Investigating an Alpine proglacial sediment budget using field measurements, airborne and terrestrial LiDAR data

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Abstract The ongoing recession of Alpine glaciers since the end of the Little Ice Age (LIA) has exposed stores of glacial sediment to the activity of paraglacial processes. Slope wash, fluvial processes and mass movements (including debris flows, slides and falls) within the proglacial area (i.e. the area within the LIA terminal moraines) have received comparatively little attention in previous studies of the (pro)glacial sediment budget that have focused mainly on suspended and bedload sediment transport in proglacial streams. Additionally, there is a need for research concerning the relative importance of non-glacial and glacial contributions to the sediment budget and the downstream consequences of increased proglacial geomorphic activity. The PROSA joint project (High-resolution measurements of morphodynamics in rapidly changing **PRO**glacial **S**ystems of the **A**lps) is designed to tackle these problems through a quantification of the aforementioned hillslope and channel processes within the forefield of the Gepatsch Glacier (Central Alps, Austria) using high-resolution LiDAR data. On the local scale, field measurements and digital elevation models from multi-epoch terrestrial LiDAR data will be combined to map and quantify sediment (re-)mobilisation, erosion and deposition. The catchment-scale sediment budget will be established by multi-epoch high-resolution airborne LiDAR data, upscaling of local findings using geomorphological models including the appraisal of slope–channel coupling, and an assessment of fluvial sediment export beyond the outlet of the catchment (which consists of a reservoir). This paper summarises the processes effective in proglacial systems, works out research needs with respect to sediment budgets in changing proglacial areas, and outlines the research framework of the PROSA joint project. It complements two papers on preliminary results published in this volume.

Key words proglacial sediment budget; airborne LiDAR; terrestrial LiDAR; Central Alps; Tyrol

INTRODUCTION: PROGLACIAL MORPHODYNAMICS AND SEDIMENT BUDGETS

Since the end of the Little Ice Age (LIA), alpine glaciers have been receding. At many locations, the rising of the equilibrium line (on average by 54 m between 1920 and 1950 for 17 European glaciers, see Klok & Oerlemans, 2003) has led to glaciers being tens of metres thinner, and up to several kilometres shorter today than they were during the 1850s to 1870s. Abermann *et al.* (2009) give an overview of glacier area and volume changes between 1969 and 2006 for the Austrian Ötztal Alps. Glacier recession and its causes have led, and will continue to lead, to changes in permafrost distribution (e.g. Kneisel & Kääb, 2007), river runoff (e.g. Moore *et al.*, 2009b), soil development (e.g. Egli *et al.*, 2006), vegetation (e.g. Moreau *et al.*, 2008) and the activity of geomorphic processes. Generally, all of these components are interacting.

Non-glacial geomorphic processes directly conditioned by former glaciation have been referred to as paraglacial processes (Church & Ryder, 1972; Ballantyne, 2002b), and different conceptual models of the development of process activity have been developed (Church & Slaymaker, 1989; Ballantyne, 2002a). The formation of paraglacial sediment storage landforms from the erosion or (re-)mobilisation of glacigenic sediments such as moraines, and the successive reworking of the former, are being witnessed at great intensity in the forefields of alpine glaciers. The area that has become ice-free since the end of the LIA, which we refer to as the proglacial area, is characterised by particularly high morphodynamics. The geomorphic processes involved include small and large mass movements, debris flows, the dissection of drift-mantled slopes and moraines by slope wash and linear erosion, and fluvial processes within the proglacial channel network. Knight & Harrison (2009) argue that these paraglacial processes reworking stores of unconsolidated sediment will, under conditions of present and future climate change, be ranked among the most relevant processes of sediment and landscape dynamics in low- and mid-latitudes.

While single processes have been the subject of several case studies (see following sections), field studies of proglacial areas including multiple processes, their rates and interactions are rare (Warburton, 1990; O'Farrell *et al.*, 2009; Beylich *et al.*, 2009). Compared to research on the reaction of mountain permafrost to increased mean temperatures (e.g. Haeberli *et al.*, 2010), surface processes in proglacial areas, which are not necessarily periglacial (i.e. not frost- or permafrost-related; see Slaymaker, 2011), have received comparatively little attention, despite the consequences potentially arising from increased rates of these processes that may persist long after permafrost has disappeared.

