf-banked solifluction lobes in their mature, stable stage (Figure 8.16 D; Chapter 6). Geomorphic processes no longer occur, paraglacial adjustment is completed (Figure 8.16 B).

It has been suggested that biogeomorphic succession dynamics are cyclic and follow an adaptive cycle (Corenblit et al., 2007). This also applies for biogeomorphic succession on lateral moraine slopes (see Chapter 9). The presented biogeomorphic succession model follows the general ideas of the geoecological model for glacier foreland succession presented by Matthews (1992) with a decreasing importance of abiotic and increasing importance of biotic factors. However, the different biogeomorphic successional phases can also be linked to different successional models (Figure 8.16 E). For the pioneer phase, trait-based successional models offer the best explanation, as they focus on the role of dispersal strategy, growth rates (Model r- & K-strategists; MacArthur and Wilson, 1967) and adaptations to disturbances (CSR primary plant strategies; Grime, 1977), which determine pioneer colonization on lateral moraine slopes. In the biogeomorphic phase, facilitation by ecosystem engineers is the key control for establishment of lateral successional species, as suggested by Clements (1928) and Connell and Slatyer (1977). In addition, with increasing soil development, available resources (Tilmann, 1985, 1988) start to affect succession and increase competition, which favours trees and shrubs as competitive K-strategists or C-competitors (Grime, 1977). This results in the inhibition of ecosystems engineers in the ecologic phase (Connell and Slatyer, 1977). Thus, biogeomorphic succession dynamics on lateral moraine slopes represent a sequence of classic successional models. A similar sequence of changing successional regimes controlling ecosystem development was described by Cutler et al. (2008) for lava flows in Iceland. Here, the initial colonization model explains successional dynamics in early stages with pioneer nucleation in safe sites and pioneer patch growth. In later stages, ecosystem development follows the geoecological model.

In comparison to biogeomorphic succession in coastal and fluvial environments, biogeomorphic succession on lateral moraine slopes is not linked to time since glacier retreat, which would be comparable to time since the last high magnitude flood. Instead, biogeomorphic succession is probably linked to time since the last high-magnitude geomorphic disturbance such as debris flows or snow avalanches. However, these usually do not produce completely bare ground, but instead only partly destroying vegetation. Thus, linking biogeomorphic succession to a time component is difficult for lateral moraine slopes.

8.4.5 Biogeomorphic patch dynamics

The presented results show that vegetation classes and geomorphic processes are spatially associated in patches (Figures 8.4, 8.5, 8.9, 8.10). This indicates that biogeomorphic succession is a patch-internal process of the patch mosaic. How this patch mosaic shifts in time can be described as biogeomorphic patch dynamics (Figure 8.17). While the classic patch dynamics concept concentrates on disturbance-induced mosaic changes (Pickett et al., 1999; Pickett and White, 1987), this concept includes the role of biogeomorphic feedbacks for patch creation and dynamics (Hastings et al., 2007; Stallins, 2006; Wright et al., 2004). Thereby, it highlights plants can modify geomorphic disturbances regimes through biogeomorphic feedbacks and thus control spatiotemporal vegetation and geomorphic dynamics.

As discussed in the previous Section 8.4.3, the patch mosaic at the investigated lateral moraine slopes is made up by patches in different successional stages. These follow either the material-controlled pathway or the disturbance-controlled successional pathway, which was interpreted as a biogeomorphic succession (Figure 8.17 A). Patch-internal succession is controlled either by terrain age for the material-controlled pathway or decreasing geomorphic activity for biogeomorphic succession.

Through disturbances and ecosystem engineering during biogeomorphic succession, this patch mosaic changes in time. Geomorphic disturbances create new patches in the patch mosaic with a process-specific patch shape, size and material properties (Montgomery, 1999; Turner et al., 2001). These disturbance patches can show an internal differentiation related to different landforms (Figure 8.17 B). The presented maps show that species distribution and material properties in debris flow-affected areas differ between complex initiation areas and debris flow

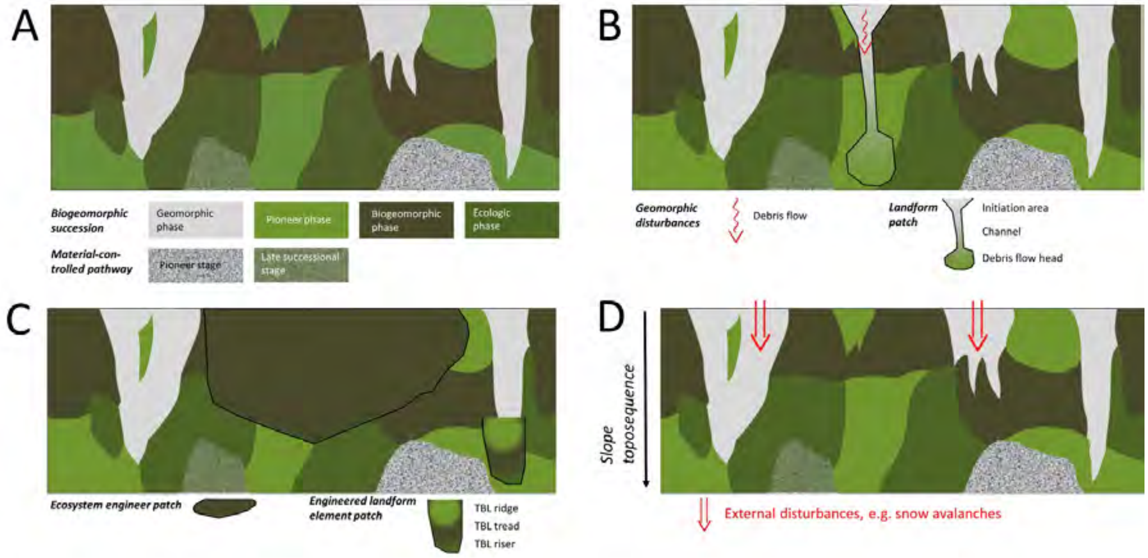

Figure 8.17: Biogeomorphic patch dynamics on lateral moraine slopes. **A** Illustration of patch mosaic with patches in different biogeomorphic succession phases and patches in different stages of the material-controlled pathway. **B** Changes of the patch mosaic resulting from geomorphic disturbances which can create landform patches. **C** Changes of the patch mosaic resulting from ecosystem engineering, including ecosystem engineer patches and engineered landform element patches. **D** Toposequence and external disturbance controls on patch mosaic changes.

cones (Figures 8.4, 8.9). These 'landform patches' can be explained by the decreasing movement velocity and erosive power of debris flows towards the slopefoot (Hungr, 2005). This results in a quicker vegetation recovery in debris flow depositional areas (Wooten et al., 2016) in comparison to complex initiation areas and channels. The (re)starting point of patch-internal biogeomorphic succession following disturbance patch creation is determined by geomorphic disturbance intensity (process magnitude) and the state (successional phase) of the affected area prior to the disturbance (cf. Corenblit et al, 2015). If disturbances affect patches of the material-controlled successional pathway or patches in later biogeomorphic successional phases, they can subsequently follow the linked successional pathway (compare Sections 8.4.3, 8.4.4).

Ecosystem engineering can create ecosystem engineer patches and landform element patches in the biogeomorphic phase (Figure 8.17 C). The role of ecosystem engineers for patch creation has been highlighted in previous studies (Hastings et al., 2007; Wright et al., 2004) and is supported by the results from this study. The geomorphic and vegetation maps (Figures 8.4, 8.5, 8.9, 8.10) suggest that patches of the ecosystem engineer *D. octopetala* (vegetation class 2) can develop to large sizes if the disturbance interval is sufficiently long (e.g. 1920s moraine ridge, southern lateral moraine complex, Figure 8.9). Thereby, they can overgrow disturbance-related patches, e.g. complex initiation areas, and change their process regime to bound solifluction, which shows at the northern lateral moraine complex (Figure 8.9). This overriding of larger disturbance patches by smaller patches has been described in the hierarchical patch dynamics concept (Coller et al., 2000; Wu, 1999) and was previously found previously in alpine environments (Zeng et al., 2007) and other stressful habitats (Cutler et al., 2008). Ecosystem engineer patches can develop in all slope positions and are therefore independent from the dominant toposequence gradient (Figure 8.17 D), which strongly influences paraglacial adjustment and vegetation succession (Sections 8.2, 8.3). Large engineer patches in upper slope and crest positions can exert a key control on spatial and temporal paraglacial adjustment and linked vegetation succession. By limiting geomorphic activity in upslope positions, ecosystem engineer patches also promote vegetation succession in slopefoot positions, as these are no longer affected by high-magnitude geomorphic disturbances. At the investigated lateral moraine slopes, this shows in the central area of the northern lateral moraine complex, where later successional tree species mainly occur below upper slope engineer patches (vegetation class 2). Thus, ecosystem engineer patches can result in historical path dependency of landscape development as suggested by Stallins (2006). Landform element patches are created by ecosystem engineering within patches situated in the biogeomorphic phase. This fine-scale patch creation through ecosystem engineering has been shown for turf-banked solifluction lobes (TBL), where fine-scale species distribution and landform element activity (of riser, tread, ridge) are closely interlinked (Chapters 5, 6).

A decreasing impact of disturbances in time, which is usually expected in glacier forelands (Robbins and Matthews, 2010) could not be detected at lateral moraine slopes in the Turtmann glacier foreland. Instead, high geomorphic activity on older terrain is probably fuelled by external larger magnitude disturbances such as snow avalanches (Figure 8.17 D). These often completely remove vegetation cover (Major, 1977, Patten and Knight, 1994), thereby delay paraglacial adjustment and keep the biogeomorphic patch dynamics running at the investigated lateral moraine slopes. In other settings without external disturbances, biogeomorphic patch dynamics on lateral moraine slopes are probably limited and stop with increasing terrain age, when stable mosaic situations are can created by positive interactions during ecosystem development (Cutler et al., 2008).

The biogeomorphic patch dynamics concept highlights the strong linkage of physical and biotic patchiness described by Wu and Loucks (1995) and demonstrates how patterns and heterogeneity are produced by recursive feedbacks between disturbances and vegetation, as suggested by Stallins (2006). It represents a helpful concept for environments with discrete disturbances, e.g. hillslopes, in comparison to fluvial and coastal environments, which are characterized by large hydrogeomorphologic disturbances. Yet, the occurrence of a shifting mosaic and hierarchical patchiness has also been suggested for fluvial systems (Coller et al., 2000; Corenblit et al., 2014). The applicability of the biogeomorphic patch dynamics concept in these systems needs to be tested, as well as in other high mountain biogeomorphic ecosystems, such as talus slopes, complex cones and alluvial fans (Baroni et al., 2007; Gentili et al., 2010; Lane et al., 2016b).

In addition, together with the biogeomorphic succession concept, it highlights the importance of bi-directional biogeomorphic studies to understand paraglacial adjustment and vegetation succession on lateral moraine slopes. By addressing spatial geomorphic and vegetation patterns, this concept could help to understand sediment dynamics, sediment connectivity (cf. Brierley et al., 2006; Messenzehl et al., 2014) and natural hazards (e.g. debris flows) in glacier forelands.

8.5 Conclusion

By combining permanent plot data and geomorphic and vegetation mapping at a slope scale, this chapter demonstrates that paraglacial adjustment and vegetation succession and their spatial patterns on lateral moraine slopes are strongly linked by biogeomorphic feedbacks during temporal biogeomorphic succession and spatiotemporal biogeomorphic patch dynamics. Key findings are:

(1) **Slope toposequence, material properties and ecosystem engineering by the dwarf shrub *Dryas octopetala* L. control paraglacial adjustment of lateral moraine slope, which follows a sequence of paraglacial processes and landform succession**. Paraglacial adjustment is first completed at slopefoot positions and in blocky material. Rockfall and snow avalanches from adjacent valley slopes delay paraglacial adjustment at fine material-rich crest positions. Independently from toposequence and material controls, ecosystem engineering induces a key change in process regime from gullying to solifluction processes. These affect large lateral moraine slope areas and are therefore an important paraglacial process for sediment reworking. A sequence of paraglacial process and landform succession was found, starting with dead ice induced geomorphic processes at young terrain in Stage I, followed by highly active gullying processes in Stage II. Ecosystem engineering shifts the process regime to solifluction processes in Stage III. No occurring geomorphic processes and advanced

ecosystem development with vegetation stratification and most developed soils indicate stabilization and the completion of paraglacial adjustment in Stage IV. Geomorphic maps show that paraglacial succession is spatially variable on lateral moraine slopes, depending on the identified controls. This limits the applicability of chronosequence approaches and highlights the importance of geomorphic mapping to understand sediment dynamics.

(2) **Vegetation succession on lateral moraine slopes occurs along two successional pathways in a patch mosaic and is strongly controlled by material properties and geomorphic activity, linked to ecosystem engineering, slope gradient and toposequence position.** Two simultaneously occurring successional pathways can explain a patch mosaic of vegetation classes found on the investigated lateral moraine slopes. The **material-controlled successional pathway** explains *Salix* shrub development on stable blocky material, driven by initial material properties and terrain age. The **disturbance-controlled successional pathway** occurs on geomorphically active finer material and is controlled by a decreasing geomorphic activity, linked to ecosystem engineering by *D. octopetala*. While pioneer species dominate in highly active mass movement and water soil erosional patches, the ecosystem engineer *D. octopetala* can induce a transition of these patches to intermediate and later successional stages by promoting less active solifluction processes and soil development. Establishment of later successional tree and shrubs species is facilitated in the stabilized patches with advanced soil development. By changing material distribution and creating new patches, geomorphic processes can link the two successional pathways and decrease patch sizes with increasing terrain age. The disturbance-controlled pathway dominates on older terrain and indicates that time-dependent primary vegetation succession on lateral moraine slopes in time switches to patch dynamics, driven by geomorphic processes and snow avalanches originating from adjacent slopes above.

(3) **Paraglacial adjustment and vegetation succession are strongly linked on lateral moraine slopes and follow a biogeomorphic succession, which in space occurs in a shifting patch mosaic described by biogomorphic patch dynamics.** Linked paraglacial adjustment and vegetation succession can be described as biogeomorphic succession in four phases. In the (i) geomorphic phase, dead ice melt and related geomorphic processes inhibit vegetation colonization but create the initial material and geomorphometric setting. When dead ice melt is completed and climatic conditions improve, pioneer species can colonize in the (ii) pioneer phase, which are adapted to dominant guylling processes by their morphological and life

history response traits. With deceasing processes frequency or in between high magnitude processes, ecosystem engineer species can establish. They further decrease geomorphic activity through their root and above-ground biomass effect traits and change the process regime to solifluction processes in a (iii) biogeomorphic phase with most intense biogeomorphic feedbacks. Turf-banked solifluction lobes as biogeomorphic structures can develop through ecosystem engineering. By promoting soil development and stabilizing the slope, ecosystem engineers facilitate the establishment of later successional shrub and tree species. Biotic interactions dominate in the (iv) ecologic phase. Later successional species exclude ecosystem engineers through competition, vegetation is stratified and soils are well developed. Paraglacial adjustment is completed. In space, biogeomorphic succession occurs in patches, which make up patch mosaic together with patches of the material-controlled successional pathway. Changes of these patch mosaic occur through geomorphic disturbances and ecosystem engineering, described as biogeomorphic patch dynamics. Geomorphic disturbances create new patches, which are often controlled by slope toposequence and related differing landforms. If the disturbance-free time is sufficient, ecosystem engineer patches can overgrow disturbance patches in the biogeomorphic phase, smaller scale landform element patches can develop. In upper slope and crest positions, ecosystem engineer patches can strongly control the future development of the lower lateral moraine slope. Biogeomorphic patch dynamics are on-going at the investigated lateral moraine slope through moraine slope-external disturbances, e.g. snow avalanches.

Results from this study demonstrate the strong linkage between paraglacial adjustment and vegetation succession on lateral moraine slopes, which is spatially variable. This limits chronosequence approaches and highlights the importance of bi-directional biogeomorphic studies to understand lateral moraine slope development, sediment dynamics and natural hazards

9 SYNTHESIS: SCALE-RELATED BIOGEOMORPHIC FEEDBACKS AND THEIR LINKAGES IN LATERAL MORAINE BIOGEOMORPHIC ECOSYSTEMS

‚How could slow geomorphic processes possibly be affected by fast biological ones?’ (Holling, 1992, p. 481)

‚We are recognizing that for some [...] systems on the surface of Earth, broad-scale properties can emerge from lower-level interactions between geomorphic and ecological components’ (Stallins, 2006, p. 208)

This chapter addresses thesis objective 5. It provides a summary of findings in this thesis and assigns them to the hierarchical levels and their related scales described in the thesis design (Chapter 3). Based on determined geomorphic, ecologic and biogeomorphic components and processes, lateral moraines and glacier forelands are identified as biogeomorphic ecosystems. Subsequently, this chapter demonstrates how scale-related feedbacks are interacting across scales in this biogeomorphic ecosystem, using a panarchy approach based on adaptive cycles. Finally, limitations of this thesis are discussed in relation to the study’s hierarchical levels.

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9 SYNTHESIS

9.1 Scale-related biogeomorphic feedbacks on lateral moraine slopes

In all hierarchical levels of the investigated lateral moraine slope system, scale-related biogeomorphic feedbacks have been detected in this thesis and were described using existing or novel biogeomorphic concepts (Figure 9.1).

Mechanisms for biogeomorphic feedbacks in the focal level are explained by the dwarf shrub ***Dryas octopetala*** **L.** acting **as *ecosystem engineer*** in the lower level -1 (Figure 9.1 A). Ecosystem engineering relates to a spatial scale of 1 cm² to 5 m² and a timescale of seconds to years. *D. octopetala* changes mechanical, hydrological, thermal and chemical material and surface properties in its environment through its adapted root and above ground biomass traits (Chapters 4 and 6). This ecosystem engineering affects higher-level geomorphic processes, vegetation communities and their feedbacks.

The concepts of a biogeomorphic feedback window and ecosystem engineering of biogeomorphic structures describe biogeomorphic feedbacks in the focal level 0 (Figure 9.1 B, C). They occur on a spatial scale of approximately 5 m² to 1 ha and in a timescale of months to decades. The ***biogeomorphic feedback window*** (Figure 9.1 B) describes the conditions under which feedbacks between geomorphic processes, landforms and plants can occur (Chapter 4). They depend on the relationship between (i) geomorphic process magnitude, ecological severity and process frequency (geomorphic disturbance regime) and (ii) plant species resilience (speed to regrow after a disruptive event) and resistance (magnitude of disturbance that can be absorbed), determined by its traits. Feedbacks between the ecosystem engineer *D. octopetala* and solifluction processes in the biogeomorphic feedback window can create ***turf-banked solifluction lobes (TBL) as biogeomorphic structures*** (Figure 9.1 C). Biogeomorphic structure creation can be described as an ecosystem engineering process, which links engineer traits to resulting changes of material and surface properties and depending geomorphic processes (Chapter 6). Large and thick TBLs can be produced in this process, which provide variable habitats for others species at the lobe elements riser, tread and ridge. In addition, they are an important component of paraglacial adjustment (Chapter 5).

In the higher level +1, conditions for feedbacks in the focal level 0 are set by the temporal sequence of biogeomorphic succession, which is spatially represented in biogeomorphic patch dynamics (Figure 9.1 D, E). **Biogeomorphic succession** occurs in a timescale of decades to centuries and links paraglacial adjustment and vegetation succession in four phases with a

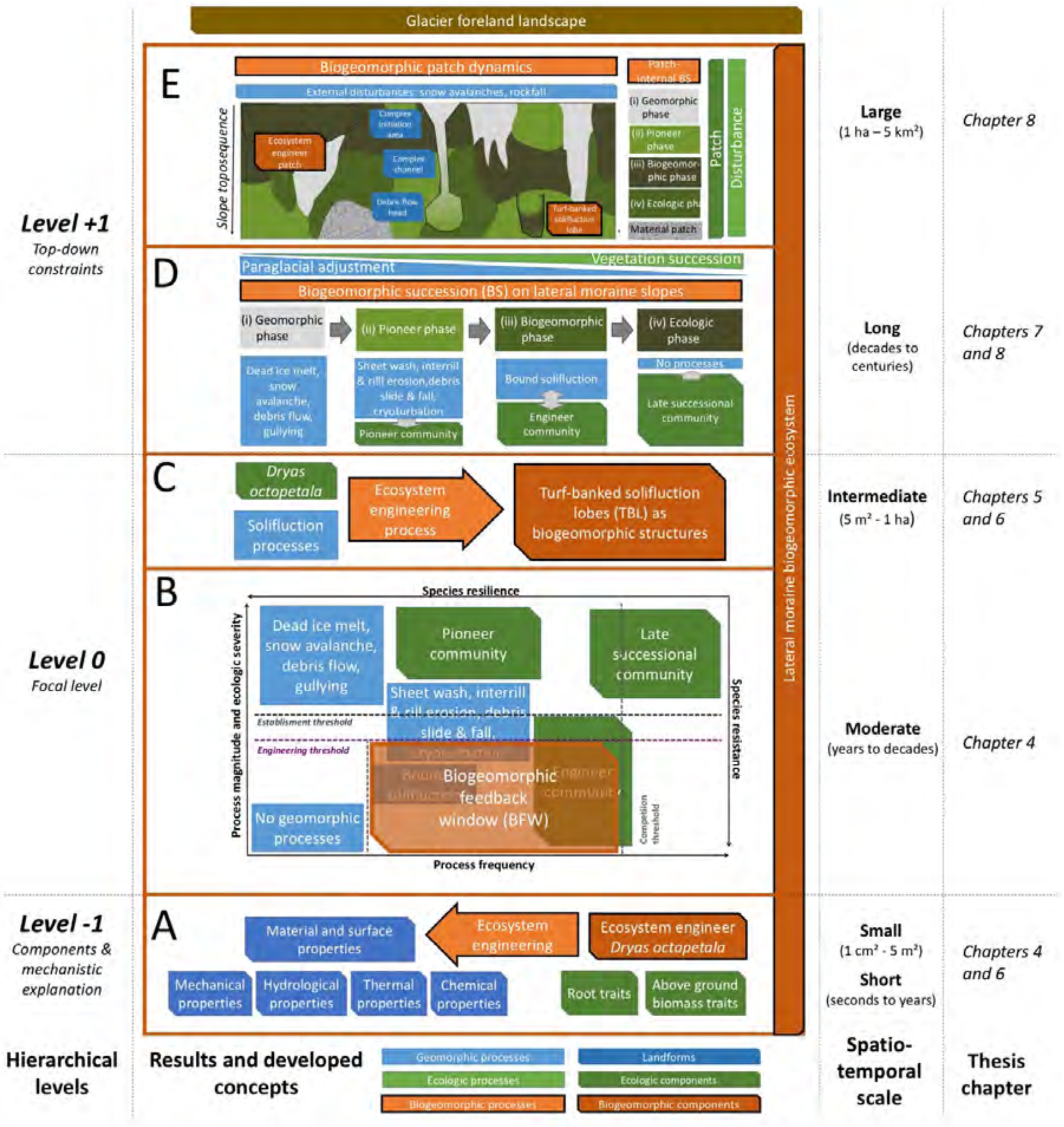


Figure 9.1: Summary of thesis results and developed biogeomorphic concepts in relation to investigated hierarchical levels. On level -1, ecosystem engineering by *Dryas octopetala* L. was identified (**A**), which affects material and surface properties on short and small scales. In level 0, a biogeomorphic feedback window describes conditions for biogeomorphic feedbacks (**B**), which depend on the relationship between geomorphic process magnitude and frequency and plant species resilience and resistance on a moderate timescale. At an intermediate spatial scale, turf-banked solifluction lobes as biogeomorphic structures are created in an ecosystem engineering process in level 0 (**C**). In level +1, biogeomorphic succession links paraglacial adjustment and vegetation succession on lateral moraine slopes in four phases on a long timescale (**D**). At a large spatial scale, biogeomorphic patch dynamics describe how the slope-scale patch mosaic changes through geomorphic processes and ecosystem engineering (**E**). The lateral moraine slope biogeomorphic ecosystem (Section 9.2), consisting of geomorphic processes, landforms, ecologic processes and components and their scale-related biogeomorphic feedbacks, is indicated.

decreasing importance of geomorphic and increasing importance of biotic components (Chapters 7 and 8; Figure 9.1 D). In space, biogeomorphic succession elapses in patches. These compose a slope-scale patch mosaic of disturbance- and material related patches in a spatial scale of 1 ha to 5 km² (Figure 9.1 E). How this patch mosaic changes, is described in the concept of **biogeomorphic patch dynamics** (Chapter 8). New patches are created by geomorphic processes, influenced by a main toposequence gradient, and by ecosystem engineering. Biogeomorphic patch dynamics are kept on-going on older terrain by external disturbances, such as snow avalanches.

9.2 Lateral moraines as biogeomorphic ecosystems

Corenblit et al. (2015) stated eight criteria to identify biogeomorphic ecosystems based on their physical environment properties and adapted plant functional traits. In biogeomorphic ecosystems, (i) unstable (unconsolidated) sediments dominate and are (ii) subject to a physical disturbance regime. This disturbance regime consists of (iii) low to medium magnitude variations and (iv) medium to high magnitude fluctuations (extreme events) and is linked to an (v) environmental gradient. Occurring plants must possess (vi) response traits to react to the geomorphic disturbances and environment and (vii) effect traits to control them. In addition, they need (viii) feedback traits which offer a response to induced changes in their environment.

