Vegetation Cover on Alpine Rock Glaciers in Relation to Surface Velocity and Substrate

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Abstract

This study analyzes the relationship between vegetation cover and surface velocity on alpine rock glaciers. Fieldwork was conducted in four areas in the Tyrolean Alps (Austria). Total vegetation cover and cover of each distinct species were assessed. In addition, the percentage of fine-grained material was measured. The results were compared to surface movement, calculated from two DSMs derived from multitemporal airborne laser scanning data. The assumption that surface movement is a limiting factor for plant growth could be confirmed. No direct relationship between surface movement and vegetation cover could be established. Especially, the availability of fine-grained substrate has to be taken into account in the explanation of vegetation cover on rock glaciers. The vegetation cover and amount of fine-grained material correlate in areas with surface movement below 1.5m/a. In areas with velocities >1.5m/a, vegetation cover seems to be mainly affected by surface velocity.

Keywords: alpine flora; extreme environments; permafrost; rock glaciers; vegetation cover.

Introduction

Active rock glaciers are widespread features in alpine environments and are commonly regarded as indicators of discontinuous permafrost (Barsch 1996).

Vegetation on rock glaciers has been investigated mainly by Burga (1987, 1999), Cannone (1997), Cannone & Gerdol (2003), and Burga et al. (2004). A key question regarding the special environmental conditions on active rock glaciers is which parameters are crucial in controlling the establishment of plants on such unstable surfaces. The substrate character and surface deformation are responsible for the growth of primarily pioneer plants (Burga et al. 2004), mainly the same plants that are growing in glacier forefields (Burga 1999). The crucial factors for colonization of alpine glacier forefields are the availability of fine detritic material, water supply, and favorable microclimatic conditions (Matthews 1992). These also seem to be important factors for vegetation on active rock glaciers. According to Burga (1999), there is also a correlation between the grain size of the substrate and the occurrence of some vascular plant species in glacier forefields, where some species grow mainly on silt and fine sand while others prefer rather coarse-grained materials. Surface deformation is a locally crucial parameter of plant occurrence, but it can affect the vegetation cover also as a secondary factor by modifying the quality of the substrate. For example, it can occur through the creation of pockets containing fine-grained material on the rock glacier surface, or the accumulation of fine substrate in the furrows caused by the moving surface. The movement of substrate undoubtedly plays a major role for the plant cover on active rock glaciers, but factors such as grain size and other plant growth controlling parameters, such as the availability of fine-grained substrate or water and microclimate, must also be considered. While less vegetation occurs in areas with high surface instability (Cannone & Gerdol 2003), a clear relation between vegetation cover, surface change, and other parameters has yet to be proved.

All previous studies have focused on smaller parts of rock glaciers, where flow velocity was measured. Hence the spatial distribution of areas in which a comparison between vegetation cover, surface parameters, and surface change is possible has been limited. With surface velocities calculated from airborne laser scanning (ALS) to derive high-resolution and accurate digital surface models (DSMs), the possibilities for calculating surface change and velocity of rock glaciers increase drastically. Velocities can, for example, be calculated for the entire surface of a rock glacier. Therefore, this study aims at improving the understanding of the relationship of surface velocity and substrate on rock glaciers with the occurrence of vegetation.

Study Areas, Methods, and Data

Study areas

The four study areas are high alpine cirques containing one or several active rock glaciers located in the Stubai and Ötztal Alps, Tyrol (Austria) (see Figs. 1 and 2).

The rock glacier Äusseres Hochebenkar (AHK) (Fig. 2.1) is located in the Gurgler Tal south of Obergurgl. It is a big, tongue-shaped rock glacier with a length of about 1600 m, and it fills the entire cirque. The history of investigation goes back to the 1930s (Pillewitzer 1938), with a long record of flow velocity and other data (Vietoris 1958, 1972, Haeberli & Patzelt 1982, Schneider & Schneider 2001). The rock glacier AHK covers relatively steep terrain and, with velocities of up to 5 m/a, is one of the fastest moving rock glaciers known

(Barsch 1996:126ff). It reaches from 2830 m to ca. 2360 m altitude.

The Innere Ölgrube (OGR) (Fig. 2.3) is a small side valley of the Kaunertal containing a composite rock glacier. The OGR has been thoroughly investigated recently (Berger et al. 2004, Krainer & Mostler 2002, 2006, Hausmann et al. 2007a, Krainer et al. 2007) with special regards to its surface velocity and internal structure. It consists of two separate tongue-shaped rock glaciers that lie side by side and therefore appear as one (see Fig. 2). The study areas Inneres Reichenkar (RKR) and Schrankar (SKR) are located in the westernmost part of the Stubai Alps, in the Sulztal, a side-valley of the Ötztal. The rock glacier Reichenkar, one of the longest and most active rock glaciers in Austria (Hausmann et al. 2007b), has also been intensively investigated, especially during the last decade (Chiesi et. al. 1999, 2003, Krainer & Mostler 2000, 2002, 2006, Hausmann et al. 2007b, Krainer et al. 2002, 2007). A large amount of surface velocity, discharge, and geophysical data have been collected.