The aim of this paper is twofold. First, we give an overview of the processes taking place in proglacial systems and set forth research needs in this field, though a comprehensive review for all aspects of the issue is out of scope for this contribution. Second, we propose a methodological framework designed to tackle some of the outlined problems, which forms the basis for an interdisciplinary research project.

Geomorphic processes in proglacial areas

Mass movements Deglaciation can be followed by enhanced activity of mass movements delivering either fresh debris from steep rock slopes or debris from moraines or debris-mantled slopes to the proglacial area. These processes act on different spatial and temporal scales. Glacial debuttressing, a consequence of shrinking glaciers, can cause or enhance both local, rapid mass movements (e.g. Cossart *et al.*, 2008) ranging from rockfall to rock avalanches (1–>10^6 m^3, e.g. Matthews & Shakesby, 2004), and deep-seated, slower slope deformations (e.g. sagging, Kellerer-Pirklbauer *et al.*, 2010). Landslides of varying depth and creeping movements occur on moraines (e.g. Hugenholtz *et al.*, 2008) and debris-covered slopes (e.g. Holm *et al.*, 2004). Perhaps the largest body of research is about rock glaciers (see Haeberli *et al.*, 2010 and references therein), and periglacial landforms that are sometimes part of proglacial areas.

Debris flows Steep deposits of sediments, e.g. scree-covered slopes or rockfall talus, are often prone to debris-flow initiation. Barlow *et al.* (2009) show in their study area a dependence of "debris slide" occurrence on sediment storage landforms. They conclude that the activity of this process is transport-limited and the result of paraglacial relaxation. In their study of paraglacial reworking of steep moraines, Curry *et al.* (2006) name debris flows as the dominating agent of sediment transfer. Palacios *et al.* (1999) report a linkage of debris flow initiation on terminal moraines with glacier retreat, and Chiarle *et al.* (2007) identify three mechanisms of debris-flow initiation in a proglacial context: intense and prolonged rainstorms, short rainstorms, and triggering by meltwater (either lake outburst or melt-out of buried ice).

Full-depth snow avalanches This type of avalanche occurs mostly in spring when the snow cover is isothermal, homogenised and frequently wet, and can cause significant erosion and debris transport on steep debris- or soil-covered slopes (e.g. Heckmann *et al.*, 2002; Freppaz *et al.*, 2010). Although no study deals with this process particularly in a proglacial context, we assume that these avalanches can both initiate within the proglacial area (where sediment is redistributed), and reach the proglacial area from tributary slopes (constituting a sediment input to the system).

Slope wash and linear erosion on hillslopes Lateral and terminal moraines, as well as steep, drift-mantled hillslopes, are subject to intense gullying after deglaciation. Curry *et al.* (2006) infer from geomorphological mapping and tachymetric surveys of a chronosequence of deglaciated moraine slopes in the Swiss Central Alps, that incision reaches the greatest extent *c.* 50 years after deglaciation. Average erosion rates are reported to range in the order of 10^1 to 10^2 mm per year, which exceeds the rates normally seen in regions without paraglacial influence. Schiefer & Gilbert (2007) also report an increase in process rates shortly after deglaciation due to sediment availability and lack of vegetation cover.

Fluvial processes These processes play a major role in reworking and redistributing the deposits of the other processes (Ballantyne, 2002b). The high variability of meltwater discharge (both on a diurnal and an annual scale) and precipitation (Hicks *et al.*, 1990) are important drivers of proglacial fluvial dynamics, including sediment transport and changes in channel morphology (usually braided river). Changes such as the migration of bars and channels, or the formation and destruction of terraces have been detected on a wide range of temporal scales, from decades (Luchi *et al.*, 2007) to weeks (Warburton, 1994) and even days (Milan *et al.*, 2007).