This thesis shows that lateral moraines fulfil all criteria: (i) Unstable sediments left behind by the retreating glacier are a typical feature of glacier forelands and lateral moraine slopes (Figure 9.2 A, B; Chapters 2, 8). Geomorphic processes reworking these sediments make up the (ii) physical disturbance regime on lateral moraine slopes. It consists of both (iii) low to medium magnitude variations through water soil erosional (Figure 9.2 C, D) and periglacial processes (Figure 9.2 E) and (iv) medium to high magnitude fluctuations through debris flows (Figure 9.2 F), snow avalanches (Figure 9.2 G) and landsliding (Figure 9.2 H). The slope toposequence (Figure 9.2 I) represents the main environmental gradient on lateral moraine slopes, which controls geomorphic and vegetation dynamics and patterns (see Chapter 8). Therefore, it is comparable to the transverse gradient of hydrogeomorphic connectivity and topography in fluvial systems, to wave energy and salinity gradients in coastal systems and wind exposure and submersion duration gradients at coastal dunes (Corenblit et al., 2015). (v) Response traits to geomorphic environment and disturbance regime have been developed by both pioneer and engineer species. Life history and morphological response traits enable pioneer species to quickly recover after high magnitude

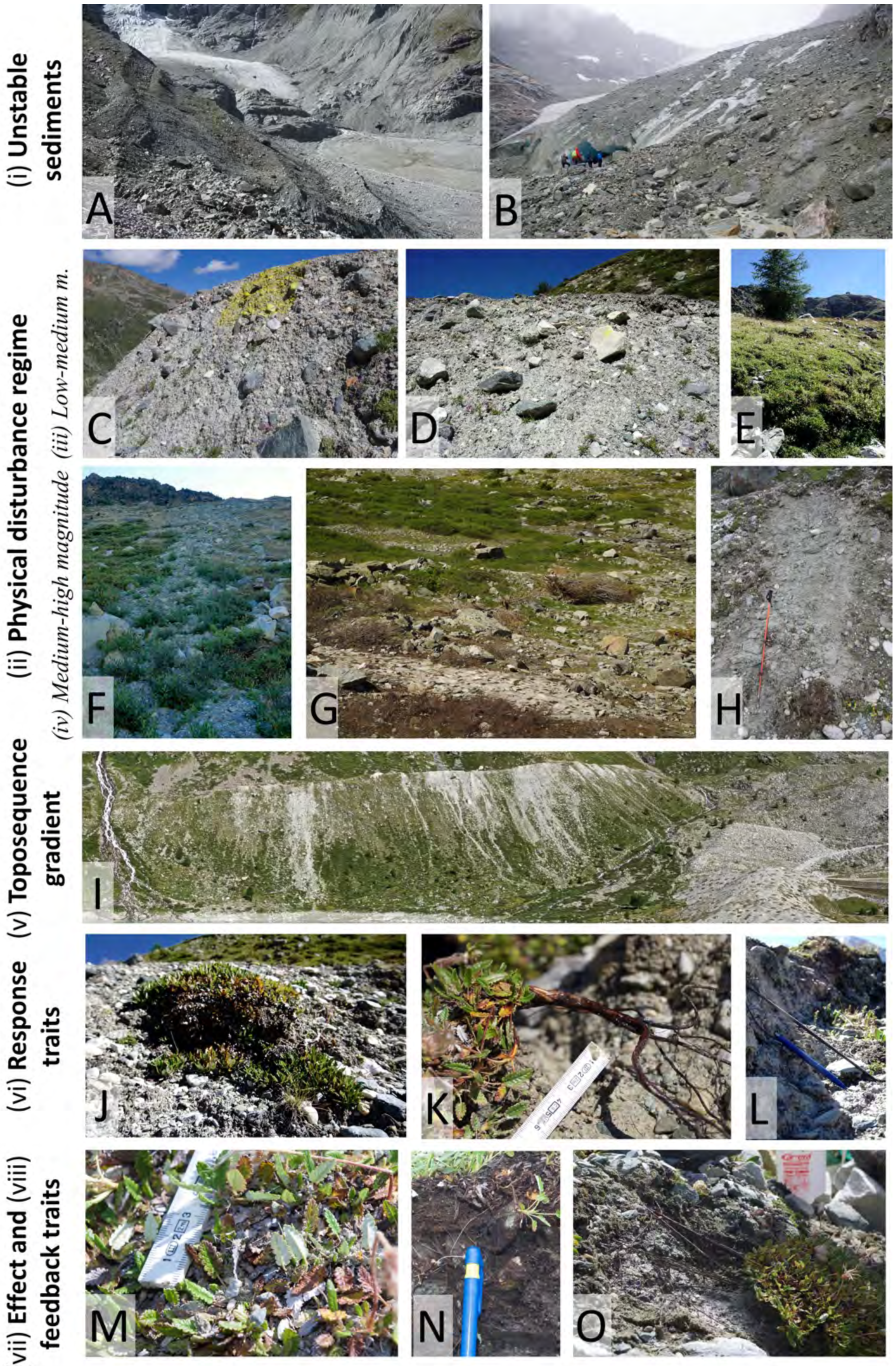


Figure 9.2: Illustration of a lateral moraine biogeomorphic ecosystem, based on photography from Turtmann glacier foreland. **A** Unstable lateral moraine slope sediments. **B** Unstable sediments at the glacier front immediately following glacier retreat. **C** Moraine crest with spray paint square in 2014 and **D** in 2016 with spray point square removed by water soil erosional processes and individual clast slide. **E** Bound solifluction. **F** Debris flow deposit. **G** Snow avalanche deposit. **H** Shallow landslide at moraine crest. **I** Geomorphic and vegetation patterns at lateral moraine slope demonstrating toposequence gradient. **J** Establishment of *D. octopetala* from plant fragments. **K** *D. octopetala* root system. **L** High tensile strength root (*Salix serpyllifolia*) at tension crack. **M** Fine sediment trapped in *D. octopetala* mat structure. **N** *D. octopetala* organic mat. **O** *D. octopetala* roots growing upslope.

disturbances and to resist low to medium magnitude disturbances (see Chapter 4). Engineer response traits to high magnitude disturbances include *D. octopetala*'s ability to establish from plant fragments (Figure 9.2 J), while its high tensile strength, deeply-rooted roots (Figure 9.2 K, L) enable it to anchor under low to medium magnitude disturbances (see Chapter 4). Its mat structure and thick organic mat (Figure M, N) are (vi) effect traits which change the disturbance regime to low magnitude solifluction processes (Chapters 4, 6). A feedback trait to this modification is its high phenotyphic plasticity, which enables its roots to respond to downslope solifluction movement by growing upslope (Chapter 6, Figure 9.2 O). *Salix* dwarf shrub engineer species growing on lateral moraine slopes possess partly similar traits (see Chapter 4).

Based on this evidence, lateral moraines can be identified as biogeomorphic ecosystems. In comparison to fluvial and coastal BEs, lateral moraine BEs possess the most variable physical disturbance regime. It is characterized by various types of geomorphic disturbances, which are mostly punctual. This makes lateral moraine BE dynamics unpredictable (Levin 1992) and results in the detected spatial heterogeneity. It is likely that other systems with a similarly varied disturbance regime, such as talus slopes or complex cones (Baroni et al., 2007; Gentili et al., 2010; Lane et al., 2016b), behave in a comparable way and are also BEs. In addition, the presented results on biogeomorphic interactions in the entire glacier foreland area (Chapter 7), indicate that glacier forelands, and especially their glaciofluvial floodplain, are probably also biogeomorphic ecosystems.

How structure and function in lateral moraine BEs is created by the scale-related biogeomorphic feedback (Figure 9.2) and their linkages which will be presented in the following section.

9.3 Linking the scales: Panarchical biogeomorphic dynamics in lateral moraine BEs

Following the panarchy concept by Holling et al. (2002), the hierarchical lateral moraine BE can be considered as a dynamic, adaptive entity whose levels interact (Figure 9.3). Biogeomorphic dynamics in each level of the lateral moraine BE can be described by adaptive cycles. At small spatial and short temporal scales in level -1, the ecosystem engineer life cycle represents an adaptive cycle. At intermediate spatial and moderate temporal scales in the focal level 0, patch-internal biogeomorphic succession proceeds in an adaptive cycle, while patch mosaic development and changes during biogeomorphic patch dynamics follow an adaptive cycle at the largest spatial scale in level +1. Stability and instabilities in these adaptive cycles can result from processes and structures at larger or smaller scales (Holling et al., 2002; Dikau, 2006). Larger scale

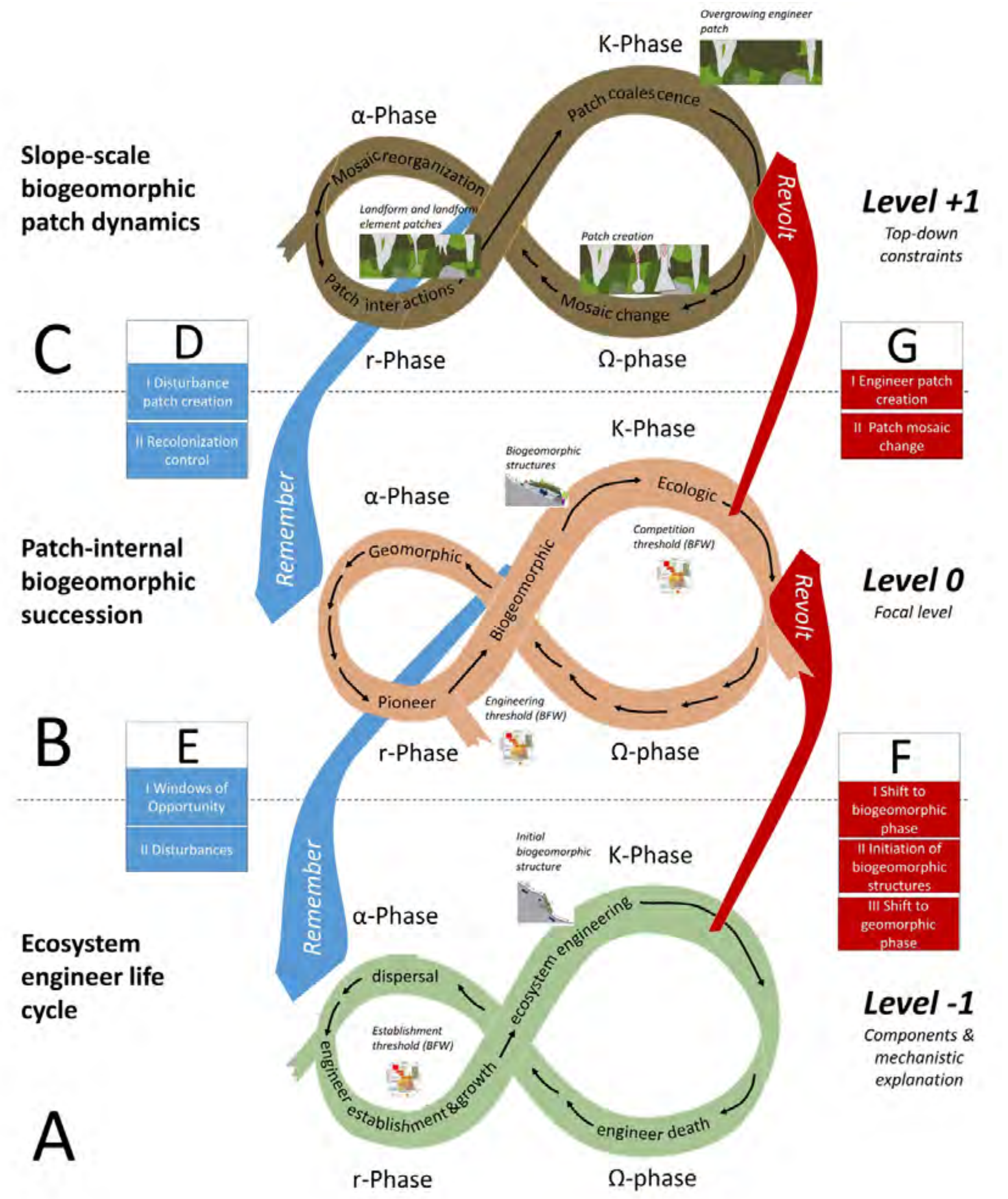


Figure 9.3: Panarchy of lateral moraine BE which is creating its structure and function. In the lowest level -1, the ecosystem engineer life cycle follows an adaptive cycle (**A**). It influences the focal level 0 adaptive cycle of of patch-internal biogeomorphic succession (**B**) through Revolt interactions. Dynamics during the engineer adaptive cycle can (I) shift the biogeomorphic succession to its biogeomorphic phase, (II) initiate biogeomorphic structures and (III) shift the biogeomorphic succession to its geomorphic phase (**F**). In turn, the biogeomorphic succession adaptive cycle influences the engineer adaptive cycle through Remember interactions, which include the setting of (I) Windows of Opportunity and the production of (II) Disturbances (**E**). In level +1, slope-scale biogeomorphic patch dynamics follow an adaptive cycle (**C**). This cycle is influenced by the biogeomorphic succession adaptive cycle through Revolt interactions, which comprise the (I) creation of engineer patches and other (II) changes in the patch mosaic (**G**). In turn, the patch dynamics adaptive cycle influences the biogeomorphic succession adaptive cycle by the (I) creation of disturbance patches and (II) controlling patch recolonization during Remember interactions (**D**).

adaptive cycles influence smaller scale cycles through *Remember* interactions, while smaller scales impact larger scale adaptive cycles through *Revolt* interactions. In the subsequently described panarchy of the lateral moraine BE, these scale interactions are not limited to the Ω-Phase of the influencing adaptive cycle, as described by Holling et al. (2002), but can also occur during other phases of the adaptive cycles. In addition, adaptive cycles can be left in every stage and change to a different adaptive cycle according to Widlok et al. (2012).

9.3.1 Smallest scale adaptive cycle: Ecosystem engineer life cycle (level -1)

On a small scale, ecosystem engineering is probably the most relevant detail according to Levin (1992) for higher levels dynamics. It can be represented as an adaptive cycle based on the life cycle of an ecosystem engineer, in this case *D. octopetala* (Figure 9.13 A; cf. Chapters 4, 6). The *α-Phase* (reorganization phase) of the adaptive cycle is characterized by engineer dispersal. *D. octopetala* disperses either through wind, followed by seed germination, or by plant fragments, which can be transported by geomorphic processes. Position and timespan of engineer establishment in the *r-Phase* (exploitation phase) depend on the availability of safe sites, site-specific environmental conditions and disturbance regime (Chapters 6, 8). Once an establishment threshold is crossed, the engineer aims at rapid growth and resource acquisition (r-strategy; Holling, 1992; MacArthur and Wilson, 1967). It is likely that engineer growth first focuses on root development to improve anchoring at the slope, similar to the rapid anchorage of ecosystem engineers in other BEs (Corenblit et al., 2015). With expanding engineer root system, mat growth and organic mat development, the connectedness between the engineer and its environment increases. System organization, related to plant morphology, starts to control feedbacks between engineer traits and material and surface slope properties in the *k-Phase* (conservation phase; cf. Holling, 2001). Engineer roots increase slope stability and change hydrological slope properties, engineer mat structure traps fine material and its organic mat changes thermal properties and promotes soil development during an ecosystem engineer process (Chapters 4). Ecosystem engineers become strongly connected to solifluction processes that characterize their geomorphic environment (Chapters 5, 6). When the engineer dies, the system loses its connectedness and stability and proceeds to the *Ω-phase* (release phase). Ecosystem engineers can die from natural causes (age of *D. octopetala* up to 100 years; Wookey et al., 1995), through competition by tree and shrub species, through environmental constraints or by removal trough high magnitude geomorphic disturbances (Chapters 4, 8). Following engineer death, the adaptive cycle restarts or switches into a different adaptive cycle, depending on engineer diaspore availability and environmental conditions.

9.3.2 Intermediate scale adaptive cycle: patch-internal biogeomorphic succession (level 0)

On an intermediate scale in level 0, patch-internal biogeomorphic succession follows an adaptive cycle, which is characterized by a changing intensity of biogeomorphic feedbacks (Figure 9.3 B; Chapters 7, 8). The *α-Phase* represents the geomorphic phase of biogeomorphic succession. In this phase, geomorphic processes dominate and (re)organize the physical system structure, e.g. by material redistribution and shaping of slope geomorphometry (Chapter 8). In addition, plant diaspores are introduced into the system. Pioneer and engineer species subsequently establish in the *r-Phase*, which represents both pioneer phase and biogeomorphic phase within biogeomorphic succession. They are separated by the engineering threshold described in the biogeomorphic feedback window (Chapter 4). Pioneer species are r-strategists with a ruderal behaviour, which aim at rapid growth (Holling, 2001) and are highly resilient towards occurring geomorphic disturbances (Chapter 4). They dominate until ecosystem engineer species cover increases sufficiently to cross an engineering threshold towards the biogeomorphic phase (Chapters 4, 7, 8). Now, biogeomorphic feedbacks start to build up structure and organization in the system. Initial biogeomorphic structures can develop (Chapters 6, 8), biomass and system connectedness slowly increase and the system enters the *K-Phase*. In the beginning of the K-Phase, biogeomorphic feedbacks dominate and biogeomorphic structures increase in size (Chapters 7, 8). Their spatial organization starts to influence system dynamics, e.g. by inducing offsite erosional effects and changing the hydrological properties of the slope (Chapters 5, 6). Soils develop and increase resource availability. With increasing connectedness and resources, the establishment of later successional tree and shrub species is facilitated, which are more competitive than engineers. When the competition threshold, described in the biogeomorphic feedback window, is crossed, K-strategists start to dominate in the later *K-Phase,* which represents the ecologic phase of biogeomorphic succession (Chapters 4, 8). System resilience decreases, as increasing vegetation stratification by tree and shrub species raises its vulnerability to high magnitude disturbances (Chapter 8). Due to internal system fluctuations (e.g. biogeomorphic structure collapse, Chapter 6) or external disturbances (e.g. snow avalanches, Chapter 8), the system can lose its stability and enter the *Ω-Phase*. Destruction of vegetation and soils releases stored capital and energy in the system. The adaptive cycle can be left and a new adaptive cycle with a different starting point for biogeomorphic succession can be entered (Chapter 8), or the adaptive cycle restarts with the α-Phase. However, as discussed in Chapter 8, return to the same adaptive cycle following a high magnitude disturbance is unlikely, as these usually create new initial conditions in relation to biological heritage and material properties.

9.3.3 Largest scale adaptive cycle: slope-scale biogeomorphic patch dynamics (level +1)

On a large scale in level +1, changes of the slope-scale patch mosaic, described in the concept of biogeomorphic patch dynamics, follow an adaptive cycle (Chapter 8). Immediately following deglaciation, the initial spatial organization of patches is defined in a first *α-Phase*, e.g. through slope geomorphometry and material distribution, linked to glacier sediment source and deposition and geomorphic processes. This patch mosaic is modified during subsequent adaptive cycles of biogeomorphic patch dynamics. These are characterized by slow patch-internal succession along different pathways (Chapter 8) during the r and K-Phases, and subsequent rapid mosaic change and reorganization in the α- and Ω-Phases. In the *r-Phase,* patch interactions, e.g. diaspore and sediment exchanges, build up structure and organization of the patch mosaic. The development of landform patches (e.g. complex initiation areas, channels and debris flow heads) in this stage is influenced by the slope toposequence (Chapter 8). Moreover, ecosystem engineering can create smaller-scale landform element patches (e.g. TBL riser, tread and ridge) in this stage (Chapters 6, 8). Consequently, patchiness increases during this phase. As patch-internal succession proceeds, more and more patches are situated in later successional phases. The proportion of patches in early successional phases decreases. In the *K-Phase,* later successional patches coalesce and engineer patches overgrow disturbance-related patches. Patches become increasingly connected, mosaic patchiness decreases. Patch organization starts to strongly control patch interactions. For example, engineer patches in crest positions limit sediment transport to the slopefoot. As many patches are situated ecologic or late successional phases, high amounts of biomass are stored and the mosaic becomes vulnerable towards external disturbances, e.g. snow avalanches (Chapter 8). Vulnerability is further increased by the development of tension cracks and the accumulation of fine material in crest positions, which precondition mass movement disturbances. At the same time, system resilience decreases as increasing patch homogeneity reduces the available species pool. In the subsequent *Ω-Phase,* patch mosaic structure and organization is disrupted either by internal patch change, e.g. due to solifluction lobe collapse (Chapter 6), or by external impacts. The latter comprise snow avalanches and heavy rainfalls that trigger landsliding and debris flows (Chapter 8). Connectedness and stored capital (biomass) decrease, while patchiness and associated system resilience increase as new patches are created.

In the subsequent *α-Phase,* the reorganizing patch mosaic can be invaded by structures and processes from neighbouring systems, e.g. diaspores from adjacent slopes (Allen et al., 2014). New patch mosaic structures and patch-internal successional pathways, e.g. the linked successional pathway (Chapter 8), can be tested.

During subsequent adaptive cycles of biogeomorphic patch dynamics, system history is recorded in the patch mosaic and the underlying geomorphic palimpsest. In contrast to the slow dynamics described for large scale adaptive cycles in the panarchy concept, mosaic patterns can change rather quickly during the adaptive cycle of biogeomorphic patch dynamics. Recurrence intervals of internal and external disturbances control these pattern changes. If the recurrence interval is short, pattern changes already occur during earlier phases of the adaptive cycle. Thus, many adaptive cycles of biogeomorphic patch dynamics do not reach the K-Phase, or just locally at a smaller spatial scale. To better reconcile slope-scale spatiotemporal patch dynamics with a large scale adaptive cycle, more research is needed (see Section 9.4).

9.3.4 Scale interactions: Remember

Remember interactions link the biomorphic patch dynamics adaptive cycle at the highest level with the patch-internal biogeomorphic succession adaptive cycle at the focal level (Figure 9.3 D), and the latter adaptive cycle with the ecosystem engineer adaptive cycle at the lowest level (Figure 9.3 E).

By creating new patches and controlling their recolonization, biogeomorphic patch dynamics at level +1 set conditions for patch-internal biogeomorphic succession at level 0 (Figure 9.3 D). Patch mosaic changes can provide new patches for patch-internal biogeomorphic succession (Figure 9.3 D, I Disturbance patch creation). The post-disturbance state of the new patch, related to vegetation damage, deposited diaspores and material properties, determines in which phase the new adaptive cycle starts. In addition, patch location and patch dynamics adaptive cycle phase determine subsequent biogeomorphic succession dynamics (Figure 9.3 D II Recolonization control). Patch location decides whether the new patch receives further sediment input, e.g. from upslope patches, while patch dynamics adaptive cycle phase determines which species can recolonize the patch. During the r-Phase of the patch dynamics adaptive cycle, pioneer diaspore availability is high, but decreases with decreasing patchiness and the dominance of later successional patches in the K-Phase. Engineer diaspore availability determines the trajectory of patch-internal succession. If no engineer diaspores are available, patch-internal succession could switch to a different patch-internal successional pathway (Chapter 8) and thereby a different adaptive cycle (Figure 9.3 B).

Patch-internal biogeomorphic succession sets conditions for ecosystem engineer development at a lower scale, as its adaptive cycle phase determines Windows of Opportunity (Chapter 2) and disturbance intensity at the engineer site (Figure 9.3 E). As the frequency of high magnitude processes decreases with proceeding biogeomorphic succession, more Windows of Opportunity become available for engineer establishment towards the K-Phase (Figure 9.3 E, I Windows of Opportunity, Chapters 2, 4). During the α- and r-Phases of patch-internal biogeomorphic succession, high geomorphic activity will inhibit engineer establishment, while it is favoured by low activity during the transition from r- to K-Phase. Once the later successional species dominate in the K-Phase, engineers cannot establish due to high competition (Chapters 4, 8).

Furthermore, patch-scale disturbances can strongly affect engineer life cycle and development (Figure 9.3 E, II Disturbances). This effect depends not only on the disturbance type, determined by the higher level adaptive cycle phase, but also on the adaptive cycle phase in which engineer development is situated. In the r-Phase, disturbances, such as a falling individual clast, can completely destroy the small-sized ecosystem engineer. The ecosystem engineer adaptive cycle will enter the Ω-Phase and a new cycle will start (Figure 9.3 A). However, with increasing engineer size in the K-Phase, the engineer will only partly be destroyed by disturbances and the adaptive cycle can continue.

9.3.5 Scale interactions: Revolt

Revolt interactions link the ecosystem engineer adaptive cycle at the lowest level with the patch-internal biogeomorphic succession adaptive cycle at the focal level (Figure 9.3 F), and this latter adaptive cycle with the biomorphic patch dynamics adaptive cycle at the highest level (Figure 9.3 G).

Ecosystem engineer development impacts higher level patch-internal biogeomorphic succession by inducing a shift to its biogeomorphic phase, initiating biogeomorphic structures and a shift to its geomorphic phase (Figure 9.3 F).As described in the biogeomorphic feedback window (Chapter 4), biogeomorphic feedbacks, and therefore the biogeomorphic phase (transition from r- to K-Phase of biogeomorphic succession adaptive cycle) can only start when an ecosystem engineer species covers more than 35% of a specified surface area (engineering threshold; Figure 9.3 F, I Shift to biogeomorphic phase). Thus, the ecosystem engineer adaptive cycle in level -1 determines when this threshold is crossed and thereby represents a key control for patch-internal biogeomorphic succession in level 0. In addition, ecosystem engineers can initiate small scale solifluction bulges during their K-Phase (Figure 9.3 F, II Initiation of biogeomorphic structures, Chapter 6). These can develop into large biogeomorphic structures during the biogeomorphic phase of the patch-internal biogeomorphic succession (Chapters 6, 8) and even control landform element patch development at the highest level. However, small scale engineer death in the Ω-Phase of the engineer adaptive at level -1 can also provoke the Ω-Phase of biogeomorphic succession at level 0, as geomorphic processes can re-occur when engineer cover is removed. The probability for this effect is particularly high if engineer death affects the entire engineer population in a patch, e.g. due to climatic disturbances such as heat.