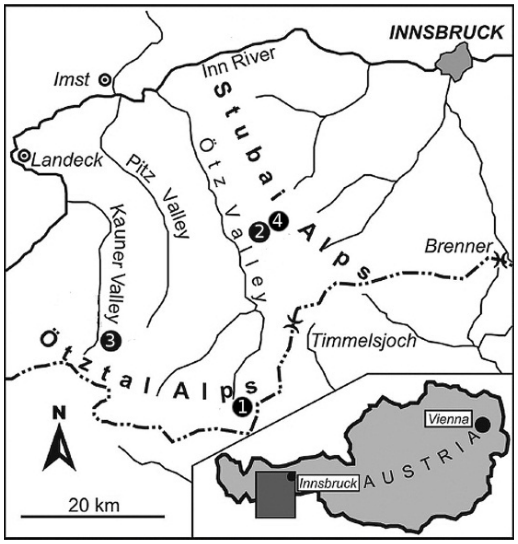

Figure 1. Location of the study sites: (1) Äusseres Hochebenkar, (2) Innere Ölgrube, (3) Inneres Reichenkar, and (4) Schrankar.

The SKR is a big cirque enclosed by high peaks with a steep cirque threshold to the south, containing several rock glaciers of different activity and material. In this study, two rock glaciers were investigated, both of which are significantly smaller and less active than the rock glaciers at the other study sites.

Field data

For this study, the total vegetation cover and the cover of each distinct species were assessed in squares of 3 x 3 m, located roughly every 15 m, along several longitudinal and transversal transects on each rock glacier, using the Braun-Blanquet method (Braun-Blanquet 1964) with a percent scale (Dierschke 1994). In addition, the percentage of fine-grained

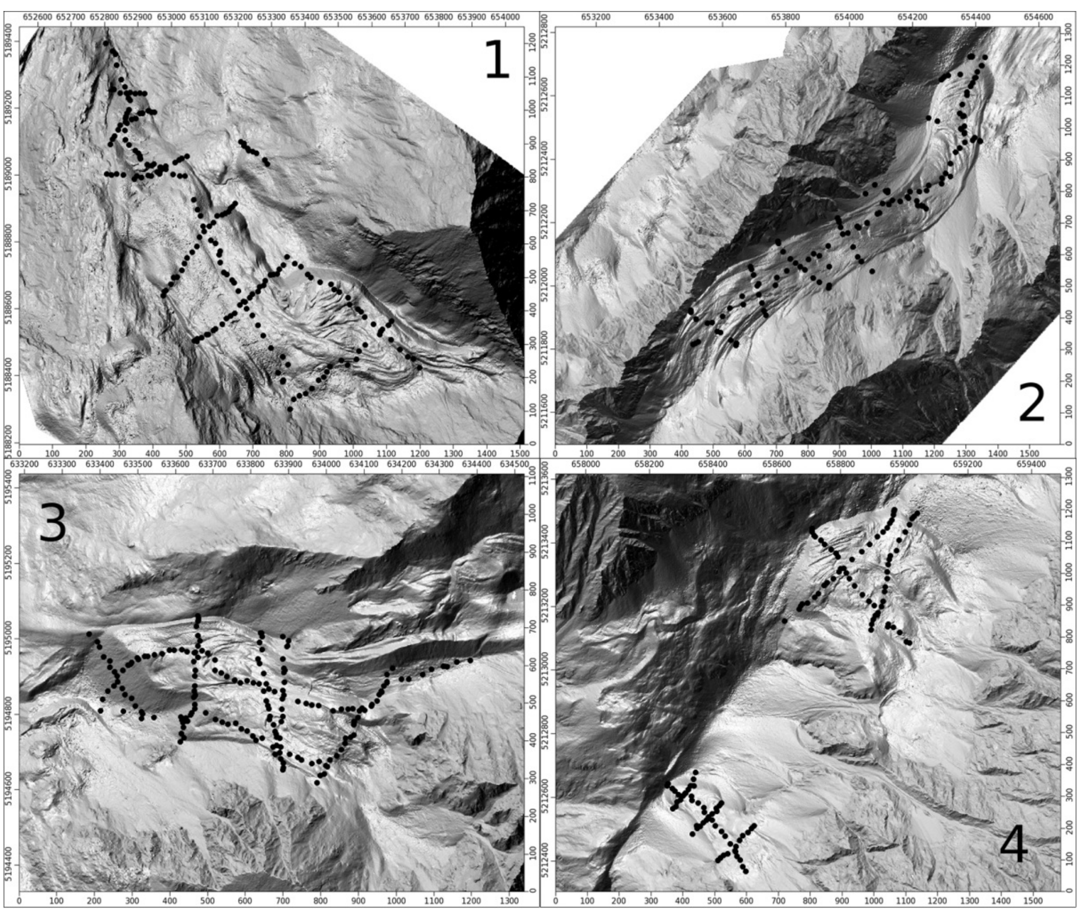

Figure 2. Location of the mapped squares in the study sites. (1) Äusseres Hochebenkar, (2) Inneres Reichenkar, (3) Innere Ölgrube, and (4) Schrankar.