Proglacial sediment budgets

Establishing a sediment budget requires the quantification of erosion and sediment transport rates of geomorphic processes, the delineation of the spatial distribution of sediment pathways, and the assessment of changes in sediment storage (cf. Slaymaker, 1991). The majority of previous studies has focused on the sediment yield of (pro-)glacial systems, either by measuring fluvial sediment flux in proglacial streams or by quantifying the amount of sediment deposited (over a given time) in sediment sinks such as proglacial lakes (e.g. Loso *et al.*, 2004). The results of these studies constitute exclusively the "output" component of a sediment budget, a differentiation with respect to sediment sources (rockwall, moraine deposits, other sediments) and geomorphic processes is not possible and changes in sediment storage cannot be accounted for. However, the contribution of different processes, especially the relative contributions of glacial and non-glacial processes, represents an important research problem calling for a sediment budget approach (Harbor & Warburton, 1993; Hallet *et al.*, 1996, and references therein). Warburton (1990) includes in his sediment budget of a proglacial valley sandur the contribution of other processes, namely fluvial sediment transport in tributary channels, soil movement on hillslopes adjacent to these channels, and the erosion of the valley sandur bluffs (e.g. by undercutting). As the time of observation was limited to one ablation season (*c.* two months), episodic mass movements were not accounted for. Beylich *et al.* (2009) calculate a subrecent (after the LIA) sediment budget for a proglacial braidplain. The study conducted by O'Farrell *et al.* (2009) reports erosion rates of periglacial processes that deliver sediments to the proglacial zone of a glacier in Alaska, inferred from storage volume and ^{10}Be datings. A comparison with an eight-year record of sediment yield measured at the glacier terminus shows that non-glacial processes contribute 80 ± 45% of the sediment exported from the proglacial area.

In some parts of proglacial areas, a variety of geomorphic processes form well-connected sediment cascades along which sediments are effectively routed from sediment sources (rockwalls, debris, moraines), via the glacier and/or the proglacial channel network, to the catchment outlet. In contrast, lateral moraines and fluvial terraces may act as buffers disconnecting the channel network from adjacent slopes, and sediments are stored in debris cones and other depositional landforms (Owen & Sharma, 1998; Müller, 1999). The spatial and functional configuration of landforms and processes governs lateral (slope–channel) and longitudinal (within channel) connectivity (e.g. Brierley *et al.*, 2006), which is an important factor of a sediment budget. Beylich *et al.* (2009), for example, report that hillslope–channel coupling was very limited in their study area.

Research needs

We argue that a sediment budget approach, accounting as much as possible for all contributing processes and sediment pathways, forms an important basis for understanding, modelling and predicting the reaction of proglacial systems to ongoing glacier retreat. The importance of sediment budget studies in changing cold environments, and respective research frameworks are set forth by Beylich *et al.* (2011).

For the proglacial zone of Alpine glaciers, we identify the following major research needs:

1. the investigation of the present-day sediment budget of the proglacial area, including both glacial (i.e. the quantification of sediment release from the glacier itself) and non-glacial processes, and the assessment of their relative importance;
2. the investigation of interactions between multiple processes and process–form feedbacks within the proglacial area, e.g. the formation of secondary storage landforms at the foot of intensely gullied lateral moraines and their re-working by fluvial undercutting;
3. the temporal scale of paraglacial morphodynamics, i.e. the progression of increasing and decreasing rates of geomorphic processes with time since deglaciation. What role does the exhaustion of paraglacial sediment stores or a self-stabilisation of slopes through adjustment play for the attenuation of process rates? How important is the development of stabilising factors such as vegetation cover?
4. the investigation of the sensitivity (c.f. Brunsden, 2001) of proglacial systems, i.e. of how sediments and geomorphic change are propagated through the proglacial area. Will enhanced sediment release following present and projected glacier retreat affect downstream sections of the proglacial rivers, or is the proglacial subsystem sufficiently buffered? If not, it will have implications for applied geomorphology, such as changes in natural hazards or the accelerating infilling of reservoirs due to increasing bedload discharge.