Patch-internal biogeomorphic succession in level 0 influences larger scale biogeomorphic patch dynamics in level +1 by creating engineer patches and providing opportunities for patch mosaic change through disturbances (Figure 9.3 G). During the biogeomorphic phase of the patch-internal biogeomorphic succession adaptive cycle in level 0, engineer patches can expand and overgrow disturbance patches (Figure 9.3 G, I Engineer patch creation; Chapter 8). Thereby, they add to decreasing mosaic patchiness during the K-Phase of the biogeomorphic patch dynamics adaptive cycle in level +1. Location of the level 0 engineer patch in the patch mosaic controls where and if the larger scale patch mosaic in level +1 changes (Section 9.3.3, Chapter 8). Renewed patch-scale geomorphic activity in the Ω- and α-Phases of the biogeomorphic succession adaptive cycle in level 0 can affect neighbouring patches, e.g. through sediment input, and thereby change the patch mosaic in level +1 (Figure 9.3 G, II Patch mosaic change). The Ω-Phase is triggered in the higher level biogeomorphic patch dynamics adaptive cycle.

In summary, the presented panarchy of a lateral moraine slope BE demonstrates how structure and function in BEs, i.e. their network of geomorphic and ecologic processes, components and interactions, can be created. Furthermore, it demonstrates how small scale ecosystem engineering can lead to the emergence of slope-scale geomorphic and vegetation patterns and dynamics. Vice versa, it also shows how large scale patterns and dynamics influence small scale ecosystem engineer development. This highlights the importance of hierarchical, scale-related approaches for future biogeomorphic studies.

9.4 Shortcomings and potentials for future research

Due to its ‘pioneering character’ concerning biogeomorphic feedbacks in glacier forelands, this thesis employed a mainly descriptive approach to feedbacks between geomorphic processes and vegetation communities on lateral moraine slopes in the focal level. This resulted in some shortcomings and limitations in the adjoining hierarchical levels, concerning both lower level mechanisms and components for feedbacks and higher level constraints on these feedbacks (see Figures 3.1, 9.1).

At the lower level, shortcomings relate to ecosystem engineer traits of *D. octopetala*, which were only assessed based on available literature and not quantified. Likewise, small scale material, soil and hydrological patterns were not determined. Thus, neither the influence of engineer traits on material and surface mechanical, thermal and hydrological properties, nor the influence of these properties on the engineer life cycle could not be quantified. Further research on small scale ecosystem engineering, with a quantitative focus on plant traits in relation to the physical and chemical environment, would be a valuable objective for future research and has already been targeted in fluvial and coastal BES and on hillslopes (Bouma et al., 2013; Burylo et al., 2011; Gurnell, 2014; Peralta et al., 2008).

At the higher level, shortcomings arise from the limited assessment of spatiotemporal biogeomorphic dynamics. Based on the employed methods (geomorphic and vegetation mapping, permanent plot survey), the state of the lateral moraine slope system could only be assessed at a certain point in time. Developed concepts describing paraglacial adjustment and vegetation succession (Chapter 8) partly rely on chronosequence approaches, yet, this thesis showed that their application is limited by spatially highly variable dynamics. This impedes the inference of past biogeomorphic dynamics from today’s patterns. Photogrammetric techniques recently used to detect geomorphic changes in alpine and glacier foreland settings (Bennett and Evans, 2012; Micheletti et al., 2015; Schiefer and Gilbert, 2007) could help to solve this problem. Biogeomorphic studies in fluvial environments have already successfully employed these techniques combination with orthophoto vegetation interpretation (Corenblit et al., 2010b; Hortobágyi et al., 2016). However, in glacier forelands, this approach could be hampered by lower to no height differences between the vegetation successional stages in comparison to fluvial environments.

Some further shortcomings and limitations also apply for the focal level of this thesis. As this thesis focused on lateral moraine slopes, biogeomorphic feedbacks could not be investigated in detail in the entire glacier foreland area. Yet, a lot of further feedbacks can probably be detected there, especially in the glaciofluvial floodplain. Several parameters probably influencing biogeomorphic feedbacks could only be assessed rudimentarily or not at all in this study. The role of soil properties for biogeomorphic feedbacks and dynamics is only shortly broached (Chapter 8), while microbial activity and succession (cf. Nemergut et al., 2006; Zumsteg et al., 2012) could not be not considered at all. A detailed integration of soil properties, related microbial activity (cf. Meyer et al., 2015) into biogeomorphic succession dynamics on lateral moraine slopes, as carried out by Bätz et al. (2015b, 2015a) for soil development in fluvial systems, would probably be highly rewarding. Animals, such as marmots, could further influence lateral moraine slope stability. Zoogeomorphological research showed that marmots can locally impact soil properties and enhance surface runoff and erosion (Butler, 1995; Whitesides and Butler, 2016; Whitesides, 2015). Marmot burrows are often situated in crest positions at the investigated lateral moraine slopes and could decrease slope stability.

Furthermore, it has to be kept in mind that the concepts developed in this thesis are mainly based on sites-specific results obtained in a single glacier foreland area. Turtmann glacier foreland could be singular especially in terms of material composition (siliceous and calcareous material), therefore, the derived concepts need to be tested in other glacier forelands.

10 CONCLUSION

> *'Organisms and their interactions can shape and are shaped by geomorphic processes and landforms' (Stallins, 2006, p. 208)*

Based on geomorphic and ecologic data from Turtmann glacier foreland (Switzerland), this thesis demonstrated that lateral moraine slopes are biogeomorphic ecosystems, characterized by scale-related biogeomorphic feedbacks between highly dynamic geomorphic processes and adapted plants.

In reference to the thesis objectives, this study shows for the first time that:

1. **The dwarf shrub *Dryas octopetala* L. is an alpine ecosystem engineer**. Through its adapted root and above ground biomass traits, it affects material and surface thermal, mechanical, chemical and hydrological properties. Thereby, it changes occurring geomorphic processes, facilitates establishment for other species and promotes soil and landform development.
2. **Biogeomorphic feedbacks on lateral moraine slopes occur in a ‚biogeomorphic feedback window' depending on geomorphic process magnitude and frequency and plant species traits.** Processes with high magnitude or frequency favour pioneer species that can quickly regrow due to their high resilience. When process frequency sufficiently decreases, or the interval between high magnitude processes is long enough (establishment threshold), ecosystem engineers can establish and cross a cover-related engineering threshold. Through their adapted traits, they change the process regime from water soil erosional processes to bound solifluction in the biogeomorphic feedback window. Biogeomorphic feedbacks cease when more competitive later successional species replace ecosystem engineers (competition threshold).
3. **Turf-banked solifluction lobes are biogeomorphic structures produced in an ecosystem engineering processes.** Their development can be described in a four stage conceptual biogeomorphic model. Through its stabilizing roots, the ecosystem engineer *D. octopetala* can initiate solifluction lobes on slopes during the initiation stage. Fine material accumulation behind initial risers is enhanced by the dense *D. octopetala* mat structure and a lobe tread develops with active needle ice and frost creep processes in the formation stage. When this lobe tread is covered by the thick engineer organic mat, near-surface frost creep is reduced and deeper gelifluction promoted. Large turf-banked solifluction lobes can develop in the differentiation stage. Their lobe elements riser, tread and ridge possess distinct

geomorphometric and material properties and provide variable habitats with specific species compositions. With on-going vegetation development, lobes stabilize in the mature stage. Turf-banked solifluction lobe development is cyclic and represents an important paraglacial process.

4. **Paraglacial adjustment and vegetation succession are strongly linked in glacier forelands and interact during a four-phase biogeomorphic succession, which can be independent from terrain age. On lateral moraine slopes, this biogeomorphic succession proceeds in patches and creates a slope-scale mosaic pattern characterized by biogeomorphic patch dynamics.** In a geomorphic phase, dead ice melt and related mass movement processes inhibit vegetation colonization but create the initial material and geomorphometric setting. Pioneer species can colonize once dead ice melt is completed in the pioneer phase, which is characterized by gullying processes. Once ecosystem engineer species can establish and cross the cover-related engineering threshold, they change the process regime to solifluction processes through their root and above-ground biomass effect traits. Turf-banked solifluction lobes as biogeomorphic structures can develop in this biogeomorphic phase. Ecosystem engineering facilitates the establishment of later successional shrub and tree species by advancing slope stabilization and soil development. In the ecologic phase, later successional species exclude the ecosystem engineer through competition. Biotic interactions become dominant, paraglacial adjustment is completed. On lateral moraine slopes, biogeomorphic succession occurs in patches of a slope-scale patch mosaic. Geomorphic disturbances and ecosystem engineering change this patch mosaic during biogeomorphic patch dynamics. New patches are created by geomorphic disturbances, often controlled by slope toposequence. In addition, ecosystem engineer patches can overgrow disturbance patches in the biogeomorphic phase. Smaller scale landform element patches can develop through ecosystem engineering. Geomorphic processes from adjacent slopes keep biogeomorphic patch dynamics on-going, which control paraglacial adjustment and vegetation succession on lateral moraine slopes.

5. **Lateral moraines are biogeomorphic ecosystems (BEs) in which scale-related feedbacks and their linkages in a panarchy of adapted cycles control their system dynamics, structure and function.** Lateral moraine slopes possess a distinct physical disturbance regime and are colonized by plants adapted to it through response, effect and feedback traits. Therefore, lateral moraines are biogeomorphic ecosystems. Within these BEs, small scale biogeomorphic

feedbacks occur during an adaptive cycle of ecosystem engineering. On an intermediate scale, patch-internal biogeomorphic succession follows an adaptive cycle, while slope-scale patch mosaic changes during a large scale biogeomorphic patch dynamics adaptive cycle. Remember and revolt interactions link the scales and their adaptive cycles in a panarchy and create BE structure and function, relating to the network of geomorphic and ecologic processes and components and their interactions. Described scale-related biogeomorpic feedback and scale linkages highlight the importance of hierarchical, scale-based research approaches in biogeomorphology.

The presented results can contribute to an effective environmental management in alpine environments. By providing safe sites, the identified ecosystem engineer *D. octopetala* could aid successful restoration of alpine slopes, such as degraded ski slopes (Urbanska, 1997). The consideration of process magnitude and frequency on disturbed slopes could help to select species with traits adapted to the dominant disturbance regime, as presented in the biogeomorphic feedback window concept. Concerning sediment management in glacier forelands, this study demonstrates that lateral moraine slopes can potentially contribute sediments to hydropower station reservoirs even a century after glacier retreat. Biogeomorphic feedbacks and their spatial patterns strongly control if and where geomorphic processes transport sediments. Therefore, spatial geomorphic and vegetation patterns and their interactions need to be investigated to understand sediment dynamics in glacier forelands.

Finally, the presented panarchy concept demonstrates the importance of small scale components for landscape development. This is especially relevant in a changing climate. If higher temperatures affect ecosystem engineer occurrence and life cycle (cf. Welker et al., 1997; Wookey et al., 1995), resulting small scale changes in biogeomorphic feedbacks could, through scale interactions, affect slope-scale biogeomorphic dynamics and thereby sediment transport and the occurrence of natural hazards in glacier forelands.

11 OUTLOOK: THE TRAJECTORY OF BIOGEOMORPHOLOGY – WHERE WE (SHOULD) GO

Within the last decade, biogeomorphology has made quite a turn from a unidirectional, geomorphology-focused view on the geomorphic role of organisms to the integrative view of feedback biogeomorphology described in this thesis (Chapter 2.2). A great source of valuable ecological concepts was recently tapped (e.g. Corenblit et al., 2011, Gurnell, 2014), which helped to develop the understanding of coupled geomorphic and ecologic systems as biogeomorpic ecosystems (Corenblit et al., 2015). Yet, geomorphology has just as much to offer for future biogeomorphic research. This includes soil mechanical, thermal and hydrological knowledge to improve the understanding of small scale ecosystem engineering and a detailed knowledge of geomorphic systems and their inherent relationships between geomorphic processes, landforms and material to advance the understanding of BEs. In the end, this geomorphic knowledge is what delimits biogeomorphology from geoecology, landscape ecology and other disciplines investigating feedbacks between the biotic and abiotic environment.

Based on results from this thesis and the state of biogeomorphic research in general, future biogeomorphic research areas can be identified:

1) **From traits to processes and landforms:** Research determining ecosystem engineer effect traits and quantifying their impact on material and surface mechanical, hydrological, thermal and chemical properties needs to be intensified to understand ecosystem engineering processes in BEs. Subsequently, the ecosystem engineering process needs to be explicitly linked to changes in geomorphic processes and landforms to better understand landscape development and the creation of biogeomorphic structures in in BEs.
2) **High mountain and periglacial biogeomorphology:** So far, biogeomorphic research concentrated on fluvial and coastal environments and very few explicit biogeomorphic research has been carried out in high mountain and periglacial environments. As these environments are increasingly affected by climate change, we need to understanding if and how biogeomorphic feedbacks drive their landscape response. Extensive geomorphic and ecologic research previously carried out in these environments will provide an invaluable knowledge base for this task.
3) **Global biogeomorphology:** Knowledge from previous biogeomorphic research has often been derived in similar geographic settings, e.g. European rivers (Corenblit et al., 2009; Francis et

al., 2009). Yet, it has been recently suggested by Corenblit et al. (2015) that biogeomorphic feedbacks and BEs occur worldwide. To further verify this view, especially for rivers and glacier forelands, biogeomorphic research in different geomorphic and ecologic settings needs to be advanced. This should include regions with high erosion rates (e.g. Taiwan, New Zealand) and different biogeographic regions. Here, it needs to be tested if biogeomorphic feedbacks can occur despite high geomorphic dynamics, and if ecosystem engineer species from different biogeographic regions possess similar response, effect and feedback traits to similar geomorphic constraints. Collectively, this could help to develop a a 'global biogeomorphic feedback window' to determine the distribution and importance of BEs worldwide.

4) **Scales in biogeomorphology:** As demonstrated in this thesis, multi-scale biogeomorphic investigations can greatly help to understand how structure and function are created in BEs. Thus, a more multi-scale biogeomorphic research is needed, which will also help to improve scale concepts in biogeomorphology. In addition, detailed knowledge on scale linkages could help to integrate biogeomorphic feedbacks into large scale geomorphic approaches, such as sediment budgets, connectivity and landscape evolution modelling.

5) **Methods in biogeomorphology:** Recent research showed that new methods from geomorphology, such as photogrammetry and Structure from Motion, are valuable tools to quantify biogeomorphic dynamics on all scales (Hortobágyi et al., 2016). By linking them with new methods from ecology and remote sensing, such as hyperspectral imaging, to overall understanding of BEs could be further increased. As stated by Viles (2016), new methods promote cross-disciplinary research, so biogeomorphology will greatly benefit from them.

For a genuine future biogeomorphology, the contributions of geomorphology and ecology need to be equal. This necessitates the ongoing integration of existing and new concepts from both ecology and geomorphology into biogeomorphology and the subsequent development of new biogeomorphic concepts. Thus, biogeomorphic research will continue to walk a tight rope: it needs to lift the conceptual and methodical weights from both disciplines and, at the same time, keep the right balance between geomorphology and ecology (Figure 10.1). Increased research collaboration, especially in mixed geomorphologists and ecologists teams, can greatly assist in accomplishing this task (Haussmann, 2011).

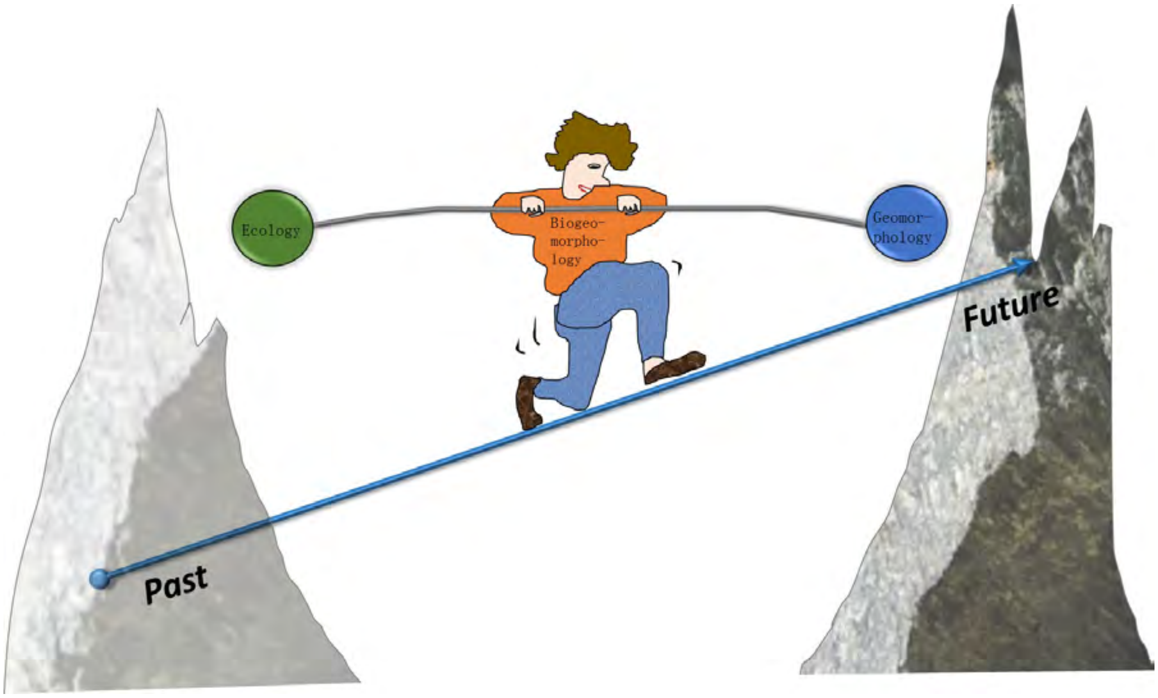


Figure 11.1: Biogeomorphology walking a tight rope: struggling to lift conceptual and methodical weights from both ecology and geomorphology and keep the right balance between them at the same time.

In 84% of the land's surface, geomorphic dynamics are linked to biota (Corenblit et al., 2011). Depite growing biogeomorphic research, only a small share of existing biogeomorphic feedbacks has probably been investigated in this large area, and even less are fully understood. Thus, Naylor et al. (2002)'s statement still comes true after nearly 15 years:

We have only just begun to scratch the surface…

REFERENCES

Aalto J, le Roux PC, Luoto M. 2013. Vegetation Mediates Soil Temperature and Moisture in Arctic-Alpine Environments. Arctic, Antarctic, and Alpine Research **45** : 429–439. DOI: 10.1657/1938-4246-45.4.429

Ad-hoc-AG Boden. 2005. Bodenkundliche Kartieranleitung . 5th ed. Schweizerbart'sche, E.: Stuttgart

Ahnert F. 1988. Modelling landform change. Modelling Geomorphological Systems. John Wiley and Sons New York. 1988. p 375-400, 18 fig, 31 ref.

Ahnert F. 1998. Introduction to Geomorphology . Hodder Arnold: London : New York

Akerman J. 1993. Solifluction and creep rates 1972–1991, Kapp Liné, West Spitsbergen. In Solifluction and Climatic Variation in the Holocene. , Frenzel B, Matthews JA, and Glaser (eds). Gustav Fischer Verlag: Stuttgart; 225–250.

Alatalo JM, Jägerbrand AK, Molau U. 2016. Impacts of different climate change regimes and extreme climatic events on an alpine meadow community. Scientific Reports **6** : 21720. DOI: 10.1038/srep21720

Allen CR, Angeler DG, Garmestani AS, Gunderson LH, Holling CS. 2014. Panarchy: theory and application. Ecosystems **17** : 578–589.

Anderson EW, Cox NJ. 1978. A comparison of different instruments for measuring soil creep. CATENA 5 : 81–93. DOI: 10.1016/0341-8162(78)90001-2

Anderson JG. 1906. Solifluction: A component of sub-aerial denudation. Journal of Geology **14** : 91–122. DOI: 10.1086/621284

Andreis C, Caccianiga M, Cerabolini B. 2001. Vegetation and environmental factors during primary succession on glacier forelands: Some outlines from the Italian Alps. Plant Biosystems **135** : 295–310. DOI: 10.1080/11263500112331350930

Archer AC, Simpson MJA, Macmillan BH. 1973. Soils and Vegetation of the Lateral Moraine at Make Brun. New Zealand journal of botany **11** : 23–48.

Baas ACW, Nield JM. 2007. Modelling vegetated dune landscapes. Geophysical Research Letters **34** : L06405. DOI: 10.1029/2006GL029152

Baewert H, Bimboese M, Bryk, Alexander, Rascher E, Schmidt K-H, Morche D. 2014. Roughness determination of coarse grained alpine river bed surfaces using Terrestrial Laser Scanning data. Zeitschrift für Geomorphologie Supplementary Issue 1 **58** : 81–95. DOI: http://dx.doi.org/10.1127/0372-8854/2013/S-00127

Balke T. 2013. Establishment of biogeomorphic ecosystems : a study on mangrove and salt marsh pioneer vegetation. PhD thesis, Radboud University, Nederland. [online] Available from: http://repository.ubn.ru.nl/handle/2066/113022 (Accessed 24 March 2014)

Balke T, Bouma TJ, Horstman EM, Webb EL, Erftemeijer PL, Herman PM. 2011. Windows of opportunity: thresholds to mangrove seedling establishment on tidal flats. Marine Ecology Progress Series **440** : 1–9. DOI: 10.1016/S0277-3791(02)00005-7

Balke T, Herman PM, Bouma TJ. 2014. Critical transitions in disturbance-driven ecosystems: identifying Windows of Opportunity for recovery. Journal of Ecology **102** : 700–708. DOI: 10.1111/1365-2745.12241

Balke T, Klaassen PC, Garbutt A, van der Wal D, Herman PM, Bouma TJ. 2012. Conditional outcome of ecosystem engineering: A case study on tussocks of the salt marsh pioneer Spartina anglica. Geomorphology **153** : 232–238. DOI: 10.1016/j.geomorph.2012.03.002

Balke T, Webb EL, van den Elzen E, Galli D, Herman PMJ, Bouma TJ. 2013. Seedling establishment in a dynamic sedimentary environment: a conceptual framework using mangroves. Journal of Applied Ecology **50** : 740–747. DOI: 10.1111/1365-2664.12067

REFERENCES

Ballantyne CK. 1995. Paraglacial debris-cone formation on recently deglaciated terrain, western Norway. The Holocene **5** : 25–33. DOI: 10.1177/095968369500500104

Ballantyne CK. 2001. Measurement and theory of ploughing boulder movement. Permafrost and Periglacial Processes **12** : 267–288. DOI: 10.1002/ppp.389

Ballantyne CK. 2002a. A general model of paraglacial landscape response. The Holocene **12** : 371–376. DOI: 10.1191/0959683602hl553fa

Ballantyne CK. 2002b.Paraglacial geomorphology. Quaternary Science Reviews **21** : 1935–2017.

Ballantyne CK. 2005. Paraglacial landsystems. In Glacial Landsystems , Evans DJA (ed). Hodder Arnold: London; 432–461.

Ballantyne CK. 2013. A 35-Year Record of Solifluction in a Maritime Periglacial Environment. Permafrost and Periglacial Processes **24** : 56–66. DOI: 10.1002/ppp.1761

Ballantyne CK, Benn DI. 1994. Paraglacial Slope Adjustment and Resedimentation Following Recent Glacier Retreat, Fåbergstølsdalen, Norway. Arctic and Alpine Research **26** : 255–269. DOI: 10.2307/1551938

Ballantyne CK, Matthews JA. 1982. The Development of Sorted Circles on Recently Deglaciated Terrain, Jotunheimen, Norway. Arctic and Alpine Research **14** : 341–354. DOI: 10.2307/1550796

Ballantyne CK, Matthews JA. 1983. Desiccation Cracking and Sorted Polygon Development, Jotunheimen, Norway. Arctic and Alpine Research **15** : 339–349. DOI: 10.2307/1550830

Bamberg SA, Major J. 1968. Ecology of the Vegetation and Soils Associated with Calcareous Parent Materials in Three Alpine Regions of Montana. Ecological Monographs **38** : 127–167. DOI: 10.2307/1942290

Baroni C, Armiraglio S, Gentili R, Carton A. 2007. Landform-vegetation units for investigating the dynamics and geomorphologic evolution of alpine composite debris cones (Valle dell'Avio, Adamello Group, Italy). Geomorphology **84** : 59–79.

Barsch D, Caine N. 1984. The Nature of Mountain Geomorphology. Mountain Research and Development **4** : 287–298. DOI: 10.2307/3673231

Bast A, Wilcke W, Graf F, Lüscher P, Gärtner H. 2014. The use of mycorrhiza for eco-engineering measures in steep alpine environments: effects on soil aggregate formation and fine-root development. Earth Surface Processes and Landforms **39** : 1753–1763. DOI: 10.1002/esp.3557

Bätz N, Verrecchia EP, Lane SN. 2015a. Organic matter processing and soil evolution in a braided river system. CATENA **126** : 86–97. DOI: 10.1016/j.catena.2014.10.013

Bätz N, Verrecchia EP, Lane SN. 2015b. The role of soil in vegetated gravelly river braid plains: more than just a passive response? Earth Surface Processes and Landforms **40** : 143–156. DOI: 10.1002/esp.3631

Bauder A, Ruegg R (eds). 2009. Gletscherberichte (1881-2009). "Die Gletscher der Schweizer Alpen" . Jahrbücher der Expertenkommission für Kryosphärenmessnetze der Akademie der Naturwissenschaften Schweiz (SCNAT) herausgegegeben seit 1964 durch die Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW) der ETH Zürich. No. 1-126, (http://glaciology.ethz.ch/swiss-glaciers/).