THE PROSA JOINT PROJECT

Research agenda

The PROSA joint project (High-resolution measurements of morphodynamics in rapidly changing PROglacial Systems of the Alps) comprises five working groups from different disciplines, including geomorphology, applied geology, geophysics, glaciology and geodesy. This composition is necessary for the following reasons:

1. the proglacial system is driven by glacial and glaciofluvial dynamics (glaciology);
2. information on subsurface processes (structure and cubature of sediment storage, distribution of ground ice, subglacial sediment dynamics) is needed (geophysics);
3. different geomorphic processes operate and interact, affecting both bedrock and sediments (geomorphology, geology);
4. although the system is regarded as highly dynamic, the short time scale of a publicly funded research project, and the low rate of surface change induced by the majority of geomorphic processes on a monthly scale require the reliable detection of subtle surface changes. Hence, there is a need for high-resolution, highly accurate and precise surveying techniques, and for a rigorous error assessment in order to distinguish significant changes from noise (geodesy).

Following recent clarifications (e.g. Slaymaker, 2011) in the ongoing confusion around the terms “paraglacial” *vs* “proglacial” *vs* “periglacial”, we use the term paraglacial for non-glacial geomorphic processes and landforms that represent the system’s transient response to deglaciation, and the term proglacial to define the spatial scale. More specifically, we focus on paraglacial processes in response to recent deglaciation (i.e. since the end of LIA, “neo-paraglacial” *sensu* Matthews & Shakesby, 2004) that occur in the proglacial area. Within this comparatively small area, we expect to observe the onset, maximum intensity and the attenuation of process rates; on a broader spatial scale, however, many landscapes are still in the process of adjustment to deglaciation after the last glaciation (Church & Slaymaker, 1989; Ballantyne, 2002b). Hence, the research project outlined here is focused on (though not fully restricted to) the area that was glaciated around the year 1850 and that is defined by distinct terminolateral moraines.

Study area

The Kaunertal Valley is located in the Austrian Central Alps, and is a tributary of the Upper Inn River system. We have selected the upper reaches of the valley (Fig. 1) which is drained by the