Bauder A, Ruegg R (eds). 2015. Gletscherberichte (1881-2015). "Die Gletscher der Schweizer Alpen" . Jahrbücher der Expertenkommission für Kryosphärenmessnetze der Akademie der Naturwissenschaften Schweiz (SCNAT) herausgegegeben seit 1964 durch die Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW) der ETH Zürich. No. 1-126, (http://glaciology.ethz.ch/swiss-glaciers/).

Bearth P. 1980. Geologischer Atlas der Schweiz. Blatt 1308 St. Niklaus, Erläuterungen. . Bern

Bedehäsing J. 2007. Analoge und digitale geomorphologische Kartographie im Turtmanntal/Mattertal, Schweizer Alpen . Diploma thesis (unpublished), University of Bonn, Bonn, Germany

Beer A. 2009. Einfluss des Klimawandels auf den Sedimenttransport in Einzugsgebieten alpiner

Stauhaltungen. Konzeptionelles Modell und Feldstudie im Turtmanntal . Diploma thesis. Karlruhe Institute of Technology, Karlsruhe, Germany (URL: http:// www.wsl.ch/info/mitarbeitende/beer/klimsed.pdf).

Benedict JB. 1970a. Downslope Soil Movement in a Colorado Alpine Region: Rates, Processes, and Climatic Significance. Arctic and Alpine Research **2** : 165–226. DOI: 10.2307/1550306

Benedict JB. 1970b. Frost Cracking in the Colorado Front Range. Geografiska Annaler. Series A, Physical Geography **52** : 87. DOI: 10.2307/520600

Benedict JB. 1976. Frost creep and gelifluction features: A review. Quaternary Research **6** : 55–76. DOI: 10.1016/0033-5894(76)90040-5

Benedict JB. 1989. Use of Silene acaulis for Dating: The Relationship of Cushion Diameter to Age. Arctic and Alpine Research **21** : 91–96. DOI: 10.2307/1551520

Benn DI, Evans DJA. 2010. Glaciers & glaciation . Hodder Education: London

Bennett GL, Evans DJA. 2012. Glacier retreat and landform production on an overdeepened glacier foreland: the debris-charged glacial landsystem at Kviarjokull, Iceland. Earth Surface Processes and Landforms **37** : 1584–1602. DOI: 10.1002/esp.3259

Bennett MR, Huddard D, Glasser NF, Hambrey MJ. 2000. Resedimentation of debris on an ice-cored lateral moraine in the high Arctic (Kongsvegen, Svalbard). Geomorphology **35** : 21–40.

Benninghoff WS. 1952. Interaction of Vegetation and Soil Frost Phenomena. ARCTIC **5** : 34–44. DOI: 10.14430/arctic3898

Bertalanffy L von. 1950. An Outline of General System Theory. British Journal for the Philosophy of Science **Vol. 1** : 134–165.

Berthling I, Eiken T, Sollid JL. 2001. Frost heave and thaw consolidation of ploughing boulders in a mid-alpine environment, Finse, Southern Norway. Permafrost and Periglacial Processes **12** : 165–177. DOI: 10.1002/ppp.367

Bertoldi W, Gurnell AM, Drake NA. 2011. The topographic signature of vegetation development along a braided river: Results of a combined analysis of airborne lidar, color air photographs, and ground measurements. Water Resources Research **47** : W06525. DOI: 10.1029/2010WR010319

Beyer HL. 2004. Hawth’s Analysis Tools for ArcGIS . Available at http://www.spatialecology.com/htools

Birks HJB. 1980. The present flora and vegetation of the moraines of the Klutlan Glacier, Yukon Territory, Canada: A study in plant succession. Quaternary Research **14** : 60–86. DOI: 10.1016/0033-5894(80)90007-1

Blöschl G, Kirnbauer R. 1992. Flächendetaillierte Modellierung der Schneeschmelze in einem alpinen Einzugsgebiet. 171–190 pp. [online] Available from: http://www.interpraevent.at/palm-cms/upload_files/Publikationen/Tagungsbeitraege/1992_1_161.pdf (Accessed 4 October 2016)

de Boer DH. 1992. Hierarchies and spatial scale in process geomorphology: a review. Geomorphology **4** : 303–318. DOI: 10.1016/0169-555X(92)90026-K

Bogen J. 1988. Glacial sediment production and development of hydro-electric power in glacierized areas. Annals of Glaciology **13** : 6–11.

Böhmer HJ, Richter M. 1997. Regeneration of plant communities–an attempt to establish a typology and a zonal system. Plant Res Dev **45** : 74–88.

Boulton GS, Dent DL. 1974. The Nature and Rates of Post-Depositional Changes in Recently Deposited till from South-East Iceland. Geografiska Annaler. Series A, Physical Geography **56** : 121–134. DOI: 10.2307/520702

Bouma TJ, Temmerman S, van Duren LA, Martini E, Vandenbruwaene W, Callaghan DP, Balke T, Biermans G, Klaassen PC, van Steeg P, Dekker F, van de Koppel J, de Vries MB, Herman PMJ. 2013. Organism traits determine the strength of scale-dependent bio-geomorphic feedbacks: A flume study on three intertidal plant species. Geomorphology **180**–**181** : 57–65. DOI: 10.1016/j.geomorph.2012.09.005

Bouma TJ, Friedrichs M, Van Wesenbeeck BK, Temmerman S, Graf G, Herman PMJ. 2009. Density-dependent linkage of scale-dependent feedbacks: a flume study on the intertidal macrophyte Spartina anglica. Oikos **118** : 260–268. DOI: 10.1111/j.1600-0706.2008.16892.x

Box EO. 1981. Macroclimate and plant forms: an introduction to predictive modeling in phytogeography . Dr. W. Junk

Bracken L. 2004. Headward erosion. Goudie A (ed). Encyclopedia of Geomorphology **1** : 513–515.

Bridge S r. j., Johnson E a. 2000. Geomorphic principles of terrain organization and vegetation gradients. Journal of Vegetation Science **11** : 57–70. DOI: 10.2307/3236776

Brierley G, Fryirs K, Jain V. 2006. Landscape connectivity: the geographic basis of geomorphic applications. Area **38** : 165–174.

Brockmann-Jerosch H. 1925. Die Vegetation der Schweiz . Rascher & Co: Zürich

Brunsden D. 1996. Geomorphological events and landform change. Zeitschrift für Geomorphologie, N.F. Suppl.-Bd. **40** : 273–288.

Brunsden D, Thornes JB. 1979. Landscape Sensitivity and Change. Transactions of the Institute of British Geographers **4** : 463–484. DOI: 10.2307/622210

Burga CA, Krusi B, Egli M, Wernli M, Elsener S, Ziefle M, Fischer T, Mavris C. 2010. Plant succession and soil development on the foreland of the Morteratsch glacier (Pontresina, Switzerland): Straight forward or chaotic? Flora-Morphology, Distribution, Functional Ecology of Plants **205** : 561–576.

Burylo M, Rey F, Bochet E, Dutoit T. 2011. Plant functional traits and species ability for sediment retention during concentrated flow erosion. Plant and Soil **353** : 135–144. DOI: 10.1007/s11104-011-1017-2

Butler DR. 1992. The grizzly bear as an erosional agent in mountainous terrain. Zeitschrift für Geomorphologie **36** : 179–189.

Butler DR. 1995. Zoogeomorphology: Animals as Geomorphic Agents . Cambridge University Press

Caccianiga M, Luzzaro A, Pierce S, Ceriani RM, Cerabolini B. 2006. The functional basis of a primary succession resolved by CSR classification. Oikos **112** : 10–20.

Caine N. 1976. A uniform measure of subaerial erosion. Geological Society of America Bulletin **87** : 137–140.

Calamita G, Brocca L, Perrone A, Piscitelli S, Lapenna V, Melone F, Moramarco T. 2012. Electrical resistivity and TDR methods for soil moisture estimation in central Italy test-sites. Journal of Hydrology **454**–**455** : 101–112. DOI: 10.1016/j.jhydrol.2012.06.001

Cammeraat LH. 2002. A review of two strongly contrasting geomorphological systems within the context of scale. Earth Surface Processes and Landforms **27** : 1201–1222. DOI: 10.1002/esp.421

Cannone N, Diolaiuti G, Guglielmin M, Smiraglia C. 2008. Accelerating climate change impacts on alpine glacier forefield ecosystems in the European Alps. Ecological Applications **18** : 637–648. DOI: 10.1890/07-1188.1

Cannone N, Guglielmin M. 2010. Relationships between periglacial features and vegetation development in Victoria Land, continental Antarctica. Antarctic Science **22** : 703–713. DOI: 10.1017/S0954102010000751

Carrivick JL, Geilhausen M, Warburton J, Dickson NE, Carver SJ, Evans AJ, Brown LE. 2013. Contemporary geomorphological activity throughout the proglacial area of an alpine catchment. Geomorphology **188** : 83–95. DOI: 10.1016/j.geomorph.2012.03.029

Chapin FS, Walker LR, Fastie CL, Sharman LC. 1994. Mechanisms of Primary Succession Following

Deglaciation at Glacier Bay, Alaska. Ecological Monographs **64** : 149–175. DOI: 10.2307/2937039

Chiarle M, Iannotti S, Mortara G, Deline P. 2007. Recent debris flow occurrences associated with glaciers in the Alps. Global and Planetary Change **56** : 123–136. DOI: 10.1016/j.gloplacha.2006.07.003

Chorley RJ, Kennedy BA. 1971. Physical geography: a systems approach . Prentice-Hall: London

Chorley RJ, Schumm SA, Sugden DE. 1984. Geomorphology . Methuen

Church M. 1996. Space, Time and the Mountain - How Do We Order What We See? In The Scientific Nature of Geomorphology , Rhoads BL and Thorn CE (eds). Wiley: Chichester, UK; 147–170.

Church M, Ryder JM. 1972. Paraglacial Sedimentation: A Consideration of Fluvial Processes Conditioned by Glaciation. Geological Society of America Bulletin **83** : 3059–3072. DOI: 10.1130/0016-7606(1972)83[3059:PSACOF]2.0.CO;2

Cichini K, Schwienbacher E, Marcante S, Seeber GUH, Erschbamer B. 2011. Colonization of experimentally created gaps along an alpine successional gradient. Plant Ecology **212** : 1613–1627. DOI: 10.1007/s11258-011-9934-y

Clements FE. 1916. Plant succession: an analysis of the development of vegetation . Carnegie Institution of Washington

Clements FE. 1928. Plant succession and indicators: a definitive edition of plant succession and plant indicators . The Wilson Company: New York

Coaz J. 1887. Erste Ansiedlung phanerogamer Pflanzen auf vom Gletscher verlassenem Boden. Mittheilungen der Naturforschenden Gesellschaft Bern : 3–12.

Coller AL, Rogers KH, Heritage GL. 2000. Riparian vegetation-environment relationships: complimentarity of gradients versus patch hierarchy approaches. Journal of Vegetation Science **11** : 337–350.

Connell JH, Slatyer RO. 1977. Mechanisms of Succession in Natural Communities and Their Role in Community Stability and Organization. The American Naturalist **111** : 1119–1144.

Cooper A, Mccann T, Bunce RGH. 2006. The Influence of Sampling Intensity on Vegetation Classification and the Implications for Environmental Management. Environmental Conservation **33** : 118–127. DOI: 10.1017/S0376892906002967

Cooper EJ, Alsos IG, Hagen D, Smith FM, Coulson SJ, Hodkinson ID, Bakker JP. 2004. Plant recruitment in the High Arctic: Seed bank and seedling emergence on Svalbard. Journal of Vegetation Science **15** : 115–124. DOI: 10.1658/1100-9233(2004)015[0115:PRITHA]2.0.CO;2

Corenblit D Steiger J, González E, Gurnell AM, Charrier G, Darrozes J, Dousseau J, Julien F, Lambs L, Larrue S, Roussel E, Vautier F, Voldoire O. 2014. The biogeomorphological life cycle of poplars during the fluvial biogeomorphological succession: a special focus on Populus nigra L. Earth Surface Processes and Landforms 39 : 546–563. DOI: 10.1002/esp.3515

Corenblit D, Baas, A, Balke T, Bouma T, Fromard F, Garófano-Gómez V, González E, Gurnell AM, Hortobágyi B, Julien F, Kim D, Lambs L, Stallins JA, Steiger J, Tabacchi E, Walcker R. 2015 . Engineer pioneer plants respond to and affect geomorphic constraints similarly along water–terrestrial interfaces world-wide. Global Ecology and Biogeography 24 : 1363–1376. DOI: 10.1111/geb.12373

Corenblit D, Steiger J, Charrier G, Darrozes J, Garófano-Gómez V, Garreau A, González E, Gurnell AM, Hortobágyi B, Julien F, Lambs L, Larrue S, Otto T, Roussel E, Vautier F, Voldoire O. 2016. Populus nigra L. establishment and fluvial landform construction: biogeomorphic dynamics within a channelized river. Earth Surface Processes and Landforms 41 : 1276–1292. DOI: 10.1002/esp.3954

Corenblit D, Baas ACW, Bornette G, Darrozes J, Delmotte S, Francis RA, Gurnell AM, Julien F, Naiman RJ, Steiger J. 2011. Feedbacks between geomorphology and biota controlling Earth surface processes and landforms: A review of foundation concepts and current understandings. Earth-Science Reviews **106** : 307–

331.

Corenblit D, Steiger J, Delmotte S. 2010a. Abiotic, residual and functional components of landforms. Earth Surface Processes and Landforms **35** : 1744–1750. DOI: 10.1002/esp.2064

Corenblit D, Steiger J, Gurnell AM, Tabacchi E, Roques L. 2009. Control of sediment dynamics by vegetation as a key function driving biogeomorphic succession within fluvial corridors. Earth Surface Processes and Landforms **34** : 1790–1810. DOI: 10.1002/esp.1876

Corenblit D, Steiger J, Tabacchi E. 2010b. Biogeomorphologic succession dynamics in a Mediterranean river system. Ecography **33** : 1136–1148. DOI: 10.1111/j.1600-0587.2010.05894.x

Corenblit D, Tabacchi E, Steiger J, Gurnell AM. 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches. Earth-Science Reviews **84** : 56–86. DOI: 10.1016/j.earscirev.2007.05.004

Cossart E. 2008. Landform connectivity and waves of negative feedbacks during the paraglacial period, a case study: the Tabuc subcatchment since the end of the Little Ice Age (massif des Écrins, France). Géomorphologie: relief, processus, environnement **4** : 249–260.

Costin AB, Thom BG, Wimbush DJ, Stuiver M. 1967. Nonsorted Steps in the Mt. Kosciusko Area, Australia. Geological Society of America Bulletin **78** : 979–992. DOI: 10.1130/0016-7606(1967)78[979:NSITMK]2.0.CO;2

Cowie NM, Moore RD, Hassan MA. 2014. Effects of glacial retreat on proglacial streams and riparian zones in the Coast and North Cascade Mountains. Earth Surface Processes and Landforms **39** : 351–365. DOI: 10.1002/esp.3453

Cowles HC. 1899. The ecological relations of the vegetation on the sand dunes of Lake Michigan .. . Chicago, The University of Chicago press.

Cowles HC. 1901. The plant societies of Chicago and its vicinity. . The Geographic Society of Chicago: Chicago.

Cox NJ. 1989. Review of Biogeomorphology. Progress in Physical Geography **13** : 620–624.

Crocker RL, Major J. 1955. Soil Development in Relation to Vegetation and Surface Age at Glacier Bay, Alaska. The Journal of Ecology **43** : 427. DOI: 10.2307/2257005

Crozier MJ. 1999. The frequency and magnitude of geomorphic processes and landform behaviour. In Zeitschrift für Geomorphologie, Supp.-Bd. 115 , Crozier MJ and Mäusbacher R (eds). Gebrüder Bornträger: Berlin, Stuttgart; 35–50.

Currie WS. 2011. Units of nature or processes across scales? The ecosystem concept at age 75. New Phytologist **190** : 21–34. DOI: 10.1111/j.1469-8137.2011.03646.x

Curry AM. 1999. Paraglacial modification of slope form. Earth Surface Processes and Landforms **24** : 1213–1228. DOI: 10.1002/(SICI)1096-9837(199912)24:13<1213::AID-ESP32>3.0.CO;2-B

Curry AM. 2000. Observations on the distribution of paraglacial reworking of glacigenic drift in western Norway. Norsk Geografisk Tidsskrift **54** : 139–147.

Curry AM, Cleasby V, Zukowskyj P. 2006. Paraglacial response of steep, sediment-mantled slopes to post-“Little Ice Age” glacier recession in the central Swiss Alps. Journal of Quaternary Science **21** : 211–225. DOI: 10.1002/jqs.954

Curry AM, Sands TB, Porter PR. 2009. Geotechnical controls on a steep lateral moraine undergoing paraglacial slope adjustment. Geological Society, London, Special Publications **320** : 181–197.

Cutler NA, Belyea LR, Dugmore AJ. 2008. The spatiotemporal dynamics of a primary succession. Journal of Ecology **96** : 231–246.

Dahlin T, Bernstone C, Loke M. 2002. A 3-D resistivity investigation of a contaminated site at Lernacken, Sweden. GEOPHYSICS **67** : 1692–1700. DOI: 10.1190/1.1527070

D'Amico ME, Freppaz M, Filippa G, Zanini E. 2014. Vegetation influence on soil formation rate in a proglacial chronosequence (Lys Glacier, NW Italian Alps). CATENA **113** : 122–137. DOI: 10.1016/j.catena.2013.10.001

Davis WM. 1899. The geographical cycle. The Geographical Journal **14** : 481–504.

Deline P, Gruber S, Delaloye R, Fischer L, Geertsema M, Giardino M, Hasler A, Kirkbride M, Krautblatter M, Magnin F, McColl S, Ravanel L, Schoeneich P. 2015. Chapter 15 - Ice loss and slope stability in high-mountain regions. In Snow and Ice-Related Hazards, Risks, and Disasters , Haeberli W and Whiteman C (eds). Elsevier; 787.

Dierschke H. 1994. Pflanzensoziologie: Grundlagen und Methoden . UTB, Stuttgart

Dietrich WE, Dunne T. 1978. Sediment budget for a small catchment in a mountainous terrain. Zeitschrift für Geomorphologie, Supplement **29** : 191–206.

Dikau R. 1989. The application of a digital relief model to landform analysis in geomorphology. In Three dimensional applications in geographical information systems , Raper J (ed). London; 51–77.

Dikau R. 2004. Mass movement. Goudie A (ed). Encyclopedia of Geomorphology **1** : 644–653.

Dikau R. 2006. Komplexe Systeme in der Geomorphologie. Mitteilungen der Österreichischen Geographischen Gesellschaft **148** : 125–150.

Dikau R, Rasemann S, Schmidt J. 2004. Hillslope, form. Goudie A (ed). Encyclopedia of Geomorphology **1** : 644–653.

Doetsch J, Linde N, Pessognelli M, Green AG, Günther T. 2012. Constraining 3-D electrical resistance tomography with GPR reflection data for improved aquifer characterization. Journal of Applied Geophysics **78** : 68–76. DOI: 10.1016/j.jappgeo.2011.04.008

Draebing D, Eichel J. 2016. Controlling factors of turf-banked solifluction lobe evolution in the Turtmann glacier forefield, Switzerland. Geophysical Research Abstracts **18** : EGU2016-479.

Dramis F, Guida D, Cestari A. 2011. Chapter Three - Nature and Aims of Geomorphological Mapping. In Developments in Earth Surface Processes , Mike J. Smith PP and JSG (ed). Elsevier; 39–73.

Egler FE. 1954. Vegetation science concepts I. Initial floristic composition, a factor in old-field vegetation development with 2 figs. Plant Ecology **4** : 412–417.

Egli M, Mavris C, Mirabella A, Giaccai D. 2010. Soil organic matter formation along a chronosequence in the Morteratsch proglacial area (Upper Engadine, Switzerland). Catena **82** : 61–69.

Egli M, Wernli M, Burga C, Kneisel C, Mavris C, Valboa G, Mirabella A, Plötze M, Haeberli W. 2011. Fast but spatially scattered smectite-formation in the proglacial area Morteratsch: An evaluation using GIS. Geoderma **164** : 11–21. DOI: 10.1016/j.geoderma.2011.05.001

Ehrenfeld JG, Ravit B, Elgersma K. 2005. Feedback in the Plant-Soil System. Annual Review of Environment and Resources **30** : 75–115. DOI: 10.1146/annurev.energy.30.050504.144212

Eibisch K, Eichel J, Dikau R. 2015. Root tensile strength assessment of Dryas octopetala L. and implications for its engineering mechanism on lateral moraine slopes (Turtmann Valley, Switzerland). Geophysical Research Abstracts : EGU2015-5146.

Eichel J, Corenblit D, Dikau R. 2016. Conditions for feedbacks between geomorphic and vegetation dynamics on lateral moraine slopes: a biogeomorphic feedback window. Earth Surface Processes and Landforms **41** : 406–419. DOI: 10.1002/esp.3859

Eichel J, Draebing D, Wieland M, Eling C, Klingbeil L, Dikau R. 2015. Feedbacks between vegetation and solifluction processes on hillslopes: case study of an alpine turf-banked solifluction lobe. Geophysical Research Abstracts **17** : EGU2015-1738.

REFERENCES

Eichel J, Krautblatter M, Schmidtlein S, Dikau R. 2013. Biogeomorphic interactions in the Turtmann glacier forefield, Switzerland. Geomorphology **201** : 98–110. DOI: 10.1016/j.geomorph.2013.06.012

Elder K, Dozier J, Michaelsen J. 1991. Snow accumulation and distribution in an Alpine Watershed. Water Resources Research **27** : 1541–1552. DOI: 10.1029/91WR00506

Eling C, Wieland M, Hess C, Klingbeil L, Kuhlmann H. 2015. Development and Evaluation of a UAV based Mapping System for Remote Sensing and Surveying Applications. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **XL**-**1/W4** : 233–239. DOI: 10.5194/isprsarchives-XL-1-W4-233-2015

Elkington TT. 1971. Dryas Octopetala L. Journal of Ecology **59** : 887–905. DOI: 10.2307/2258146

Ellenberg H. 1988. Vegetation ecology of Central Europe . Cambridge University Press: Cambridge

Ellenberg H. 1996. Vegetation Mitteleuropas mit den Alpen: In ökologischer, dynamischer und historischer Sicht . UTB, Stuttgart

Ellenberg H. 2009. Vegetation Ecology of Central Europe . 4th ed. Cambridge University Press: Cambridge; New York

Elliott G, Worsley P. 1999. The sedimentology, stratigraphy and 14C dating of a turf-banked solifluction lobe: evidence for Holocene slope instability at Okstindan, northern Norway. Journal of Quaternary Science **14** : 175–188. DOI: 10.1002/(SICI)1099-1417(199903)14:2<175::AID-JQS432>3.0.CO;2-6

Elverfeldt K von. 2012. System Theory in Geomorphology: Challenges, Epistemological Consequences and Practical Implications . Springer Science & Business Media

Erschbamer B, Mayer R. 2011. Can successional species groups be discriminated based on their life history traits? A study from a glacier foreland in the Central Alps. Plant Ecology & Diversity **4** : 341–351. DOI: 10.1080/17550874.2012.664573

Erschbamer B, Niederfriniger Schlag R, Winkler E. 2008. Colonization processes on a central Alpine glacier foreland. Journal of Vegetation Science **19** : 855–862. DOI: 10.3170/2008-8-18464

Ewertowski M, Kasprzak L, Szuman I, Tomczyk AM. 2012. Controlled, ice-cored moraines: sediments and geomorphology. An example from Ragnarbreen, Svalbard. Zeitschrift für Geomorphologie **56** : 53–74.

Ewertowski MW, Tomczyk AM. 2015. Quantification of the ice-cored moraines' short-term dynamics in the high-Arctic glaciers Ebbabreen and Ragnarbreen, Petuniabukta, Svalbard. Geomorphology **234** : 211–227. DOI: 10.1016/j.geomorph.2015.01.023

Eybergen FA. 1986. Glacier snout dynamics and contemporary push moraine formation at the turtmannglacier, Wallis, Switzerland. In Tills and Glaciotectonics. , van der Meer JJ. (ed). Proceedings of an INQUA Symposium on the Genesis and Lithology of Glacial Deposits: Amsterdam; 217–231.

Farinotti D, Pistocchi A, Huss M. 2016. From dwindling ice to headwater lakes: could dams replace glaciers in the European Alps? Environmental Research Letters **11** : 54022. DOI: 10.1088/1748-9326/11/5/054022

Fattet M, Fu Y, Ghestem M, Ma W, Foulonneau M, Nespoulous J, Le Bissonnais Y, Stokes A. 2011. Effects of vegetation type on soil resistance to erosion: Relationship between aggregate stability and shear strength. CATENA **87** : 60–69. DOI: 10.1016/j.catena.2011.05.006

Feuillet T, Mercier D. 2012. Post-Little Ice Age Patterned Ground Development on Two Pyrenean Proglacial Areas: From Deglaciation to Periglaciation. Geografiska Annaler Series a-Physical Geography **94A** : 363–376. DOI: 10.1111/j.1468-0459.2012.00459.x

Fickert T, Friend D, Grüninger F, Molnia B, Richter M. 2007. Did Debris-Covered Glaciers Serve as Pleistocene Refugia for Plants? A New Hypothesis Derived from Observations of Recent Plant Growth on Glacier Surfaces. Arctic, Antarctic, and Alpine Research **39** : 245–257. DOI: 10.1657/1523-0430(2007)39[245:DDGSAP]2.0.CO;2

Fisher SG, Heffernan JB, Sponseller RA, Welter JR. 2007. Functional ecomorphology: feedbacks between form and function in fluvial landscape ecosystems. Geomorphology **89** : 84–96.