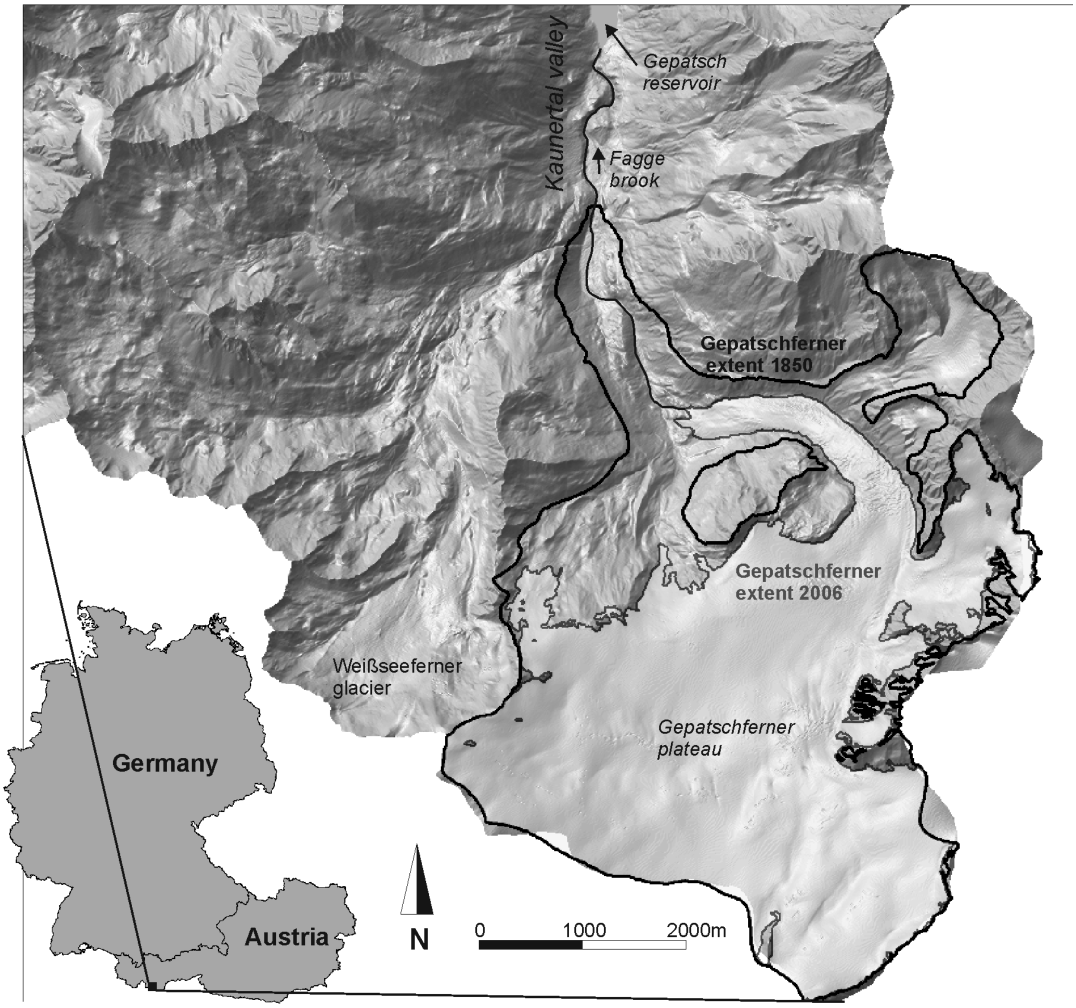

Fig. 1 Map of the study area. The PROSA project is conducted within the proglacial area inside the LIA moraines of the Gepatschferner and Weißseeferner glaciers. For the Gepatschferner Glacier, the map shows the extent around the LIA maximum and the present (2006) extent. Background: shaded relief from 10 m DEM (data source: www.tirol.gv.at).

Fagge Brook. At the mouth of the Fagge Brook, at the Gepatsch Reservoir, the catchment size is 62.5 km^2. More than 35% of the catchment is glaciated by the Weißseeferner and Gepatschferner (the latter emanates from a larger plateau). Figure 1 shows that the Gepatschferner has receded by almost 2 km since the LIA maximum. The Gepatsch Reservoir with a combined dam and power plant is located less than 2 km downstream of the LIA moraines of the Gepatsch Glacier.

The study area is underlain by crystalline rocks (siliceous para- and orthogneiss) and has a relief of 1780 m (1759–3539 m). It is characterised by relatively low annual precipitation of about 800 mm $year^{-1}$ measured at the Gepatsch Reservoir dam for the period 1988–2011 (data courtesy of TIWAG, Innsbruck) and only has a sparse vegetation cover (forest below about 2150 m). The discharge of the Fagge shows a clear diurnal and seasonal periodicity, typical of a glacial regime, with monthly means (period 1977–2011, calculated from TIWAG data) of between 0.2 $m^3 s^{-1}$ (February) and 9.5 $m^3 s^{-1}$ (July). Yearly maxima range (for the same period) from 13.6 to 59.2 $m^3 s^{-1}$. In August 2011, the second highest discharge (57.7 $m^3 s^{-1}$) was measured at the gauge. This flood undercut several sediment storage landforms, which could be well documented and quantified by pre- and post-event LiDAR surveys (see Haas *et al.*, 2012, and Morche *et al.*, 2012, this issue).

Methodological framework

In the following sections, we outline the approaches towards: (a) measuring process rates on the local scale, and (b) establishing the sediment budget for the whole proglacial area.

Terrestrial and airborne LiDAR A methodological backbone of the joint project is formed by terrestrial (on the local scale) and helicopter-based (on the catchment scale) laser scanning (LiDAR). This comparatively new technology has been employed in many geomorphological studies with very different foci. DEMs from LiDAR surveys will be used for scour-and-fill analysis (by subtracting two epochs) and for multi-scale morphometric analyses (micro-scale: roughness, macro-scale: estimation of volumes, etc.). In a high-mountain context, LiDAR has been used for monitoring rockfall (Fischer *et al.*, 2011), debris flows (Scheidl *et al.*, 2008), fluvial erosion (Haas *et al.*, 2011a), rock glaciers (Avian *et al.*, 2009), and glaciers (Abermann *et al.*, 2009). There is one study on surface changes in a high Arctic proglacial area (Irvine-Fynn *et al.*, 2011).