Fitzsimons S. 1996. Paraglacial redistribution of glacial sediments in the Vestfold Hills, East Antarctica. Geomorphology **15** : 93–108. DOI: 10.1016/0169-555X(95)00122-L

Flageollet J-C. 1996. The time dimension in the study of mass movements. Geomorphology **15** : 185–190. DOI: 10.1016/0169-555X(95)00069-H

Francis RA, Corenblit D, Edwards PJ. 2009. Perspectives on biogeomorphology, ecosystem engineering and self-organisation in island-braided fluvial ecosystems. Aquatic Sciences-Research Across Boundaries **71** : 290–304.

French HM. 2007. The Periglacial Environment . Wiley: Chichester, UK

Fryirs KA, Brierley GJ, Preston NJ, Kasai M. 2007. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. CATENA **70** : 49–67. DOI: 10.1016/j.catena.2006.07.007

Fullen MA, Catt JA. 2004. Soil erosion. Goudie A (ed). Encyclopedia of Geomorphology **1** : 412–415.

Furrer G. 1954. Solifluktionsformen im schweizerischen Nationalpark - Untersuchung und Interpretation auf morphologischer Grundlage mit 52 photographischen Abbildungen und 9 Textfiguren Band IV . Lüdin AG: Liestal

Furrer G. 1971. Erdströme als Formelemente von Solifluktionsdecken im Raum Munt Chavagl/Munt Buffalora (Schweiz. Nationalpark). . Lüdin AG: Liestal

Gamper M. 1981. Heutige Solifluktionsbeträge von Erdströmen und klimamorphologische Interpretation fossiler Böden . Lüdin AG.

Gamper M. 1983. Controls and rates of movement of solifluction lobes in the eastern Swiss Alps. 433–438 pp.

Ganopolski A, Winkelmann R, Schellnhuber HJ. 2016. Critical insolation–CO2 relation for diagnosing past and future glacial inception. Nature **529** : 200–203. DOI: 10.1038/nature16494

Garibotti IA, Pissolito CI, Villalba R. 2011. Spatiotemporal Pattern of Primary Succession in Relation to Meso-topographic Gradients on Recently Deglaciated Terrains in the Patagonian Andes. Arctic Antarctic and Alpine Research **43** : 555–567. DOI: 10.1657/1938-4246-43.4.555

Garmestani AS, Benson MH. 2013. A Framework for Resilience-based Governance of Social-Ecological Systems. Ecology and Society **18** : 9. DOI: 10.5751/ES-05180-180109

Geilhausen M, Otto J-C, Schrott L. 2012. Spatial distribution of sediment storage types in two glacier landsystems (Pasterze & Obersulzbachkees, Hohe Tauern, Austria). Journal of Maps **8** : 242–259. DOI: 10.1080/17445647.2012.708540

Gentili R, Armiraglio S, Rossi G, Sgorbati S, Baroni C. 2010. Floristic patterns, ecological gradients and biodiversity in the composite channels (Central Alps, Italy). Flora - Morphology, Distribution, Functional Ecology of Plants **205** : 388–398. DOI: 10.1016/j.flora.2009.12.013

Ghestem M, Sidle RC, Stokes A. 2011. The Influence of Plant Root Systems on Subsurface Flow: Implications for Slope Stability. BioScience **61** : 869–879. DOI: 10.1525/bio.2011.61.11.6

Ghestem M, Veylon G, Bernard A, Vanel Q, Stokes A. 2014. Influence of plant root system morphology and architectural traits on soil shear resistance. Plant and Soil **377** : 43–61. DOI: 10.1007/s11104-012-1572-1

Gilbert GK. 1877. Report on the geology of the Henry Mountains . USGS Unnumbered Series. U.S. Government Printing Office: Washington, D.C.

Gleason HA. 1926. The individualistic concept of the plant association. Bulletin of the Torrey Botanical Club : 7–26.

REFERENCES

Gletscherberichte 1881-2016. “Die Gletscher der Schweizer Alpen”, Jahrbücher der Expertenkommission für Kryosphärenmessnetze der Akademie der Naturwissenschaften Schweiz (SCNAT) herausgegegeben seit 1964 durch die Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW) der ETH Zürich. No. 1-134, (http://glaciology.ethz.ch/swiss-glaciers/).

Golley FB. 2000. I.2 Ecosystem Structure. In Handbook of Ecosystem Theories and Management , Muller F (ed). CRC Press; 21–32.

Graf F, Frei M, Böll A. 2009. Effects of vegetation on the angle of internal friction of a moraine. Forest Snow and Landscape Research **82** : 61–77.

Graf F, Gerber W. 1997. Der Einfluss von Mykorrhizapilzen auf die Bodenstruktur und deren Bedeutung für den Lebendverbau. Schweizerische Zeitschrift für Forstwesen **148** : 863–886.

Gregory KJ. 2003. Fluvial geomorphology. Goudie A (ed). **1** : 392–398.

Grime JP. 1977. Evidence for the Existence of Three Primary Strategies in Plants and Its Relevance to Ecological and Evolutionary Theory. The American Naturalist **111** : 1169–1194.

Grohmann CH, Smith MJ, Riccomini C. 2011. Multiscale Analysis of Topographic Surface Roughness in the Midland Valley, Scotland. IEEE Transactions on Geoscience and Remote Sensing **49** : 1200–1213. DOI: 10.1109/TGRS.2010.2053546

Grünewald C. 2011. Geomorphologische und glaziologische Prozesse im Zungenbereich des Turtmanngletschers, Wallis, Schweiz . Diploma thesis (unpublished), University of Bonn, Bonn, Germany

Gunderson LH. 2000. Ecological Resilience--In Theory and Application. Annual Review of Ecology and Systematics **31** : 425–439.

Gunderson LH. 2001. Panarchy: Understanding Transformations in Human and Natural Systems . Island Press

Gunderson LH, Holling CS. 2002. Panarchy: Understanding Transformations in Human and Natural Systems . Island Press: Washington, D.C.

Gurnell A. 2014. Plants as river system engineers. Earth Surface Processes and Landforms **39** : 4–25. DOI: 10.1002/esp.3397

Gurnell AM, Bertoldi W, Corenblit D. 2012. Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers. Earth-Science Reviews **111** : 129–141. DOI: 10.1016/j.earscirev.2011.11.005

Gurnell AM, Edwards PJ, Petts GE, Ward JV. 2000. A conceptual model for alpine proglacial river channel evolution under changing climatic conditions. CATENA **38** : 223–242. DOI: 10.1016/S0341-8162(99)00069-7

Gutiérrez J et al. 2012. Physical Ecosystem Engineers and the Functioning of Estuaries and Coasts. . Wolanski E and McLusky DS (eds). Academic Press: Waltham

Gutiérrez J, Jones CG. 2008. Ecosystem engineers. In Encyclopedia of Life Sciences , . John Wiley & Sons,: Chichester, UK; [online] Available from: DOI: 10.1002/9780470015902.a0021226

Gyssels G, Poesen J, Bochet E, Li Y. 2005. Impact of plant roots on the resistance of soils to erosion by water: a review. Progress in Physical Geography **29** : 189–217. DOI: 10.1191/0309133305pp443ra

Hack JT, Goodlett JC. 1960. Geomorphology and forest ecology of a mountain region in the central Appalachians . USGS Numbered Series. United States Government Printing Office: Washington, D.C.

Haeberli W, Beniston M. 1998. Climate Change and Its Impacts on Glaciers and Permafrost in the Alps. Ambio **27** : 258–265.

Haeberli W, Buetler M, Huggel C, Friedli TL, Schaub Y, Schleiss AJ. 2016. New lakes in deglaciating high-mountain regions – opportunities and risks. Climatic Change : 1–14. DOI: 10.1007/s10584-016-1771-5

Haeberli W, Whiteman C. 2015. Chapter 1 - Snow and Ice-Related Hazards, Risks, and Disasters: A General

Framework. In Snow and Ice-Related Hazards, Risks and Disasters , . Academic Press: Boston; 1–34.

Hall K, Boelhouwers J, Driscoll K. 2001. Some morphometric measurements on ploughing blocks in the McGregor Mountains, Canadian Rockies. Permafrost and Periglacial Processes **12** : 219–225. DOI: 10.1002/ppp.368

Harrington TJ, Mitchell DT. 2002. Characterization of Dryas octopetala ectomycorrhizas from limestone karst vegetation, western Ireland. Canadian Journal of Botany **80** : 970–982. DOI: 10.1139/b02-082

Harris C. 1977. Engineering properties, groundwater conditions, and the nature of soil movement on a solifluction slope in North Norway. Quarterly Journal of Engineering Geology and Hydrogeology **10** : 27–43. DOI: 10.1144/gsl.qjeg.1977.010.01.02

Harris C. 1981. Periglacial Mass-wasting: A Review of Research . Geobooks: Norwich

Harris C. 1982. The distribution and altitudinal zonation of periglacial landforms, Okstinan, Norway. Zeitschrift für Geomorphologie **26** : 283–304.

Harris C, Kern-Luetschg M, Christiansen HH, Fraser S. 2011. The role of interannual climate variability in controlling solifluction processes, Endalen, Svalbard. Permafrost and Periglacial Processes **22** : 239–253. DOI: DOI:10.1002/ppp.727

Harris C, Smith JS, Davies MCR, Rea B. 2008. An investigation of periglacial slope stability in relation to soil properties based on physical modelling in the geotechnical centrifuge. Geomorphology **93** : 437–459. DOI: 10.1016/j.geomorph.2007.03.009

Harrison S. 2001. On reductionism and emergence in geomorphology. Transactions of the Institute of British Geographers **26** : 327–229.

Harrison S, Macklin MG. 1991. Form and size characteristics of clasts on stone-banked solifluction lobes, Okstindan, North Norway. Norsk Geografisk Tidsskrift - Norwegian Journal of Geography **45** : 155–160. DOI: 10.1080/00291959108552268

Hastings A, Byers JE, Crooks JA, Cuddington K, Jones CG, Lambrinos JG, Talley TS, Wilson WG. 2007. Ecosystem engineering in space and time. Ecology Letters **10** : 153–164. DOI: 10.1111/j.1461-0248.2006.00997.x

Haubold A, Lehr D. 2009. Vegetation und Geomorphologie - Biogeomorphologie, Unpublished pioneering biogeomorphology studies from University of Bonn, Bonn

Hauck C, Vonder Mühll D. 2003. Evaluation of geophysical techniques for application in mountain permafrost studies. Zeitschrift für Geomorphologie, Supplement **132** : 161–190.

Hauenstein W. 2005. Hydropower and Climate Change—A Reciprocal Relation: Institutional Energy Issues in Switzerland. Mountain Research and Development **25** : 321–325. DOI: 10.1659/0276-4741(2005)025[0321:HACCRR]2.0.CO;2

Haugland JE. 2006. Short-term periglacial processes, vegetation succession, and soil development within sorted patterned ground: Jotunheimen, Norway. Arctic, Antarctic, and Alpine Research **38** : 82–89.

Haugland JE, Beatty SW. 2005. Vegetation establishment, succession and microsite frost disturbance on glacier forelands within patterned ground chronosequences. Journal of biogeography **32** : 145–153.

Haussmann NS. 2011. Biogeomorphology: understanding different research approaches. Earth Surface Processes and Landforms **36** : 136–138. DOI: 10.1002/esp.2097

Heckmann T et al. 2012. Quantifying proglacial morphodynamics and sediment budgets - the PROSA approach. presented at the EGU General Assembly 2012

Heckmann T, Wichmann V, Becht M. 2005. Sediment transport by avalanches in the Bavarian Alps revisited—A perspective on modelling. Geomorph. NF Suppl **138** : 11–25.

REFERENCES

Hendry GA, Grime JP. 1993. Methods in Comparative Plant Ecology: A Laboratory Manual . Springer Netherlands

Hjort J, Luoto M. 2009. Interaction of geomorphic and ecologic features across altitudinal zones in a subarctic landscape. Geomorphology **112** : 324–333. DOI: 10.1016/j.geomorph.2009.06.019

Holling CS. 1973. Resilience and Stability of Ecological Systems. Annual Review of Ecology and Systematics **4** : 1–23. DOI: 10.1146/annurev.es.04.110173.000245

Holling CS. 1992. Cross-Scale Morphology, Geometry, and Dynamics of Ecosystems. Ecological Monographs **62** : 447–502. DOI: 10.2307/2937313

Holling CS. 2001. Understanding the complexity of economic, ecological, and social systems. Ecosystems **4** : 390–405.

Holling CS, Gunderson LH. 2002. Resilience and Adaptive Cycles. In Panarchy: Understanding Transformations in Human and Natural Systems , Gunderson L and Holling CS (eds). Island Press: Washington, D.C.; 63–102.

Holling CS, Gunderson LH, Peterson GD. 2002. Sustainability and Panarchies. In Panarchy: Understanding Transformations in Human and Natural Systems , . Island Press: Washington, D.C.; 63–102.

Holling CS, Peterson GD, Allen CR. 2008. Panarchies and discontinuities. Discontinuities in ecosystems and other complex systems : 18–42.

Hörsch B. 2003. Zusammenhang zwischen Vegetation und Relief in alpinen Einzugsgebieten des Wallis (Schweiz). Ein multiskaliger GIS- und Fernerkundungsansatz . Asgard-Verlag: Sankt Augustin

Hortobágyi B, Corenblit D, Vautier F, Steiger J, Roussel E, Burkart A, Peiry J-L. 2016. A multi-scale approach of fluvial biogeomorphic dynamics using photogrammetry. Journal of Environmental Management DOI: 10.1016/j.jenvman.2016.08.069.

Horwarth JL, Sletten RS, Hagedorn B, Hallet B. 2008. Spatial and temporal distribution of soil organic carbon in nonsorted striped patterned ground of the High Arctic. Journal of Geophysical Research, Biogeosciences **113** : GS03S07. DOI: 10.1029/2007JG000511

Howard JA, Mitchell CW. 1985. Phytogeomorphology . John Wiley & Sons Inc: New York

Hugenholtz CH, Lewkowicz AG. 2002. Morphometry and environmental characteristics of turf-banked solifluction lobes, Kluane Range, Yukon Territory, Canada. Permafrost and Periglacial Processes **13** : 301–313. DOI: 10.1002/ppp.433

Hungr O. 2005. Classification and terminology. In Debris-flow Hazards and Related Phenomena , . Springer Berlin Heidelberg; 9–23.

Hupp CR, Osterkamp WR, Howard AD. 1995. Biogeomorphology, terrestrial and freshwater systems: proceedings of the 26th Binghamton Symposium in Geomorphology, held October 6-8, 1995 . Elsevier: Amsterdam

Huston M, Smith T. 1987. Plant Succession: Life History and Competition. The American Naturalist **130** : 168–198.

Huxley JS, Odell NE. 1924. Notes on Surface Markings in Spitsbergen. The Geographical Journal **63** : 207–229. DOI: 10.2307/1780934

Irvine-Fynn TDL, Barrand NE, Porter PR, Hodson AJ, Murray T. 2011. Recent High-Arctic glacial sediment redistribution: A process perspective using airborne lidar. Geomorphology **125** : 27–39. DOI: 10.1016/j.geomorph.2010.08.012

Iverson RM. 2005. Debris-flow mechanics. In Debris-flow Hazards and Related Phenomena , . Springer Berlin Heidelberg; 105–134.

Jaesche P, Huwe, Bernd, Stingl H, Veith H. 2002. Temporal variability of alpine solifluction : a modelling approach. Geographica Helvetica. **57** : 157–169. DOI: 10.5169/seals-71294

Jaesche P, Veit H, Huwe B. 2003. Snow cover and soil moisture controls on solifluction in an area of seasonal frost, eastern Alps. Permafrost and Periglacial Processes **14** : 399–410. DOI: 10.1002/ppp.471

Jäger D, Winkler S. 2012. Paraglacial processes on the glacier foreland of Vernagtferner (Ötztal Alps, Austria). Zeitschrift für Geomorphologie, Supplementary Issues **56** : 95–113. DOI: 10.1127/0372-8854/2012/S-00099

Jax K. 2005. Function and "functioning" in ecology: what does it mean? Oikos **111** : 641–648. DOI: 10.1111/j.1600-0706.2005.13851.x

Jochimsen M. 1962. Das Gletschervorfeld - keine Wüste. Jahrbuch des Österreichischen Alpenvereins **87** : 135–142.

Jomelli V, Brunstein D, Grancher D, Pech P. 2007. Is the response of hill slope debris flows to recent climate change univocal? A case study in the Massif des Ecrins (French Alps). Climatic Change **85** : 119–137.

Jonasson S. 1986. Influence of Frost Heaving on Soil Chemistry and on the Distribution of Plant Growth Forms. Geografiska Annaler. Series A, Physical Geography **68** : 185–195. DOI: 10.2307/521458

Jones CG. 2012. Ecosystem engineers and geomorphological signatures in landscapes. Geomorphology **157–158** : 75–87. DOI: 10.1016/j.geomorph.2011.04.039

Jones CG, Gutiérrez JL, Byers JE, Crooks JA, Lambrinos JG, Talley TS. 2010. A framework for understanding physical ecosystem engineering by organisms. Oikos **119** : 1862–1869. DOI: 10.1111/j.1600-0706.2010.18782.x

Jones CG, Lawton JH, Shachack M. 1994. Organisms as ecosystem engineers. Oikos **69** : 373–386. DOI: 10.2307/3545850

Kääb A, Reynolds JM, Haeberli W. 2005. Glacier and Permafrost Hazards in High Mountains. In Global Change and Mountain Regions , Huber UM, Bugmann HKM, and Reasoner MA (eds). Springer Netherlands; 225–234.

Kabala C, Zapart J. 2012. Initial soil development and carbon accumulation on moraines of the rapidly retreating Werenskiold Glacier, SW Spitsbergen, Svalbard archipelago. Geoderma **175**–**176** : 9–20. DOI: 10.1016/j.geoderma.2012.01.025

Karsdóttir L, Aradóttir AL. 2006. Propagation of Dryas octopetala L. and Alchemilla alpina L. by direct seedling and planting of stem cuttings. Icel Agric Sci **19** : 25–32.

Kaufman L, Rousseeuw PJ. 1990. Finding Groups in Data: An Introduction to Cluster Analysis . 9th ed. Wiley-Interscience: New York

Kaufmann R. 2002. Glacier foreland colonisation: distinguishing between short-term and long-term effects of climate change. Oecologia **130** : 470–475. DOI: 10.1007/s00442-001-0815-2

Keller M, Hungerbuehler G, Knecht O, Sheikh S, Beutel J, Gubler S, Fiddes J, Gruber S. 2010. iAssist: rapid deployment and maintenance of tiny sensing systems. Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems : 401–402.

Kennedy BA. 1977. A question of scale? Progress in Physical Geography **1** : 154–157. DOI: 10.1177/030913337700100111

Kent M. 2006. Numerical classification and ordination methods in biogeography. Progress in Physical Geography **30** : 399–408. DOI: 10.1191/0309133306pp489pr

Kim D. 2012. Biogeomorphic feedbacks drive dynamics of vegetation–landform complex in a coastal riparian system. Ecosphere **3** : art74. DOI: 10.1890/ES12-00028.1

King L, Schmitt E. 1993. Solifluction and thermal erosion in high arctic ecosystems, Northern Spitsbergen:

processes and effects. In Solifluction and climatic variation in the Holocene , Frenzel B (ed). 267–278.

King MS, Zimmerman RW, Corwin RF. 1988. Seismic and Electrical Properties of Unconsolidated Permafrost. Geophysical Prospecting **36** : 349–364. DOI: 10.1111/j.1365-2478.1988.tb02168.x

Kinnard C, Lewkowicz AG. 2006. Frontal advance of turf-banked solifluction lobes, Kluane Range, Yukon Territory, Canada. Geomorphology **73** : 261–276. DOI: 10.1016/j.geomorph.2005.06.010

Kinzl H. 1929. Beiträge zur Geschichte der Gletscherschwankungen in den Ostalpen. Zeitschrift für Gletscherkunde **XVII** : 66–121.

Kirkby MJ. 1967. Measurement and Theory of Soil Creep. The Journal of Geology **75** : 359–378. DOI: 10.1086/627267

Kjær KH, Krüger J. 2001. The final phase of dead-ice moraine development: processes and sediment architecture, Kötlujökull, Iceland. Sedimentology **48** : 935–952. DOI: 10.1046/j.1365-3091.2001.00402.x

Klaar MJ, Kidd C, Malone E, Bartlett R, Pinay G, Chapin FS, Milner A. 2015. Vegetation succession in deglaciated landscapes: implications for sediment and landscape stability. Earth Surface Processes and Landforms **40** : 1088–1100. DOI: 10.1002/esp.3691

Klanderud K, Totland Ø. 2004. Habitat dependent nurse effects of the dwarf-shrub Dryas octopetala on alpine and arctic plant community structure. Écoscience **11** : 410–420. DOI: 10.1080/11956860.2004.11682850

Kleinod K. 2008. Fernerkundungsgestützte Modellierung kleinräumiger Biodiversität am Beispiel des Turtmanntals in der Schweiz . Dissertation, Institute of Geography, University of Bonn.

Kneisel C. 2006. Assessment of subsurface lithology in mountain environments using 2D resistivity imaging. Geomorphology **80** : 32–44. DOI: 10.1016/j.geomorph.2005.09.012

Kneisel C. 2010. Frozen ground conditions in a subarctic mountain environment, Northern Sweden. Geomorphology **118** : 80–92. DOI: 10.1016/j.geomorph.2009.12.010

Knight J, Harrison S. 2009. Sediments and future climate. Nature Geoscience **2** : 230–230. DOI: 10.1038/ngeo491

Knight J, Mitchell WA, Rose J. 2011. Geomorphological field mapping. In Geomorphological Mapping: methods and applications , Smith MJ, Paron P, and Griffiths J (eds). Elsevier: London; 151–188.

Knight PG. 2003. Moraines. Goudie A (ed). **1** : 691–694.

Knox JC. 1972. Valley Alluviation in Southwestern Wisconsin. Annals of the Association of American Geographers **62** : 401–410.

Körner C. 2003. Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystems . Springer: Berlin, Heidelberg

Kozłowska A, Rączkowska Z. 2002. Vegetation as a tool in the characterisation of geomorphological forms and processes: an example from the Abisko Mountains. Geografiska Annaler: Series A, Physical Geography **84** : 233–244. DOI: 10.1111/j.0435-3676.2002.00178.x

Krautblatter M, Hauck C. 2007. Electrical resistivity tomography monitoring of permafrost in solid rock walls. Journal of Geophysical Research **112** : F02S20. DOI: 10.1029/2006JF000546

Kruskal JB. 1964. Nonmetric multidimensional scaling: A numerical method. Psychometrika **29** : 115–129. DOI: 10.1007/BF02289694

Kuen V, Erschbamer B. 2002. Comparative study between morphology and age of Trifolium pallescens in a glacier foreland of the Central Alps. Flora - Morphology, Distribution, Functional Ecology of Plants **197** : 379–384. DOI: 10.1078/0367-2530-00054

Küng O, Strecha C, Fua P, Gurdan D, Achtelik M, Doth K-M, Stumpf J. 2011. Simplified Building Models

Extraction from Ultra-Light Uav Imagery. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **XXXVIII-1/C22** : 217–222. DOI: 10.5194/isprsarchives-XXXVIII-1-C22-217-2011

Kutschera L, Lichtenegger E. 2013. Wurzelatlas mitteleuropäischer Waldbäume und Sträucher . Auflage: 2., Auflage. Stocker, L: Graz Austria

Kutschera L, Lichtenegger E, Sobotik M. 1997. Bewurzelung von Pflanzen in verschiedenen Lebensräumen . OÖ Landesmuseum: Linz

Labhart TP. 2009. Geologie der Schweiz . 6., aktualis. A. Ott-Verlag: Bern

Lamberti GA, Gregory SV, Ashkenas LR, Wildman RC, Moore KMS. 1991. Stream Ecosystem Recovery Following a Catastrophic Debris Flow. Canadian Journal of Fisheries and Aquatic Sciences **48** : 196–208. DOI: 10.1139/f91-027

Lane SN, Bakker M, Gabbud C, Micheletti N, Saugy J-N. 2016a. Sediment export, transient landscape response and catchment-scale connectivity following rapid climate warming and Alpine glacier recession. Geomorphology DOI: 10.1016/j.geomorph.2016.02.015

Lane SN, Borgeaud L, Vittoz P. 2016b. Emergent geomorphic–vegetation interactions on a subalpine alluvial fan. Earth Surface Processes and Landforms **41** : 72–86. DOI: 10.1002/esp.3833

Larcher W, Kainmüller C, Wagner J. 2010. Survival types of high mountain plants under extreme temperatures. Flora - Morphology, Distribution, Functional Ecology of Plants **205** : 3–18. DOI: 10.1016/j.flora.2008.12.005

Lauber K, Wagner G. 2007. Flora Helvetica. . Haupt Verlag

Laute K, Beylich AA. 2012. Influences of the Little Ice Age glacier advance on hillslope morphometry and development in paraglacial valley systems around the Jostedalsbreen ice cap in Western Norway. Geomorphology **167** : 51–69. DOI: 10.1016/j.geomorph.2012.03.010

Lavorel S, Díaz S, Cornelissen J, Garnier E, Harrison S, Mcintyre S, Pausas J, Pérez-Harguindeguy N, Roumet C, Urcelay C. 2007. Plant Functional Types: Are We Getting Any Closer to the Holy Grail? In Terrestrial Ecosystems in a Changing World , Canadell JG, Pataki DE, and Pitelka LF (eds). 149–164. DOI: 10.1007/978-3-540-32730-1_13

Lazzaro A, Franchini AG, Brankatschk R, Zeyer J. 2010. Pioneer communities in the forefields of retreating glaciers: how microbes adapt to a challenging environment. In Current Research, Technology and Education Topics in Applied Microbiology and Microbial Biotechnology , Mendez-Vilas A (ed). FORMATEX: Badajoz, Spain; 43–52.