For the purposes of catchment-scale measurements (e.g. detection and quantification of debris flows) and regionalisation of local findings, airborne LiDAR DEMs should be acquired twice a year, namely after snowmelt, and at the end of the summer but before the establishment of a snow cover. This will enable the distinction of summer- and winter-term surface changes, which is desirable because of the fundamentally different process regimes during these two seasons. Furthermore, detecting small-scale surface changes requires a refining of airborne LiDAR DEMs and their coregistration (among each other and with terrestrial LiDAR data).

Test areas on the local scale, e.g. rockwall-talus systems or dissected lateral moraines, will be monitored by repeated terrestrial LiDAR surveys. Recently, Bremer & Sass (2012) and Heckmann *et al.* (2012) have advocated the combination of airborne and terrestrial LiDAR for geomorphological research, because DEMs from airborne LiDAR surveys are available throughout the Alps, and post-event terrestrial LiDAR surveys are comparatively flexible and cost-effective. Such a combination, however, poses a major challenge to the assessment of detection levels and errors necessary for every scour-and-fill analysis (see e.g. Wheaton *et al.,* 2010). When monitoring surface changes in areas with synchronous input and output of sediments, the influence of survey frequency on the net results has to be kept in mind (Lindsay & Ashmore, 2002).

Mass movements The study area features different types of mass movements that will be dealt with separately. Rockfall will be measured on test sites using two approaches: Nets will be laid out at the foot of rockwalls in order to collect rockfall particles (e.g. Krautblatter & Moser, 2009), and the corresponding rockwall and talus sections will be repeatedly surveyed using terrestrial LiDAR (e.g. Haas *et al.*, 2009, Abellán *et al.*, 2010). Larger events are detectable with repeated airborne LiDAR (Fischer *et al.*, 2011). Both terrestrial and airborne LiDAR data will be used to characterise rockmass structure and fracture network (e.g. Sturzenegger *et al.*, 2007). The spatial variability of rockfall activity will be accounted for by investigating the relationship of measured rockfall activity with rockmass properties (e.g. Moore *et al.*, 2009a), elevation, and position relative to the glacier (past and present). Such a relationship could be used for estimating spatially-distributed rockfall rates within the study area. These rates will be coupled to a simulation model (cf. Wichmann *et al.*, 2009) to delineate source areas of rockfall, potential trajectories and deposition areas. A graph-theoretical approach (Heckmann & Schwanghart, 2011) has been proposed in order to analyse the proportion of trajectories reaching the proglacial zone directly, or via linkages (glacier, other processes delivering sediments from rockfall deposits to the proglacial zone).

There is an inventory of deep-seated landslides, which will be investigated using geotechnical (e.g. extensometer and convergence measurements) and geophysical methods. Shallow landslides will be detected using repeated airborne LiDAR surveys on the catchment scale. Field mapping and sampling (Heckmann *et al.*, 2002) will lead to an estimation of the contribution of full-depth snow avalanches.

Slope wash, linear erosion and debris flows Within the study area, these processes take place primarily on the steep lateral moraines where they cause intense gullying and the formation of secondary paraglacial deposits (storage landforms such as debris cones, e.g. at the interface of moraines and the main channel). The rates of surface change associated with these processes will be measured on test areas by repeated terrestrial LiDAR (see Haas *et al.,* 2012, this issue), and by morphometric approaches in order to estimate erosion or deposition rates on a longer timescale (e.g. Perroy *et al.*, 2010). The measurements will show if the rate of slope wash and linear erosion can be extrapolated to all areas of this type using the approach of "sediment contributing area" which is derived from the DEM using a set of thresholds and has been shown to correlate with average (coarse) sediment yield (Haas *et al*., 2011b). Debris flows, which cause substantial surface changes, will be detected by repeated terrestrial (local scale) and airborne LiDAR surveys (catchment scale) (Scheidl *et al.*, 2008, Haas *et al*., 2012, this issue). As debris flows in paraglacial land-systems can be regarded as transport-limited (Barlow *et al.*, 2009), their return period can be estimated by the return period of trigger events (e.g. rainfall intensity thresholds from observations and/or literature). The latter can be estimated from the available meteorological data using methods of extreme value statistics. These data will be complemented by an inventory of events mapped on aerial photos of the last decades.