Legendre P, Legendre L. 1998. Numerical Ecology . 2nd revised edition. Elsevier Ltd, Oxford

Levin SA. 1992. The Problem of Pattern and Scale in Ecology: The Robert H. MacArthur Award Lecture. Ecology **73** : 1943–1967. DOI: 10.2307/1941447

Levin SA. 1998. Ecosystems and the Biosphere as Complex Adaptive Systems. Ecosystems **1** : 431–436. DOI: 10.1007/s100219900037

Lewontin RC. 1969. The meaning of stability. Brookhaven Symposia in Biology **22** : 13–24.

Leyer I, Wesche K. 2007. Multivariate Statistik in der Ökologie . Springer: Berlin, Heidelberg

Linsbauer A, Paul F, Haeberli W. 2012. Modeling glacier thickness distribution and bed topography over entire mountain ranges with GlabTop: Application of a fast and robust approach. Journal of Geophysical Research: Earth Surface **117** : F03007. DOI: 10.1029/2011JF002313

Lippert W. 1966. Die Pflanzengesellschaften des Naturschutzgebietes Berchtesgaden. Berichte der Bayerischen Botanischen Gesellschaft **39** : 67–122.

REFERENCES

Loke M h., Barker R d. 1996. Practical techniques for 3D resistivity surveys and data inversion. Geophysical Prospecting **44** : 499–523. DOI: 10.1111/j.1365-2478.1996.tb00162.x

Loke MH, Barker RD. 1995. Least-squares deconvolution of apparent resistivity pseudosections. GEOPHYSICS **60** : 1682–1690. DOI: 10.1190/1.1443900

Lovett GM, Jones C, Turner MG, Weathers KC. 2007. Ecosystem Function in Heterogeneous Landscapes . Springer

Luckman BH. 1977. The Geomorphic Activity of Snow Avalanches. Geografiska Annaler. Series A, Physical Geography **59** : 31–48. DOI: 10.2307/520580

Lüdi W. 1945. Besiedlung und Vegetationsentwicklung auf den jungen Seitenmoränen des grossen Aletschgletschers: mit einem Vergleich der Besiedlung im Vorfeld des Rhonegletschers und des Oberen Grindelwaldgletschers

Lüdi W. 1958. Beobachtung über die Besiedlung von Gletschervorfeldern in den Schweizeralpen

Lukas S, Graf A, Coray S, Schlüchter C. 2012. Genesis, stability and preservation potential of large lateral moraines of Alpine valley glaciers – towards a unifying theory based on Findelengletscher, Switzerland. Quaternary Science Reviews **38** : 27–48. DOI: 10.1016/j.quascirev.2012.01.022

MacArthur RH, Wilson EO. 1967. The Theory of Island Biogeography . Princeton University Press

Mahoney JM, Rood SB. 1998. Streamflow requirements for cottonwood seedling recruitment—An integrative model. Wetlands **18** : 634–645. DOI: 10.1007/BF03161678

Major J. 1977. Snow and Avalanches. Ecology **58** : 705–706. DOI: 10.2307/1939026

Makoto K, Wilson SD. 2016. New Multicentury Evidence for Dispersal Limitation during Primary Succession. American Naturalist **187** : 804–811. DOI: 10.1086/686199

Marcante S, Winkler E, Erschbamer B. 2009. Population dynamics along a primary succession gradient: do alpine species fit into demographic succession theory? Annals of Botany **103** : 1129–1143. DOI: 10.1093/aob/mcp047

Marston RA. 2010. Geomorphology and vegetation on hillslopes: Interactions, dependencies, and feedback loops. Geomorphology **116** : 206–217. DOI: 10.1016/j.geomorph.2009.09.028

Matsuoka N. 2001. Solifluction rates, processes and landforms: a global review. Earth-Science Reviews **55** : 107–134. DOI: 10.1016/S0012-8252(01)00057-5

Matsuoka N. 2004. Solifluction. In Encyclopedia of Geomorphology , Goudie A (ed). Routledge; 984–987.

Matsuoka N. 2010. Solifluction and mudflow on a limestone periglacial slope in the Swiss Alps: 14 years of monitoring. Permafrost and Periglacial Processes **21** : 219–240. DOI: 10.1002/ppp.678

Matsuoka N. 2014. Combining Time-Lapse Photography and Multisensor Monitoring to Understand Frost Creep Dynamics in the Japanese Alps. Permafrost and Periglacial Processes **25** : 94–106. DOI: 10.1002/ppp.1806

Matthews JA. 1992. The Ecology of Recently-deglaciated Terrain: A Geoecological Approach to Glacier Forelands . Cambridge University Press: Cambridge

Matthews JA. 1999. Disturbance Regimes and Ecosystem Response on Recently-Deglaciated Terrain. In Ecosystems of disturbed ground , Walker LR (ed). Elsevier: Amsterdam; 17–37.

Matthews JA, Harris C, Ballantyne CK. 1986. Studies on a Gelifluction Lobe, Jotunheimen, Norway: 14C Chronology, Stratigraphy, Sedimentology and PalÆoenvironment. Geografiska Annaler. Series A, Physical Geography **68** : 345–360. DOI: 10.2307/521526

Matthews JA, Seppälä M, Dresser PQ. 2005. Holocene solifluction, climate variation and fire in a subarctic landscape at Pippokangas, Finnish Lapland, based on radiocarbon-dated buried charcoal. Journal of

Quaternary Science **20** : 533–548. DOI: 10.1002/jqs.932

Matthews JA, Shakesby RA, Berrisford MS, McEwen LJ. 1998. Periglacial patterned ground on the Styggedalsbreen glacier foreland, Jotunheimen, southern Norway: micro-topographic, paraglacial and geoecological controls. Permafrost and Periglacial Processes **9** : 147–166. DOI: 10.1002/(SICI)1099-1530(199804/06)9:2<147::AID-PPP278>3.0.CO;2-9

Matthews JA, Vater AE. 2015. Pioneer zone geo-ecological change: Observations from a chronosequence on the Storbreen glacier foreland, Jotunheimen, southern Norway. CATENA **135** : 219–230. DOI: 10.1016/j.catena.2015.07.016

Matthews JA, Whittaker RJ. 1987. Vegetation Succession on the Storbreen Glacier Foreland, Jotunheimen, Norway: A Review. Arctic and Alpine Research **19** : 385–395. DOI: 10.2307/1551403

McCook LJ. 1994. Understanding ecological community succession: Causal models and theories, a review. Vegetatio **110** : 115–147. DOI: 10.1007/BF00033394

McCune B, Grace J. 2002. Analysis of Ecological Communities . Mjm Software Design: Gleneden Beach, OR, US

McGraw JB. 1985. Experimental Ecology of Dryas Octopetala Ecotypes: Relative Response to Competitors. New Phytologist **100** : 233–241. DOI: 10.1111/j.1469-8137.1985.tb02775.x

Mercier D, Étienne S, Sellier D, André M. 2009. Paraglacial gullying of sediment-mantled slopes: a case study of Colletthøgda, Kongsfjorden area, West Spitsbergen (Svalbard). Earth Surface Processes and Landforms **34** : 1772–1789. DOI: 10.1002/esp.1862

Messenzehl K, Hoffmann T, Dikau R. 2014. Sediment connectivity in the high-alpine valley of Val Müschauns, Swiss National Park — linking geomorphic field mapping with geomorphometric modelling. Geomorphology **221** : 215–229. DOI: 10.1016/j.geomorph.2014.05.033

MeteoSwiss. 2016. Climate data station Turtmann, 2013-2014, Provided by MeteoSwiss, the Swiss Federal Office of Meteorology and Climatology

Meyer N, Bornemann L, Welp G, Amelung W. 2015. Nitrogen controls spatial and temporal variability of substrate-induced respiration within seven years of bare fallow. presented at the EGU General Assembly Conference Abstracts. 11978 pp. 1 April.

Micheletti N, Lambiel C, Lane SN. 2015. Investigating decadal-scale geomorphic dynamics in an alpine mountain setting. Journal of Geophysical Research: Earth Surface **120** : 2015JF003656. DOI: 10.1002/2015JF003656

Micheletti N, Lane SN. 2016. Water yield and sediment export in small, partially glaciated Alpine watersheds in a warming climate. Water Resources Research **52** : 4924–4943. DOI: 10.1002/2016WR018774

Midgley NG, Cook SJ, Graham DJ, Tonkin TN. 2013. Origin, evolution and dynamic context of a Neoglacial lateral–frontal moraine at Austre Lovénbreen, Svalbard. Geomorphology **198** : 96–106. DOI: 10.1016/j.geomorph.2013.05.017

Mills LS, Soulé ME, Doak DF. 1993. The keystone-species concept in ecology and conservation. BioScience : 219–224.

Milner AM, Fastie CL, CHAPIN III FS, Engstrom DR, Sharman LC. 2007. Interactions and linkages among ecosystems during landscape evolution. BioScience **57** : 237–247.

Minami Y, Okitsu S, Kanda H. 1997. Relationship between Plant Community and Topographic Factor on the Moraine at Deglaciated Arctic Terrain in Ny-Alesund, Svalbard. Bull. Fac. Agr., Tamagawa Univ. : 21–30.

Montgomery DR. 1999. Process Domains and the River Continuum. JAWRA Journal of the American Water Resources Association **35** : 397–410. DOI: 10.1111/j.1752-1688.1999.tb03598.x

Moore RD, Fleming SW, Menounos B, Wheate R, Fountain A, Stahl K, Holm K, Jakob M. 2009. Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality. Hydrological Processes **23** : 42–61. DOI: 10.1002/hyp.7162

Moreau M, Laffly D, Joly D, Brossard T. 2005. Analysis of plant colonization on an Arctic moraine since the end of the Little Ice Age using remotely sensed data and a Bayesian approach. Remote Sensing of Environment **99** : 244–253.

Moreau M, Mercier D, Laffly D. 2004. Un siècle de dynamiques paraglaciaires et végétal sur les marges du Midre Lovénbreen, Spitsberg nord-occidental / A century of paraglacial and plant dynamics in the Midre Lovénbreen foreland (northwestern Spitsbergen). Géomorphologie: relief, processus, environnement **10** : 157–168.

Moreau M, Mercier D, Laffly D, Roussel E. 2008. Impacts of recent paraglacial dynamics on plant colonization: A case study on Midtre Lovénbreen foreland, Spitsbergen (79° N). Geomorphology **95** : 48–60.

Mori AS, Uchida M, Kanda H. 2013. Non-stochastic colonization by pioneer plants after deglaciation in a polar oasis of the Canadian High Arctic. Polar Science **7** : 278–287. DOI: 10.1016/j.polar.2013.09.002

Mueller-Dombois D, Ellenberg H. 2003. Aims and Methods of Vegetation Ecology . The Blackburn Press: New York

Müller F. 1992. Hierarchical approaches to ecosystem theory. Ecological Modelling **63** : 215–242.

Murray A, Knaapen M, Tal M, Kirwan M. 2008. Biomorphodynamics: physical-biological feedbacks that shape landscapes. Water Resources Research **44** : W11301.

Nagl F, Erschbamer B. 2010. Kapitel 6. Pflanzliche Sukzessionen im Gletschervorfeld. Vegetation und Besiedlungsstrategien. In Glaziale und periglaziale Lebensräume im Raum Obergurgl , Erschbamer B and Koch EM (eds). innsbruck university press: Innsbruck; 121–142.

Naylor LA, Viles HA, Carter NEA. 2002. Biogeomorphology revisited: looking towards the future. Geomorphology **47** : 3–14.

Nemergut DR, Anderson SP, Cleveland CC, Martin AP, Miller AE, Seimon A, Schmidt SK. 2006. Microbial Community Succession in an Unvegetated, Recently Deglaciated Soil. Microbial Ecology **53** : 110–122. DOI: 10.1007/s00248-006-9144-7

Neumann M. 2015. Learning with Graphs using Kernels from Propagated Information, PhD thesis, University of Bonn: Bonn.

Nyenhuis M, Hölzle M, Dikau R. 2005. Rock glacier mapping and permafrost distribution modelling in the Turtmanntal, Valais, Switzerland. Zeitschrift für Geomorphologie, N.F. **49** : 275–292.

Odling-Smee FJ, Laland KN, Feldman MW. 2003. Niche construction: the neglected process in evolution . Princeton University Press.

Odling-Smee J, Erwin DH, Palkovacs EP, Feldman MW, Laland KN. 2013. Niche construction theory: a practical guide for ecologists. The Quarterly Review of Biology **88** : 4–28. DOI: 10.1086/669266

Odum EP. 1953. Fundamentals of Ecology . Saunders

Oliva M, Ruiz-Fernández J. 2016. Geomorphological processes and frozen ground conditions in Elephant Point (Livingston Island, South Shetland Islands, Antarctica). Geomorphology DOI: 10.1016/j.geomorph.2016.01.020.

Oliva M, Schulte L, Ortiz AG. 2011. The role of aridification in constraining the elevation range of Holocene solifluction processes and associated landforms in the periglacial belt of the Sierra Nevada (southern Spain). Earth Surface Processes and Landforms **36** : 1279–1291. DOI: 10.1002/esp.2116

Oliver CD, Adams AB, Zasoski RJ. 1985. Disturbance patterns and forest development in a recently deglaciated valley in the northwestern Cascade Range of Washington, U.S.A. Canadian Journal of Forest Research **15** : 221–232. DOI: 10.1139/x85-040

O'Neill RV. 1989. Perspectives in hierarchy and scale. In Perspectives in Ecological Theory , Roughgarden R, May M, and Levin SA (eds). Princeton University Press: Princeton; 140–156.

O'Neill RV, DeAngelis DL, Waide JB. 1986. A Hierarchical Concept of Ecosystems . Princeton University Press: Princeton

Orwin JF, Smart CC. 2004. The evidence for paraglacial sedimentation and its temporal scale in the deglacierizing basin of Small River Glacier, Canada. Geomorphology **58** : 175–202. DOI: 10.1016/j.geomorph.2003.07.005

Osterkamp WR, Hupp CR. 2010. Fluvial processes and vegetation - Glimpses of the past, the present, and perhaps the future. Geomorphology **116** : 274–285. DOI: 10.1016/j.geomorph.2009.11.018

Otto J-C. 2001. Das Geomorphologische System des Turtmanntals . Unveröffentlichte Diplomarbeit, Geographisches Institut, Universität Bonn

Otto J-C. 2009. Paraglacial sediment storage quantification in the Turtmann Valley, Swiss Alps . Ferger: Bergisch Gladbach

Otto J-C, Dikau R. 2004. Geomorphic analysis of a high mountain valley in the Swiss Alps. Zeitschrift für Geomorphologie, N.F. **38** : 323–341.

Otto J-C, Dikau R (eds). 2009. Landform - Structure, Evolution, Process Control: Proceedings of the International Symposium on Landform organised by the Research Training Group 437 . 1st ed. Springer

Otto J-C, Schrott L, Jaboyedoff M, Dikau R. 2009. Quantifying sediment storage in a high alpine valley (Turtmanntal, Switzerland). Earth Surface Processes and Landforms **34** : 1726–1742. DOI: 10.1002/esp.1856

Otto J-C, Smith MJ. 2013. Geomorphological mapping. Geomorphological techniques (online edition). British Society for Geomorphology, London, ISSN : 2047–371.

Paine RT. 1966. Food Web Complexity and Species Diversity. The American Naturalist **100** : 65. DOI: 10.1086/282400

Parker KC, Bendix J. 1996. Landscape-scale geomorphic influences on vegetation patterns in four environments. Physical Geography **17** : 113–141. DOI: 10.1080/02723646.1996.10642577

Parsons M, Thoms MC. 2007. Hierarchical patterns of physical–biological associations in river ecosystems. Geomorphology **89** : 127–146. DOI: 10.1016/j.geomorph.2006.07.016

Patten RS, Knight DH. 1994. Snow Avalanches and Vegetation Pattern in Cascade Canyon, Grand Teton National Park, Wyoming, U.S.A. Arctic and Alpine Research **26** : 35. DOI: 10.2307/1551874

Paul F, Kaab A, Maisch M, Kellenberger T, Haeberli W. 2004. Rapid disintegration of Alpine glaciers observed with satellite data. Geophysical Research Letters **31** : L21402. DOI: 10.1029/2004GL020816

Penck W. 1924. Die morphologische Analyse: ein Kapitel der physikalischen Geologie . Engelhern Verlag: Stuttgart

Peralta G, van Duren LA, Morris EP, Bouma TJ. 2008. Consequences of shoot density and stiffness for ecosystem engineering by benthic macrophytes in flow dominated areas: a hydrodynamic flume study. Marine Ecology Progress Series **368** : 103–115. DOI: 10.3354/meps07574

Perrone A, Lapenna V, Piscitelli S. 2014. Electrical resistivity tomography technique for landslide investigation: A review. Earth-Science Reviews **135** : 65–82. DOI: 10.1016/j.earscirev.2014.04.002

Phillips JD. 1999. Earth surface systems: complexity, order and scale . Blackwell Publishers

Phillips JD. 2003. Sources of nonlinearity and complexity in geomorphic systems. Progress in Physical Geography **27** : 1–23. DOI: 10.1191/0309133303pp340ra

Phillips JD. 2016a. Biogeomorphology and contingent ecosystem engineering in karst landscapes. Progress in Physical Geography : 309133315624641. DOI: 10.1177/0309133315624641

REFERENCES

Phillips JD. 2016b. Vanishing point: Scale independence in geomorphological hierarchies. Geomorphology **266** : 66–74. DOI: 10.1016/j.geomorph.2016.05.012

Pickett ST, Kolasa J, Jones CG. 1994. Ecological Understanding . Academic Press

Pickett STA, Collins SL, Armesto JJ. 1987. Models, mechanisms and pathways of succession. The Botanical Review **53** : 335–371. DOI: 10.1007/BF02858321

Pickett STA, White PS. 1987. The Ecology of Natural Disturbance and Patch Dynamics . Academic Press: Orlando

Pickett STA, Wu J, Cadenasso ML. 1999. Patch dynamics and the ecology of disturbed ground: A framework for synthesis. In Ecosystems of disturbed ground , Walker LR (ed). Elsevier: Amsterdam; 708–722.

Pierce S, Brusa G, Vagge I, Cerabolini BEL. 2013. Allocating CSR plant functional types: the use of leaf economics and size traits to classify woody and herbaceous vascular plants. Functional Ecology **27** : 1002–1010. DOI: 10.1111/1365-2435.12095

Pike RJ, Evans IS, Hengl T. 2009. Geomorphometry: a brief guide. Developments in Soil Science **33** : 3–30.

Pohl M, Graf F, Buttler A, Rixen C. 2012. The relationship between plant species richness and soil aggregate stability can depend on disturbance. Plant and Soil **355** : 87–102. DOI: 10.1007/s11104-011-1083-5

Poser H. 1932. Einige Untersuchungen zur Morphologie Ostgrönlands. . C.A. Reitzel: København

Prach K, Rachlewicz G. 2012. Succession of vascular plants in front of retreating glaciers in central Spitsbergen. Polish Polar Research **33** DOI: 10.2478/v10183-012-0022-3.

Price LW. 1970. Morphology and ecology of solifluction lobe development, Ruby Range, Yukon Territory, Ph.D. dissertation, University of Illinois, Urbana, IL.

Price LW. 1974. The Developmental Cycle of Solifluction Lobes*. Annals of the Association of American Geographers **64** : 430–438. DOI: 10.1111/j.1467-8306.1974.tb00991.x

Price LW. 1991. Subsurface Movement on Solifluction Slopes in the Ruby Range, Yukon Territory, Canada: A 20-Year Study. Arctic and Alpine Research **23** : 200–205. DOI: 10.2307/1551383

Prick A. 2004. Frost and frost weathering. Goudie A (ed). Encyclopedia of Geomorphology **1** : 412–415.

R Development Core Team. 2011. The R Project for Statistical Computing. [online] Available from: http://www.r-project.org/

R Development Core Team. 2014. The R Project for Statistical Computing. [online] Available from: http://www.r-project.org/ (Accessed 27 February 2014)

Raab T, Krümmelbein J, Schneider A, Gerwin W, Maurer T, Naeth M. 2012. Initial Ecosystem Processes as Key Factors of Landscape Development—A Review. Physical Geography **33** : 305–343. DOI: 10.2747/0272-3646.33.4.305

Radić V, Bliss A, Beedlow AC, Hock R, Miles E, Cogley JG. 2013. Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models. Climate Dynamics **42** : 37–58. DOI: 10.1007/s00382-013-1719-7

Raffl C, Mallaun M, Mayer R, Erschbamer B. 2006. Vegetation Succession Pattern and Diversity Changes in a Glacier Valley, Central Alps, Austria. Arctic, Antarctic, and Alpine Research **38** : 421–428. DOI: 10.1657/1523-0430(2006)38[421:VSPADC]2.0.CO;2

Rapp A. 1960. Recent Development of Mountain Slopes in Kärkevagge and Surroundings, Northern Scandinavia. Geografiska Annaler **42** : 65–200. DOI: 10.2307/520126

Rauh W. 1939. Über polsterförmigen Wuchs. Ein Beitrag zur Kenntnis der Wuchsformen der höheren Pflanzen. Nova Acta Leopold : 272–505.

Raymond Pralong M, Turowski JM, Beer A, Rickenmann D, Métraux V, Glassey T. 2011. Klimaänderung und Wasserkraft. Sektorielle Studie Wallis. Auswirkung der Klimaänderung auf die Geschiebefracht.

Reinhardt L, Jerolmack D, Cardinale BJ, Vanacker V, Wright J. 2010. Dynamic interactions of life and its landscape: feedbacks at the interface of geomorphology and ecology. Earth Surface Processes and Landforms **35** : 78–101. DOI: 10.1002/esp.1912

Reisigl H, Keller R. 1994. Alpenpflanzen im Lebensraum . Spektrum Akademischer Verlag: Stuttgart

Renschler CS, Doyle MW, Thoms M. 2007. Geomorphology and ecosystems: Challenges and keys for success in bridging disciplines. Geomorphology **89** : 1–8. DOI: 10.1016/j.geomorph.2006.07.011

Rice S, Stoffel M, Turowski JM, Wolf A. 2012. Disturbance regimes at the interface of geomorphology and ecology. Earth Surface Processes and Landforms **37** : 1678–1682. DOI: 10.1002/esp.3326

Richter M. 1994. Die Pflanzensukzession im Vorfeld des Tschierva-Gletschers/Oberengadin. Geoökodynamik **15** : 55–88.

Ridefelt H, Boelhouwers J. 2006. Observations on regional variation in solifluction landform morphology and environment in the Abisko region, northern Sweden. Permafrost and Periglacial Processes **17** : 253–266. DOI: 10.1002/ppp.560

Ridefelt H, Boelhouwers J, Etzelmüller B. 2011. Local variations of solifluction activity and environment in the Abisko Mountains, Northern Sweden. Earth Surface Processes and Landforms **36** : 2042–2053. DOI: 10.1002/esp.2225

Rings J, Scheuermann A, Preko K, Hauck C. 2008. Soil water content monitoring on a dike model using electrical resistivity tomography. Near Surface Geophysics **6** : 123–132.

Risch AC, Schütz M, Krüsi BO, Kienast F, Wildi O, Bugmann H. 2004. Detecting successional changes in long-term empirical data from subalpine conifer forests. Plant Ecology **172** : 95–105. DOI: 10.1023/B:VEGE.0000026040.01175.7c

Robbins JA, Matthews JA. 2010. Regional Variation in Successional Trajectories and Rates of Vegetation Change on Glacier Forelands in South-Central Norway. Arctic, Antarctic, and Alpine Research **42** : 351–361. DOI: 10.1657/1938-4246-42.3.351

Robbins JA, Matthews JA. 2014. Use of ecological indicator values to investigate successional change in boreal to high-alpine glacier-foreland chronosequences, southern Norway. The Holocene **24** : 1453–1464. DOI: 10.1177/0959683614544067

Rose J. 1991. Subaerial modification of glacier bedforms immediately following ice wastage. Norsk Geografisk Tidsskrifi **45** : 145–155.

Rose JP, Malanson GP. 2012. Microtopographic heterogeneity constrains alpine plant diversity, Glacier National Park, MT. Plant Ecology **213** : 955–965. DOI: 10.1007/s11258-012-0056-y

Rydgren K, Halvorsen R, Töpper JP, Njøs JM. 2014. Glacier foreland succession and the fading effect of terrain age. Journal of Vegetation Science **25** : 1367–1380. DOI: 10.1111/jvs.12184

Saco PM, Willgoose GR, Hancock GR. 2007. Eco-geomorphology of banded vegetation patterns in arid and semi-arid regions. Hydrology and Earth System Sciences **11** : 1717–1730.

Schaaf W, Bens, O., Fischer, A., Gerke, H. H., Gerwin, W., Grünewald, U., Holländer, H. M., Kögel-Knabner, I., Mutz, M., Schloter, M., Schulin, R., Veste, M., Winter, S. and Hüttl, R. F. 2011. Patterns and processes of initial terrestrial-ecosystem development. Journal of Plant Nutrition and Soil Science 174 : 229–239. DOI: 10.1002/jpln.201000158

Scherler M, Hauck C, Hoelzle M, Stähli M, Völksch I. 2010. Meltwater infiltration into the frozen active layer at an alpine permafrost site. Permafrost and Periglacial Processes **21** : 325–334. DOI: 10.1002/ppp.694

Schiefer E, Gilbert R. 2007. Reconstructing morphometric change in a proglacial landscape using historical aerial photography and automated DEM generation. Geomorphology **88** : 167–178. DOI: 10.1016/j.geomorph.2006.11.003

Schleiss A. 2005. INTERREG IIIB - Projet ALPRESERV. Conférence sur la problématique de la sédimentation dans les réservoirs - Gestion durable des sédiments dans les réservoirs alpins . Communications du Laboratoire de constructions hydrauliques. Ecole Polytechnique Fédérale de Lausanne: Lausanne

Schmid M-O, Gubler S, Fiddes J, Gruber S. 2012. Inferring snowpack ripening and melt-out from distributed measurements of near-surface ground temperatures. The Cryosphere **6** : 1127–1139. DOI: 10.5194/tc-6-1127-2012

Schmidt J, Dikau R. 1999. Extracting geomorphometric attributes and objects from digital elevation models - Semantics, methods, future needs. In GIS for Earth Surface Systems , Dikau R and Sauer H (eds). Gebrüder Bornträger: Stuttgart; 153–174.

Schmidtlein S, Tichý L, Feilhauer H, Faude U. 2010. A brute-force approach to vegetation classification. Journal of Vegetation Science **21** : 1162–1171. DOI: 10.1111/j.1654-1103.2010.01221.x

Schomacker A. 2008. What controls dead-ice melting under different climate conditions? A discussion. Earth-Science Reviews **90** : 103–113. DOI: 10.1016/j.earscirev.2008.08.003

Schröter C, Brockmann-Jerosch H, Brockmann-Jerosch MC, Günthart A, Vogler P, Huber-Pestalozzi G. 1926. Das Pflanzenleben der Alpen . Verlag von Albert Raustein: Zürich

Schrott L, Glade T. 2008. Frequenz und Magnitude natürlicher Prozesse. In Naturrisiken und Sozialkatastrophen , Felgentreff C and Glade T (eds). Spektrum Akademischer Verlag: Heidelberg; 133–140.

Schrott L, Hufschmidt G, Hankammer M, Hoffmann T, Dikau R. 2003. Spatial distribution of sediment storage types and quantification of valley fill deposits in an alpine basin, Reintal, Bavarian Alps, Germany. Geomorphology **55** : 45–63.

Schrott L, Niederheide A, Hankammer N, Hufschmidt G, Dikau R. 2002. Sediment storage in a mountain catchment: geomorphic coupling and temporal variability (Reintal, Bavarian Alps, Germany). Zeitschrift für Geomorphologie, N.F. **127** : 175–196.

Schumann K, Gewolf S, Tackenberg O. 2016. Factors affecting primary succession of glacier foreland vegetation in the European Alps. Alpine Botany **126** : 105–117. DOI: 10.1007/s00035-016-0166-6

Schumm SA. 2006. To interpret the earth . Cambridge University Press: Cambridge

Schumm SA, Lichty RW. 1965. Time, space, and causality in geomorphology. American Journal of Science **263** : 110–119. DOI: 10.2475/ajs.263.2.110

Schweingruber FH, Münch A, Schwarz R. 2007. Dendrochronologie von Kräutern und Sträuchern im Vorfeld des Morteratschgletschers. BAUHINIA. Zeitschrift der Basler Botanischen Gesellschaft. **20** : 5–17.

Schwienbacher E, Navarro-Cano JA, Neuner G, Erschbamer B. 2012. Correspondence of seed traits with niche position in glacier foreland succession. Plant Ecology **213** : 371–382. DOI: 10.1007/s11258-011-9981-4

Sharp RP. 1958. The Latest Major Advance of Malaspina Glacier, Alaska. Geographical Review **48** : 16–26. DOI: 10.2307/211699

Sidle RC, Hirano T, Gomi T, Terajima T. 2007. Hortonian overland flow from Japanese forest plantations—an aberration, the real thing, or something in between? Hydrological Processes **21** : 3237–3247. DOI: 10.1002/hyp.6876

Sidle RC, Ochiai H. 2006. Natural Factors Influencing Landslides. In Landslides: Processes, Prediction, and Land Use , Sidle RC and Ochiai H (eds). American Geophysical Union: Washington, D.C.; 41–119.

Sigafoos RS. 1951. Soil instability in tundra vegetation. Ohio Journal of Science **51** : 281–298.

Slaymaker O. 2006. Towards the identification of scaling relations in drainage basin sediment budgets. Geomorphology **80** : 8–19. DOI: 10.1016/j.geomorph.2005.09.004

Slaymaker O. 2011. Criteria to distinguish between periglacial, proglacial and paraglacial environments. Quaestiones Geographicae : 85–94.

Small RJ. 1983. Lateral moraines of Glacier de Tsidjiore Nouve: form, development and implications. Journal of Glaciology **29** : 250–259.

Smith DJ. 1987. Observations of turf-banked solifluction lobe geomorphometry. Albertan Geographer **23** : 45–55.

Smith DJ. 1992. Long-term rates of contemporary solifluction activity in the Canadian Rocky Mountains. In Periglacial Geomorphology , Dixon J and Abrahams A (eds). Wiley and Sons: Chichester, UK; 201–222.

Smith J. 1956. Some Moving Soils in Spitsbergen. Journal of Soil Science **7** : 11–21. DOI: 10.1111/j.1365-2389.1956.tb00857.x

Snavely N, Seitz SM, Szeliski R. 2007. Modeling the World from Internet Photo Collections. International Journal of Computer Vision **80** : 189–210. DOI: 10.1007/s11263-007-0107-3

Spencer T, Viles H. 2002. Bioconstruction, bioerosion and disturbance on tropical coasts: coral reefs and rocky limestone shores. Geomorphology **48** : 23–50. DOI: 10.1016/S0169-555X(02)00174-5

Stallins JA. 2005. Stability domains in barrier island dune systems. Ecological Complexity **2** : 410–430. DOI: 10.1016/j.ecocom.2005.04.011

Stallins JA. 2006. Geomorphology and ecology: unifying themes for complex systems in biogeomorphology. Geomorphology **77** : 207–216.

Stallins JA, Parker AJ. 2003. The Influence of Complex Systems Interactions on Barrier Island Dune Vegetation Pattern and Process. Annals of the Association of American Geographers **93** : 13–29. DOI: 10.1111/1467-8306.93102

Stöcklin J, Bäumler E. 1996. Seed rain, seedling establishment and clonal growth strategies on a glacier foreland. Journal of Vegetation Science **7** : 45–56. DOI: 10.2307/3236415

Stoffel M. 2010. Magnitude–frequency relationships of debris flows—A case study based on field surveys and tree-ring records. Geomorphology **116** : 67–76.

Stokes A, Salin F, Kokutse AD, Berthier S, Jeannin H, Mochan S, Dorren L, Kokutse N, Ghani MA, Fourcaud T. 2005. Mechanical resistance of different tree species to rockfall in the French Alps. Plant and soil **278** : 107–117.

Stokes CR, Shahgedanova M, Evans IS, Popovnin VV. 2013. Accelerated loss of alpine glaciers in the Kodar Mountains, south-eastern Siberia. Global and Planetary Change **101** : 82–96. DOI: 10.1016/j.gloplacha.2012.12.010

Strömquist L. 1983. Gelifluction and Surface Wash, Their Importance and Interaction on a Periglacial Slope. Geografiska Annaler. Series A, Physical Geography **65** : 245–254. DOI: 10.2307/520589

Taber S. 1943. Perennially frozen ground in Alaska: its origin and history. Geological Society of America Bulletin **54** : 1433–1548. DOI: 10.1130/GSAB-54-1433

Tansley AG. 1920. The classification of vegetation and the concept of development. The Journal of Ecology : 118–149.

Tansley AG. 1935. The use and abuse of vegetational concepts and terms. Forest Ecology and Management **16** : 284–307.

Temme AJAM, Lange K. 2014. Proglacial soil variability and geomorphic activity – the case of three Swiss valleys. Earth Surface Processes and Landforms : 39 . 1492 - 1499. DOI: 10.1002/esp.3553

REFERENCES

Tenenbaum JB, Silva V de, Langford JC. 2000. A Global Geometric Framework for Nonlinear Dimensionality Reduction. Science **290** : 2319–2323. DOI: 10.1126/science.290.5500.2319

Teysseire P. 2006. Geotechnische Eigenschaften von Moränen . Diss., Technische Wissenschaften, Eidgenössische Technische Hochschule ETH Zürich, Nr. 16322, ETH: Zurich

Thoms MC, Parsons M. 2002. Eco-geomorphology: an interdisciplinary approach to river science. International Association of Hydrological Sciences, Publication **276** : 113–119p.

Thorn CE. 1976. A model of stony earth circle development, Schefferville, Quebec. 19–23 pp.

Thornes JB. 1985. The Ecology of Erosion. Geography **70** : 222–235.

Thornes JB. 1990. Vegetation and Erosion: Processes and Environments . Wiley

Tilman D. 1985. The resource-ratio hypothesis of plant succession. American Naturalist : 827–852.

Tilman D. 1988. Plant strategies and the dynamics and structure of plant communities . Princeton University Press.

Tobias MM. 2015. California foredune plant biogeomorphology. Physical Geography **36** : 19–33. DOI: 10.1080/02723646.2014.966224

Toy TJ, Foster GR, Renard KG. 2002. Soil Erosion: Processes, Prediction, Measurement, and Control . John Wiley & Sons

Tscherrig A. 1965. Karte der Gletscherstände des Turtmanngletschers 1850-1964 . Unveröffentlichte Karte der Forstbehörde Oberems, Wallis, Schweiz.

Turner MG, Chapin FS. 2005. Causes and Consequences of Spatial Heterogeneity in Ecosystem Function. In Ecosystem Function in Heterogeneous Landscapes , Lovett GM, Turner MG, Jones CG, and Weathers KC (eds). Springer New York; 9–30.

Turner MG, Dale VH, Gardner RH. 1989. Predicting across scales: theory development and testing. Landscape Ecology **3** : 245–252.

Turner MG, Gardner RH, O'Neill RV. 2001. Landscape ecology in theory and practice: pattern and process . Springer: New York

Urbanska KM. 1997. Restoration ecology research above the timberline: colonization of safety islands on a machine-graded alpine ski run. Biodiversity & Conservation **6** : 1655–1670. DOI: 10.1023/A:1018382923596

Van Everdingen RO. 2005. Multi-language glossary of permafrost and related ground-ice terms . International Permafrost Association: Calgary

Van Vliet-Lanoe B. 1993. Solifluction activity in the North Atlantic Arctic and Subarctic: the microstratigraphic record of changing climate during the second half of the Holocene. In Solifluction and Climatic Variation in the Holocene. , Frenzel B, Matthews JA, and Glaser (eds). Gustav Fischer Verlag: Stuttgart; 279–294.

Vanhala H, Lintinen P, Ojala A. 2009. Electrical resistivity study of permafrost on Ridnitšohkka fell in Northwest Lapland, Finland. Geophysica **45** : 103–118.

Veit H, Marti T, Winiger L. 2012. Environmental changes in Northern Iceland since the Younger Dryas inferred from periglacial slope deposits. The Holocene **22** : 325–335. DOI: 10.1177/0959683611423695

Verleysdonk S, Krautblatter M, Dikau R. 2011. Sensitivity and path dependence of mountain permafrost systems. Geografiska Annaler: Series A, Physical Geography : 113–135. DOI: DOI: 10.1111/j.1468-0459.2011.00423.x

Vetaas OR. 1997. Relationships between floristic gradients in a primary succession. Journal of Vegetation Science : 665–676.

Veylon G, Ghestem M, Stokes A, Bernard A. 2015. Quantification of mechanical and hydric components of soil reinforcement by plant roots. Canadian Geotechnical Journal **52** : 1839–1849. DOI: 10.1139/cgj-2014-0090

Viles H. 2016. Technology and geomorphology: Are improvements in data collection techniques transforming geomorphic science? Geomorphology **270** : 121–133. DOI: 10.1016/j.geomorph.2016.07.011

Viles HA. 1988. Biogeomorphology . Basil Blackwell: Oxford

Viles HA. 2004. Biogeomorphology. Goudie A (ed). Encyclopedia of Geomorphology **1** : 83-86.

Vinent OD, Moore LJ. 2015. Barrier island bistability induced by biophysical interactions. Nature Climate Change **5** : 158–162.

Violle C, Navas M-L, Vile D, Kazakou E, Fortunel C, Hummel I, Garnier E. 2007. Let the concept of trait be functional! Oikos **116** : 882–892. DOI: 10.1111/j.0030-1299.2007.15559.x

Virtanen R, Luoto M, Rämä T, Mikkola K, Hjort J, Grytnes J-A, Birks HJB. 2010. Recent vegetation changes at the high-latitude tree line ecotone are controlled by geomorphological disturbance, productivity and diversity. Global Ecology and Biogeography **19** : 810–821. DOI: 10.1111/j.1466-8238.2010.00570.x

Viviroli D et al. 2011. Climate change and mountain water resources: overview and recommendations for research, management and policy. Hydrol. Earth Syst. Sci. **15** : 471–504. DOI: 10.5194/hess-15-471-2011

Walker B, Hollin CS, Carpenter SR, Kinzig A. 2004. Resilience, adaptability and transformability in social-ecological systems. Ecology and Society **9** : 5.

Walker JP, Houser PR. 2002. Evaluation of the OhmMapper instrument for soil moisture measurement. Soil Science Society of America Journal **66** : 728–734.

Walker LR, del Moral R. 2003. Primary Succession and Ecosystem Rehabilitation . Cambridge University Press: Cambridge

Walsh SJ, Butler DR, Malanson GP, Crews-Meyer KA, Messina JP, Xiao N. 2003. Mapping, modeling, and visualization of the influences of geomorphic processes on the alpine treeline ecotone, Glacier National Park, MT, USA. Geomorphology **53** : 129–145. DOI: 10.1016/S0169-555X(02)00350-1

Wang C, Temmerman S. 2013. Does biogeomorphic feedback lead to abrupt shifts between alternative landscape states?: An empirical study on intertidal flats and marshes. Journal of Geophysical Research: Earth Surface **118** : 229–240. DOI: 10.1029/2012JF002474

Washburn AL. 1979. Geocryology : a survey of periglacial processes and environments / A. L. Washburn . E. Arnold: London

Watanabe T, Shiraiwa T, Ono Y. 1989. Distribution of periglacial landforms in the Langtang Valley, Nepal Himalaya. Bulletin of glacier research : 209–220.

Watt AS. 1947. Pattern and process in the plant community. The Journal of Ecology : 1–22.

Welch DM. 1970. Substitution of Space for Time in a Study of Slope Development. The Journal of Geology **78** : 234–239.

Welker JM, Molau U, Parsons AN, Robinson CH, Wookey PA. 1997. Responses of Dryas octopetala to ITEX environmental manipulations: a synthesis with circumpolar comparisons. Global Change Biology **3** : 61–73. DOI: 10.1111/j.1365-2486.1997.gcb143.x

Wheaton JM, Gibbins C, Wainwright J, Larsen L, McElroy B. 2011. Preface: Multiscale Feedbacks in Ecogeomorphology. Geomorphology **126** : 265–268. DOI: 10.1016/j.geomorph.2011.01.002

White PS. 1979. Pattern, process, and natural disturbance in vegetation. The Botanical Review **45** : 229–299. DOI: 10.1007/BF02860857

Whitesides C, Butler D. 2016. Bioturbation by gophers and marmots and its effects on conifer germination.

Earth Surface Processes and Landforms : **41**: 2269–2281. DOI: 10.1002/esp.4046

Whitesides CJ. 2015. The bioturbation of Olympic marmots (Marmota olympus) and their impacts on soil properties. Physical Geography **36** : 202–214. DOI: 10.1080/02723646.2015.1035625

Whittaker RH. 1974. Climax Concepts and Recognition. In Vegetation Dynamics , Knapp R (ed). Springer Netherlands; 137–154.

Whittaker RJ. 1987. An Application of Detrended Correspondence Analysis and Non-Metric Multidimensional Scaling to the Identification and Analysis of Environmental Factor Complexes and Vegetation Structures. Journal of Ecology **75** : 363–376. DOI: 10.2307/2260424

Widlok T, Aufgebauer A, Badtmöller M, Dikau R, Hoffmann T, Kretschmer I, Panagiotopoulos K, Pastoors A, Peters R, Schäbitz F, Schlummer M, Solich M, Wagner B, Weniger GC, Zimmermann A. 2012. Towards a theoretical framework for analyzing integrated socio-environmental systems. Quaternary International 274 : 259–272.

Williams PJ. 1957. Some Investigations into Solifluction Features in Norway. The Geographical Journal **123** : 42–55. DOI: 10.2307/1790722

Williams PJ, Smith MW. 1991. The Frozen Earth: Fundamentals of Geocryology . Cambridge University Press

Wilmanns O. 1993. Ökologische Pflanzensoziologie . Quelle & Meyer: Heidelberg

Wilson SD, Nilsson C. 2009. Arctic alpine vegetation change over 20 years. Global Change Biology **15** : 1676–1684. DOI: 10.1111/j.1365-2486.2009.01896.x

Wolman MG, Miller JP. 1960. Magnitude and frequency of forces in geomorphic processes. The Journal of Geology : 54–74.

Wookey PA, Robinson CH, Parsons AN, Welker JM, Press MC, Callaghan TV, Lee JA. 1995. Environmental constraints on the growth, photosynthesis and reproductive development of Dryas octopetala at a high Arctic polar semi-desert, Svalbard. Oecologia **102** : 478–489. DOI: 10.1007/BF00341360

Wooten RM, Witt AC, Miniat CF, Hales T, Aldred JL. 2016. Frequency and magnitude of selected historical landslide events in the Southern Appalachian Highlands of North Carolina and Virginia: relationships to rainfall, geological and ecohydrological controls and effects. In Natural Disturbances and Historic Range of Variation: Type, Frequency, Severity, and Post-disturbance Structure in Central Hardwood Forests USA , Greenburg CH and Collins BS (eds). Springe.

Wright JP, Gurney WS, Jones CG. 2004. Patch dynamics in a landscape modified by ecosystem engineers. Oikos **105** : 336–348.

Wu J. 1999. Hierarchy and scaling: extrapolating information along the scaling ladder. Canadian Journal of Remote Sensing **25** : 367–380.

Wu J, Levin SA. 1997. A patch-based spatial modeling approach: conceptual framework and simulation scheme. Ecological Modelling **101** : 325–346. DOI: 10.1016/S0304-3800(97)00056-2

Wu J, Loucks OL. 1995. From balance of nature to hierarchical patch dynamics: a paradigm shift in ecology. Quarterly review of biology : 439–466.

Zemp M, Haeberli W, Hoelzle M, Paul F. 2006. Alpine glaciers to disappear within decades? Geophysical Research Letters **33** : L13504. DOI: 10.1029/2006GL026319

Zeng Y, Malanson GP, Butler DR. 2007. Geomorphological limits to self-organization of alpine forest-tundra ecotone vegetation. Geomorphology **91** : 378–392. DOI: 10.1016/j.geomorph.2007.04.019

Zuber E. 1968. Pflanzensoziologische und ökologische Untersuchungen an Strukturrasen (besonders Girlandenrasen) im schweizerischen Nationalpark . Lüdin: Liestal.

Zumsteg A, Luster J, Goeransson H, Smittenberg RH, Brunner I, Bernasconi SM, Zeyer J, Frey B. 2012.

Bacterial, Archaeal and Fungal Succession in the Forefield of a Receding Glacier. Microbial Ecology **63** : 552–564. DOI: 10.1007/s00248-011-9991-8

APPENDIX

A1 Species list for lateral moraine slopes in Turtmann glacier foreland

Based on data from permanent plot survey (see Chapter 4), nomenclature according to Lauber and Wagner (2007).

Family	Species
Asteraceae	*Achillea erba-rotta* subsp. *moschata* (Wulfen) Vacc.
	Achillea nana L.
	Artemisia glacialis L.
	Artemisia umbelliformis Lam.
	Cirsium spinossium (L.) Scop.
	Crepis pygmaea L.
	Erigeron gaudinii Brügger
	Hieracium bifidum aggr.
	Hieracium piliferum aggr.
	Hieracium staticifolium All.
	Homogyne alpina L. (Cass.)
	Hypochaeris radicata L.
	Leontodon hispidus L. s.l.
	Leucanthemum adustum (W. D. J. Koch) Gremli
	Senecio doronicum (L.) L.
	Solidago virgaurea subsp. *minuta* (L.) Arcang.
	Tussilago farfara L.
Boraginaceae	*Myosotis alpestris* F. W. Schmidt
	Myosotis ramosissima Rochel
Brassicaceae	*Arabis alpina* L. s.l.
	Arabis serpyllifolia Vill.
Campanulaceae	*Campanula cochlearifolia* Lam.
	Campanula scheuchzeri Vill.
Caryophyllaceae	*Cerastium arvense* L. s.l.
	Cerastium pedunculatum Gaudin
	Herniaria alpina Chaix
	Minuartia laricifolia (L.) Schinz & Thell.
	Silene exscapa All.
Celastraceae	*Parnassia palustris* L.
Crassulaceae	*Sedum atratum* L.
	Sempervivum arachnoideum L.
	Sempervivum montanum L.
Cupressaceae	*Juniperus communis* L. s.l.

Cyperaceae	*Carex capillaris* L.
	Carex limosa L.
	Carex sempervirens Vill.
	Elyna myosuroides (Vill.) Fritsch
Dryopteridaceae	*Dryopteris filix-mas* (L.) Schott
	Polystichum lonchitis (L.) Roth
Ericaceae	*Arctostaphylos uva-ursi* (L.) Spreng.
	Calluna vulgaris (L.) Hull
	Pyrola minor L.
Fabaceae	*Anthyllis vulneraria* L. s.l.
	Lotus alpinus (D.C.) Ramond
	Trifolium badium Schreb.
	Trifolium pallescens (Schreb)
	Trifolium pratense subsp. *borderi* sensu K. Lauber & G. Wagner
Gentianaceae	*Gentiana tenella* Rottb.
Juncaceae	*Luzula sudetica* (Willd.) Schult.
Lamiaceae	*Thymus polytrichus* Borbás
Lentibulariaceae	*Pinguicula alpina* L.
Melanthiaceae	*Veratrum album* L. s.l.
Onagraceae	*Epilobium angustifolium* L.
	Epilobium fleischeri Hochst.
Ophioglossaceae	*Botrychium lunaria* (L.) Sw.
Orchidaceae	*Corallorhiza trifida* Châtel.
	Nigritella nigra aggr.
Orobanchaceae	*Bartsia alpina* L.
	Euphrasia minima Schleich
	Pedicularis verticillata L.
Pinaceae	*Larix decidua* Mill.
	Pinus cembra L.
Plantaginaceae	*Linaria alpina* (L.) Mill. s.str.
	Veronica alpina L.
	Veronica aphylla L.
	Veronica fruticans Jacq
Poaceae	*Agrostis stolonifera* L.
	Anthoxanthum odoratum L.
	Deschampsia cespitosa (L.) P. Beauv.
	Festuca alpina Suter
	Festuca ovina aggr.
	Festuca quadriflora Honck

	Festuca rubra L. s.l. *Festuca rupicaprina* (Hack.) A. Kern. *Festuca violacea* Gaudin *Poa alpina* L. *Poa glauca* Vahl *Sesleria caerulea* (L.) Ard. *Trisetum distichophyllum* (Vill.) P. Beauv.
Polygonaceae	*Oxyria digyna* (L.) Hill *Polygonum viviparum* L. *Rumex scutatus* L.
Primulaceae	*Androsace obtusifolia* All.
Rosaceae	*Alchemilla hybrida* L. *Alchemilla monticola* Opiz *Dryas octopetala* L. *Potentilla aurea* L.
Rubiaceae	*Galium anisophyllon* Vill.
Salicaceae	*Salix foetida* DC. *Salix hastata* L. *Salix helvetica* Vill. *Salix herbacea* L. *Salix purpurea* subsp. *gracilis* (Wimm.) Buser *Salix reticulata* L. *Salix retusa* L. *Salix serpyllifolia* Scop.
Santalaceae	*Thesium alpinum* L.
Saxifragaceae	*Saxifraga aizoides* L. *Saxifraga oppositifolia* L. s.str. *Saxifraga paniculata* Mill.
Tofieldiaceae	*Tofieldia calyculata* (L.) Wahlenb.
Violaceae	*Viola lutea* Huds.
Woodsiaceae	*Cystopteris alpina* (Lam.) Desv. *Cystopteris fragilis* (L.) Bernh.

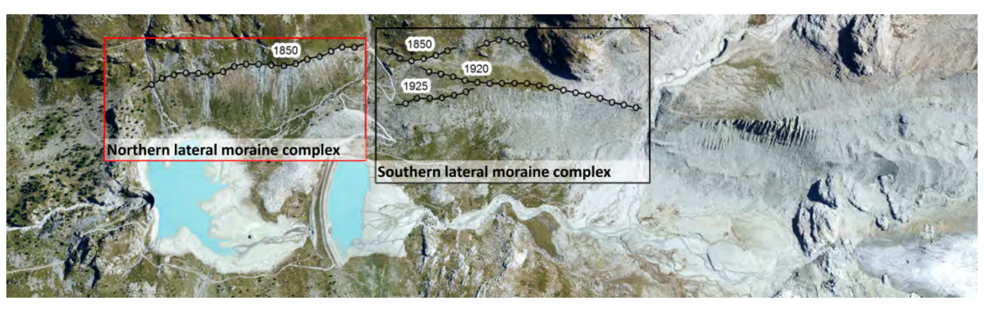
A2 Geomorphic, material and glacier history and vegetation maps of northern lateral moraine complex, Turtmann glacier foreland, Switzerland.