Fluvial processes Repeated surveying with tachymeters, differential GPS, stereophotogrammetry and LiDAR is a standard methodology to quantify channel changes and sediment budgeting of the surveyed reach (the "morphological method"', e.g. Wheaton *et al.*, 2010). Selected reaches of the proglacial channel, particularly the braidplain and zones of slope–channel coupling, will be repeatedly surveyed with a terrestrial laser scanner (e.g. Milan *et al.*, 2007) in order to reach a higher measurement frequency compared with the airborne surveys. Runoff and sediment transport (suspended and bed-load) in the proglacial stream(s) will be gauged at the glacier snout, at the mouth of a tributary brook, and where the Fagge crosses the 1850 moraines, in order to determine the sediment yield from the proglacial zone.

Changing morphodynamics The change in process rates as a function of time since deglaciation cannot be directly observed in the field due to the short time scale of the research project. Hence, we adopt a space-for-time substitution approach to the analysis of the dissection of lateral moraines by selecting test areas along a gradient of distance from the glacier terminus; such chronosequences have been used in the proglacial context for the analysis of soil (Egli *et al.*, 2006) and vegetation (Moreau *et al.*, 2008) development. The measured present-day process rates of slope-wash, linear erosion and debris flows can then be compared for test sites of different "age" with respect to deglaciation. Additionally, a detailed morphometric analysis of the LiDAR DEM is conducted in order to estimate the total amount of sediment eroded (Curry *et al.*, 2006, used cross-profiles for that purpose) and to relate the results to the estimated time since deglaciation. Similarly, rockfall activity from rockwalls in different positions relative to the glacier will be compared.

The proglacial sediment budget The sediment input from the glacier to the proglacial area is gauged in the meltwater stream near the glacier snout. The contribution of non-glacial processes to the proglacial sediment budget will be established by upscaling the results of field measurements from the local to the catchment scale, as described in the previous sections. Some processes, e.g. debris flows, are expected to be quantified directly on the catchment scale (using the airborne LiDAR surveys). The upscaling approach includes the transfer of measured process rates to similar areas, using a digital geomorphological map and spatial modelling approaches (see Becht *et al.*, 2005; Wichmann *et al.*, 2009), depending on the respective process. Slope-channel (lateral) and within-channel (longitudinal) coupling have to be assessed on the basis of the geomorphological map in order to quantify the amount of sediment actually supplied to the "conveyor belt" towards the catchment outlet. The overall result can be compared to the measurement of sediment yield at the outlet of the proglacial area in order to close the sediment budget and, for example, to estimate the sediment delivery ratio. Furthermore, the sediment yield can be balanced against delta aggradation where the Fagge Brook enters the Gepatsch Reservoir. Aggradation rates, which will be measured once a year, when the reservoir level is artificially lowered and LiDAR surveys of the delta area can be conducted (lateral input to the Fagge Brook between the LIA moraine and the reservoir may be considered marginal). Additionally, it can be compared with the 25-year dataset of solid load of the Fagge Brook published by Tschada & Hofer (1990): mean annual bedload discharge was reported as 12 410 m^3 $year^{-1}$ and suspended load as 45 930 m^3 $year^{-1}$.

CONCLUSION AND OUTLOOK

In this paper, we have highlighted the importance of sediment budget studies in changing proglacial environments and have elaborated research needs in this field. Several of these research problems are being dealt with by the PROSA joint project which was started in 2011. We argue that integrated approaches are needed for these issues, as is the case with (warming) mountain permafrost for which Haeberli *et al.* (2010) have compiled an overview of the growing body of literature and important challenges. The results are expected to contribute to basic (e.g. relative contributions of glacial and non-glacial processes, structure and connectivity of proglacial systems) and applied (consequences of increased bedload discharge for downstream reaches, such as natural hazards and filling of reservoirs) geomorphological research.

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