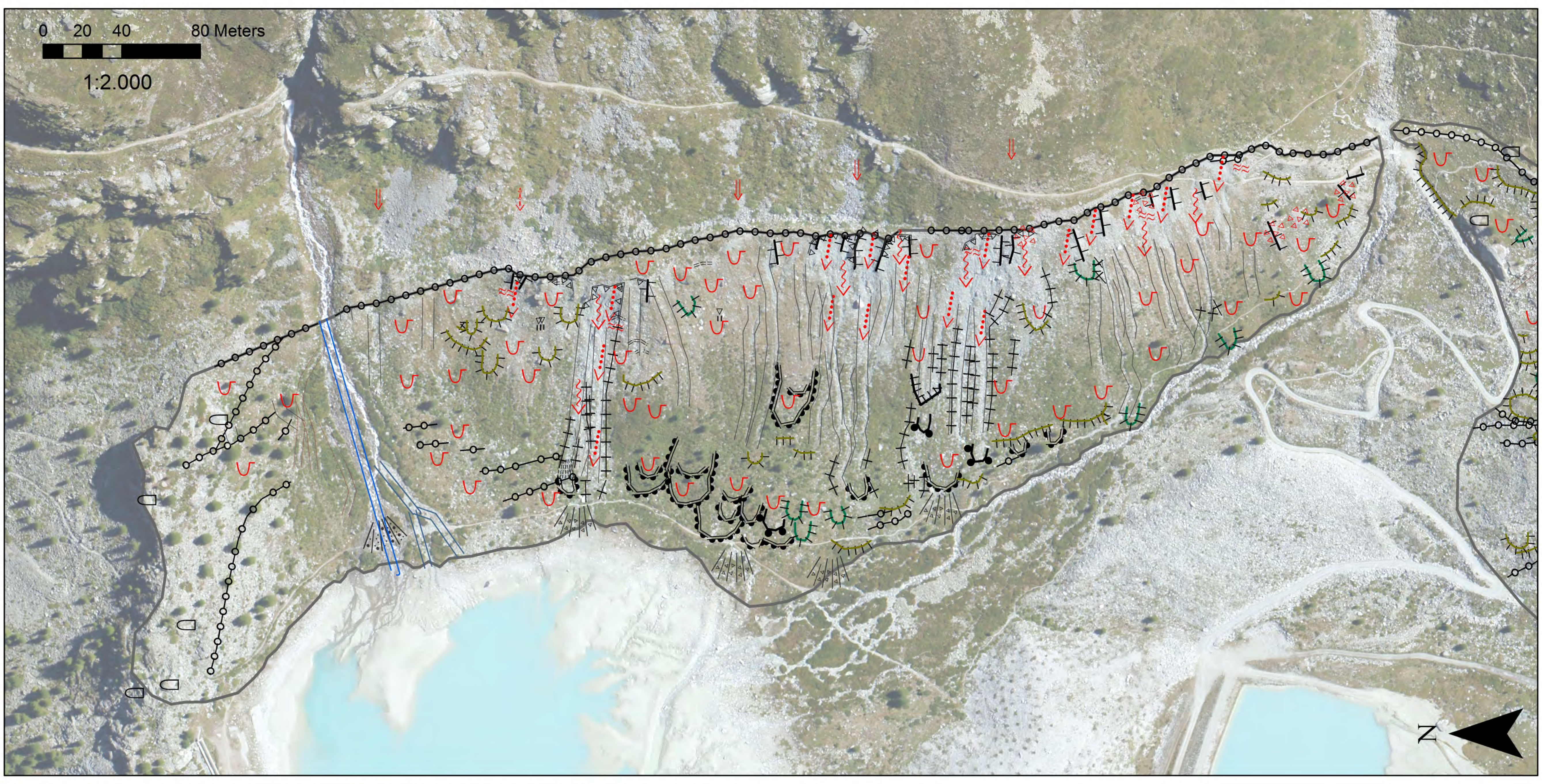
Attached to the inner back cover of this thesis.

A3 Geomorphic, material and glacier history and vegetation maps of southern lateral moraine complex, Turtmann glacier foreland, Switzerland.

Attached to the inner back cover of this thesis

(A) Geomorphic, (B) material and glacier history and (C) vegetation maps of northern lateral moraine complex, Turtmann glacier foreland, Switzerland





A Geomorphic map of northern lateral moraine complex

Mass movement process domain

- Debris flow
- Landsliding
- Debris flow levée
- Debris flow fine material deposit
- Debris flow head
- Debris flow head with solifluction
- Tension crack

Water soil erosional process domain

- Water soil erosional processes

Periglacial process domain

- Unbound solifluction
- Bound solifluction
- Cryoturbation
- Turf-banked terrace
- Turf-banked lobe riser
- Ploughing boulder

Glacial process domain

- Moraine ridge
- Whaleback

External processes

- Rockfall
- Snow avalanche

Complex process domain

- Complex initiation area
- Inter-gully wall
- Complex channel
- Complex step
- Complex cone

Fluvial process domain

- Intermittent fluvial channel
- Inactive fluvial channel
- Active fluvial channel
- Erosional step
- Fluvial fan

B Material and glacier history map of northern lateral moraine complex

Fine material (< 63 mm) dominated

- F1 Fine material with stones
- F2 Fine material with stones and blocks

Stone (> 63 mm - 200 mm) dominated

- S1 Stones with fine material
- S2 Stones with blocks
- S3 Stones with fines and blocks

Block (> 200 mm) dominated

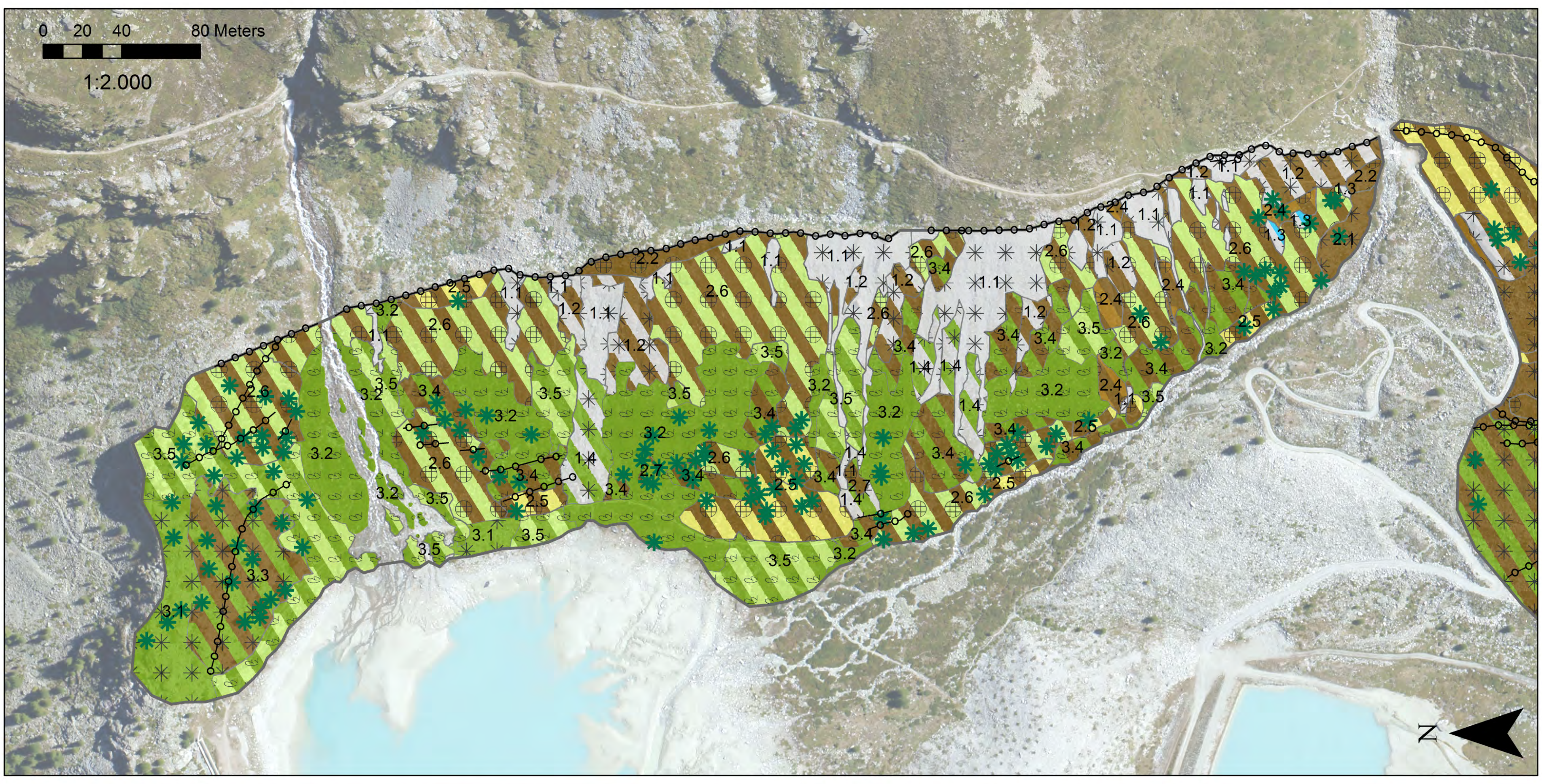
- B1 Blocks with stones
- B2 Blocks with fines and stones

Bedrock

- Br Bedrock

Glacier history

- Glacier position with year



C Vegetation map of northern lateral moraine complex

Vegetation class 1: Linaria alpina

- 1.1 with Saxifraga aizoides
- 1.2 with Dryas octopetala, Salix dwarf shrubs
- 1.3 with Hernaria alpina and Silene exscapa
- 1.4 with Salix shrubs

Vegetation class 2: Dryas octopetala

- 2.1 with Bartsia alpina (cover ≤ 50%)
- 2.2 with Bartsia alpina (cover > 50%)
- 2.3 with Salix dwarf shrubs (cover ≤ 50%)
- 2.4 with Salix dwarf shrubs (cover > 50%)
- 2.5 with Elyna myosuroides
- 2.6 with Festuca spp.
- 2.7 with Salix shrubs

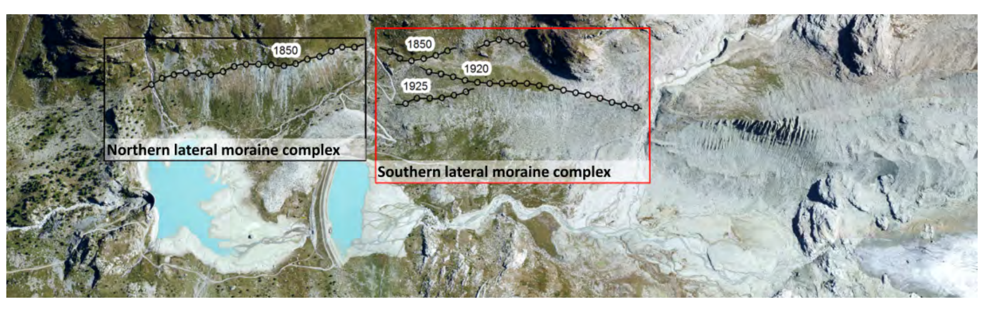
Vegetation class 3: Salix hastata

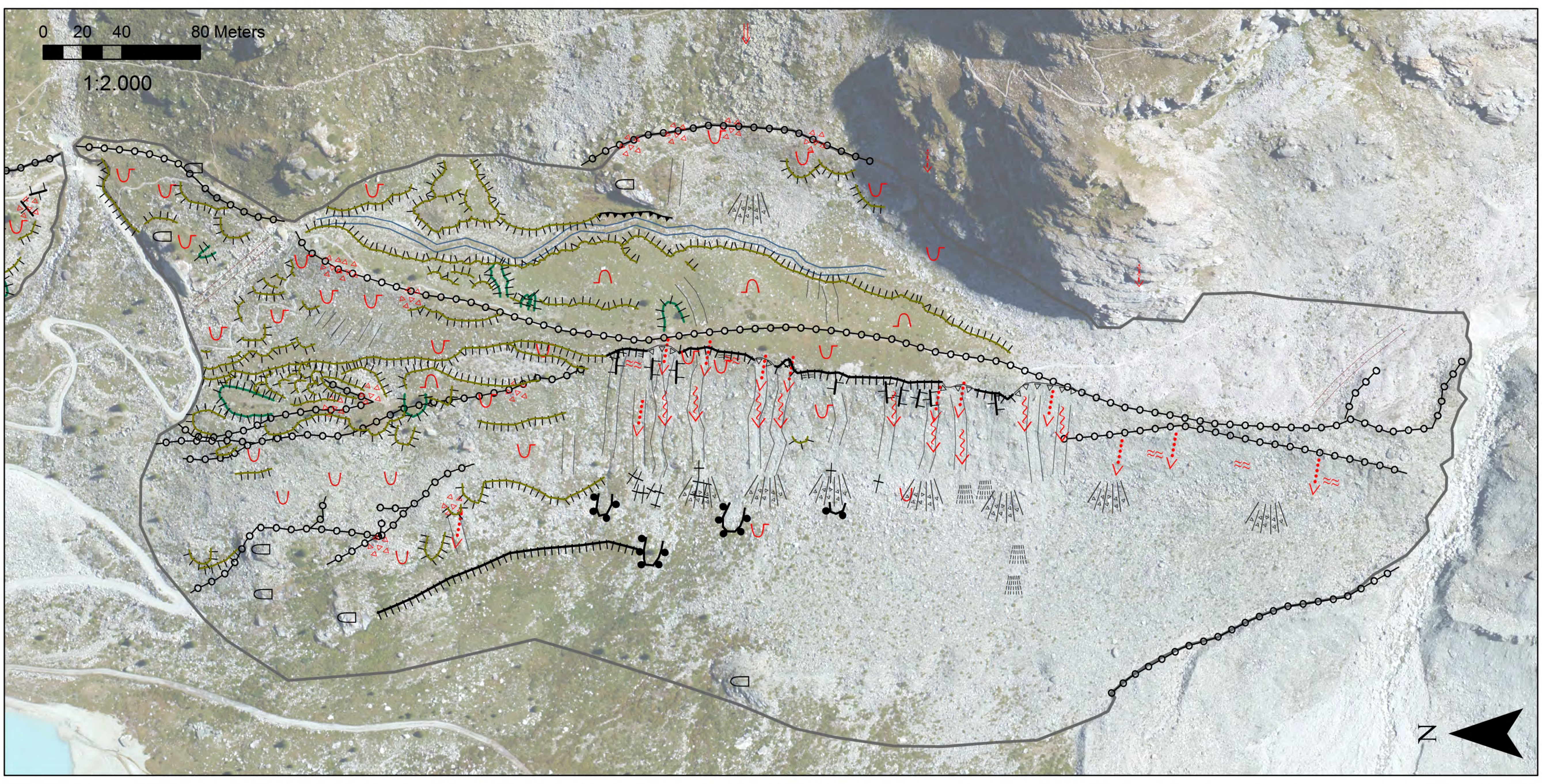
- 3.1 with Salix shrubs (cover ≤ 50%)
- 3.2 with Salix shrubs (cover > 50%)
- 3.3 with Dryas octopetela and Salix dwarf shrubs (cover ≤ 50%)
- 3.4 with Dryas octopetela and Salix dwarf shrubs (cover > 50%)
- 3.5 with Festuca spp.

Individual trees (Larix decidua, Pinus cembra)

- ✱ Tree

(A) Geomorphic, (B) material and glacier history and (C) vegetation maps of southern lateral moraine complex, Turtmann glacier foreland, Switzerland





A Geomorphic map of southern lateral moraine complex

Mass movement process domain

- Debris flow
- Landsliding
- Debris flow levée
- Debris flow fine material deposit
- Debris flow head
- Debris flow head with solifluction
- Tension crack

Water soil erosional process domain

- Water soil erosional processes

Periglacial process domain

- Unbound solifluction
- Bound solifluction
- Cryoturbation
- Turf-banked terrace
- Turf-banked lobe riser
- Ploughing boulder

Glacial process domain

- Moraine ridge
- Whaleback

External processes

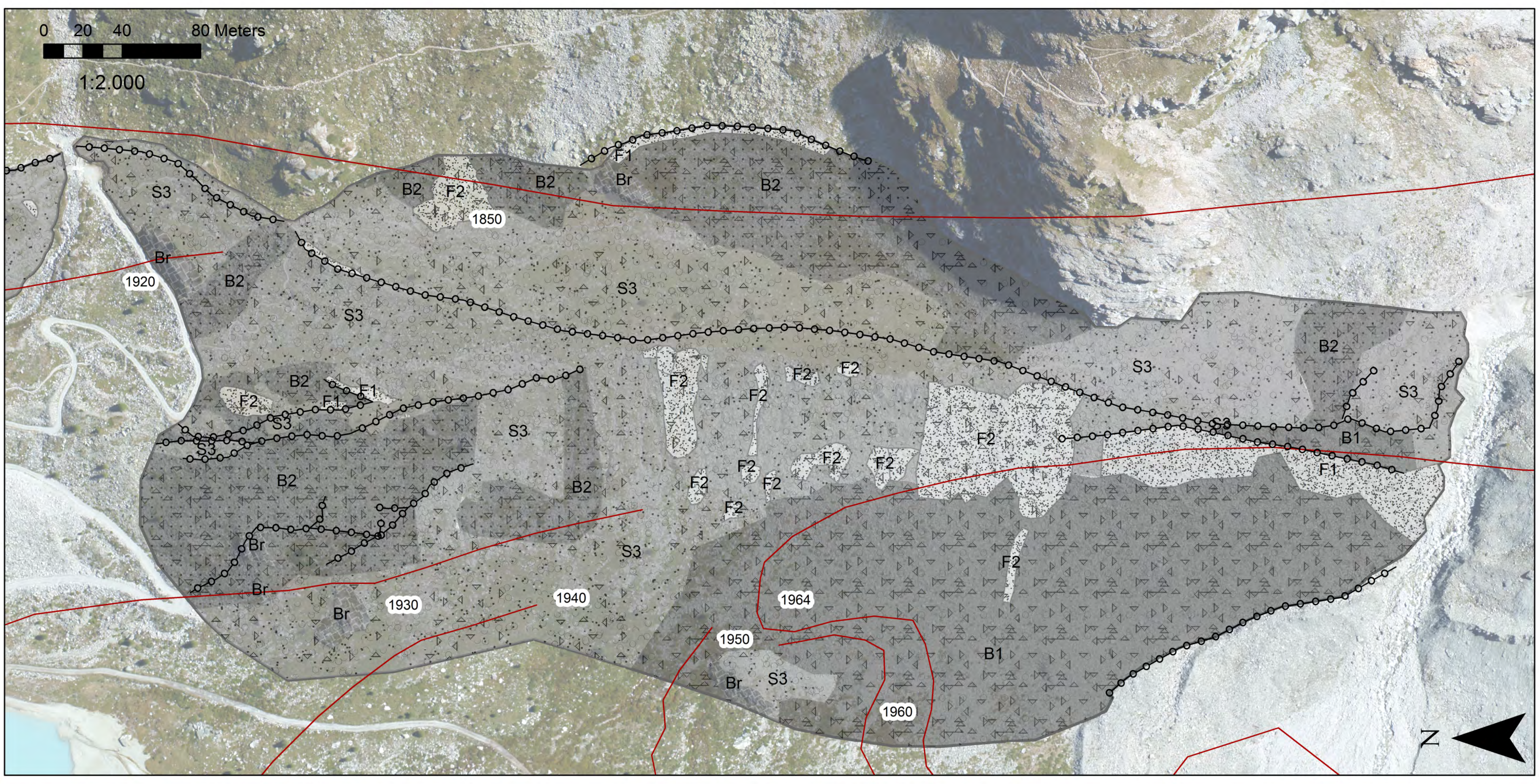
- Rockfall
- Snow avalanche

Complex process domain

- Complex initiation area
- Inter-gully wall
- Complex channel
- Complex step
- Complex cone

Fluvial process domain

- Intermittent fluvial channel
- Inactive fluvial channel
- Active fluvial channel
- Erosional step
- Fluvial fan



B Material and glacier history map of southern lateral moraine complex

Fine material (< 63 mm) dominated

- F1 Fine material with stones
- F2 Fine material with stones and blocks

Stone (> 63 mm - 200 mm) dominated

- S1 Stones with fine material
- S2 Stones with blocks
- S3 Stones with fines and blocks

Block (> 200 mm) dominated

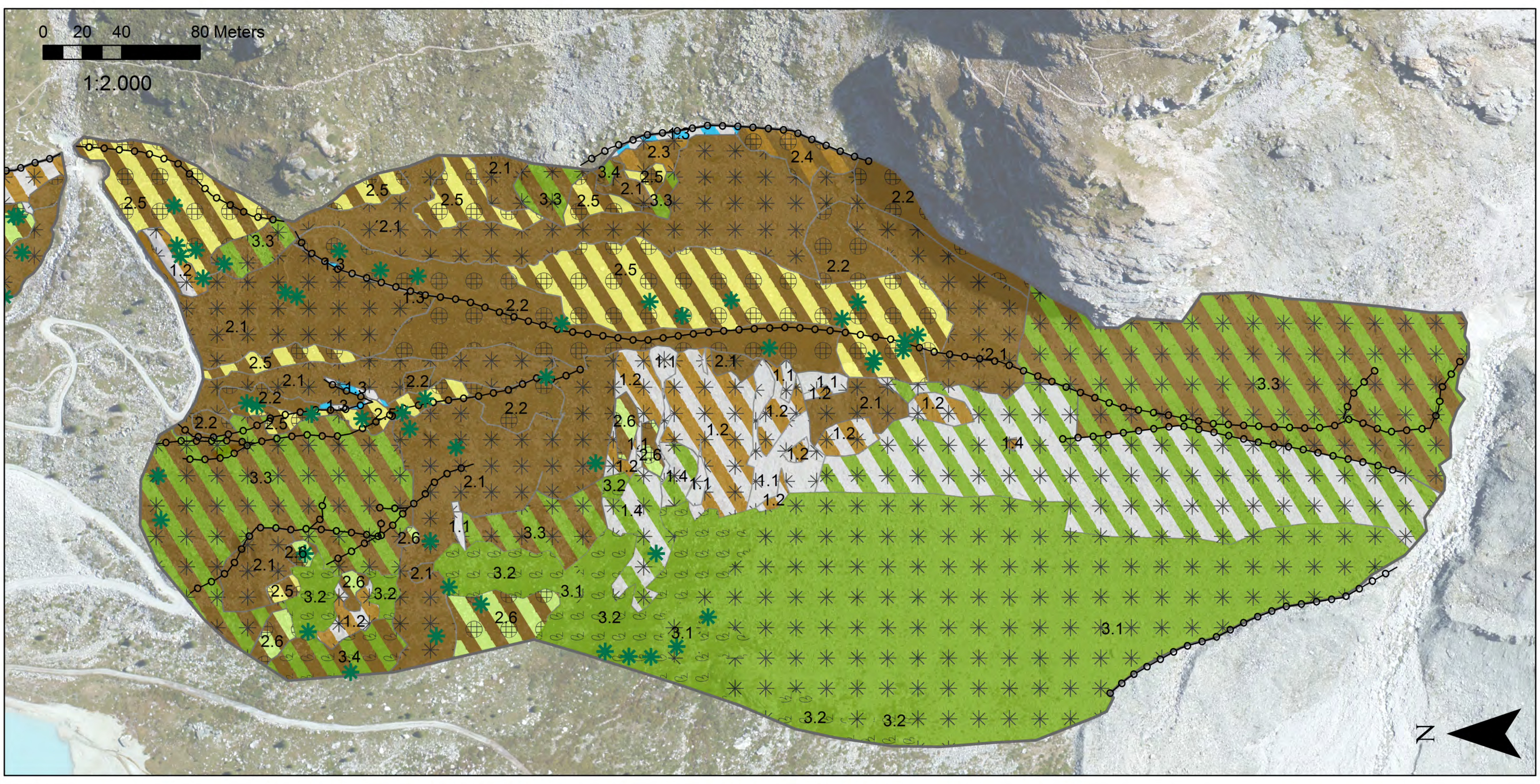
- B1 Blocks with stones
- B2 Blocks with fines and stones

Bedrock

- Br Bedrock

Glacier history

- Glacier position with year



C Vegetation map of southern lateral moraine complex

Vegetation class 1: Linaria alpina

- 1.1 with Saxifraga aizoides
- 1.2 with Dryas octopetala, Salix dwarf shrubs
- 1.3 with Hernaria alpina and Silene exscapa
- 1.4 with Salix shrubs

Vegetation class 2: Dryas octopetala

- 2.1 with Bartsia alpina (cover ≤ 50%)
- 2.2 with Bartsia alpina (cover > 50%)
- 2.3 with Salix dwarf shrubs (cover ≤ 50%)
- 2.4 with Salix dwarf shrubs (cover > 50%)
- 2.5 with Elyna myosuroides
- 2.6 with Festuca spp.
- 2.7 with Salix shrubs

Vegetation class 3: Salix hastata

- 3.1 with Salix shrubs (cover ≤ 50%)
- 3.2 with Salix shrubs (cover > 50%)
- 3.3 with Dryas octopetela and Salix dwarf shrubs (cover ≤ 50%)
- 3.4 with Dryas octopetela and Salix dwarf shrubs (cover > 50%)
- 3.5 with Festuca spp.

Individual trees (Larix decidua, Pinus cembra)

- Tree

‘Organisms and their interactions can shape and are shaped by geomorphic processes and landforms’ Stallins (2006)