material (silt, clay and sand combined) was estimated visually in each square, while the average size of the blocks was measured. For comparison, adjacent stable areas alongside the rock glaciers were also mapped. In total, 622 squares were mapped during August and September 2010; 541 of them were located on rock glaciers ranging from elevations of 2300 m to 2800 m.

Calculation of surface velocity

Surface velocity data were acquired using the image correlation program Imcorr, developed by Scambos et al. (1992), which uses two images and attempts to match small subsequences from both images. The program can be used to calculate the displacement rates of moving features. Of course, surfaces and their features on active rock glaciers change, but not much in the relatively short period of three years. The program is also widely used to measure glacier velocities (e.g., Scambos et al. 1992, Bucher 2006), where the change of the glacier surface features is a much bigger problem.

Detailed hillshades, derived from Lidar-DSMs with a resolution of 0.5 m, were used as input images for the feature detection and correlation. For all successfully matched features, Imcorr gives the x and y coordinates and a displacement value as output. These files were used to interpolate velocity-rasters. For details on the dataset, the process of surface movement calculation, and the accuracy of the results, see Bollmann et al. (2011) and Bollmann et al. (submitted). The first Lidar-acquisition campaign took place in autumn 2006 and the second in autumn 2009. Therefore, velocities were calculated over a period of three years, but mean annual values are given in this study to facilitate the comparison to other studies.

Results

Vegetation cover and frequency

Although the vegetation cover and patterns are in some ways similar on all studied rock glaciers, there are differences (see Figs. 3 and 4 and Tables 1 and 2). AHK shows the lowest number of different species, which might be explained by the scarcity of fine-grained substrate and therefore low vegetation cover. The higher vegetation cover at OGR is seen as being related to the high percentage of fine-grained material.

The values at SKR and OGR are comparable (see Figs. 3 and 4), while RKR shows less fine-grained material, which could be an explanation for the lower vegetation cover, especially in combination with the higher surface velocities.

Only six species—*Poa laxa*, *Cerastium uniflorum*, *Saxifraga bryoides*, *Oxyria digyna*, *Leucanthemopsis alpine,* and *Geum reptans*—occur at all study sites (see Table 2). These are also the most frequent species, except for *Minuartia sedoides*, which was found only at OGR but at such a high cover and frequency that it is still one of the most frequent species overall. All other species occur rarely, probably due to individual site-specific factors or coincidental germination. More field data would be needed to seriously compare the vegetation patterns of the different study areas.

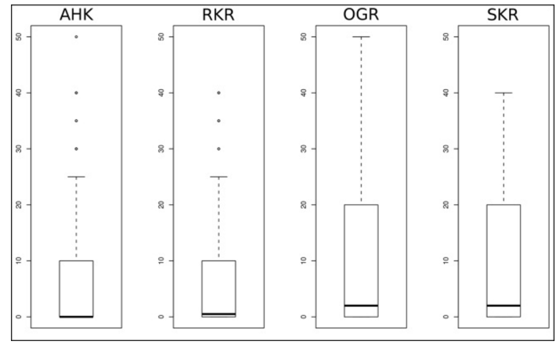

Figure 3. Values of fine-grained material in the squares on rock glaciers in all study sites. 1st quartile, median, 2nd quartile, range (95%) and outliers.

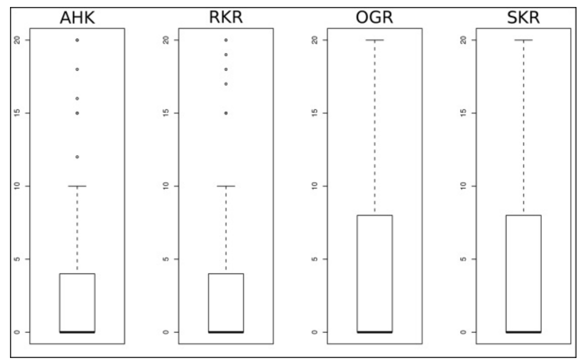

Figure 4. Total vegetation cover (%) in the squares on rock glaciers in all study sites. 1st quartile, median, 2nd quartile, range (95%) and outliers.

Table 1. Number of different species and average values for fine-grained material and total vegetation cover in the squares on rock glaciers for all study sites.

Area	Species	Fine-grained material	Vegetation cover
AHK	9	8.45%	3.19%
OGR	15	13.49%	5.57%
RKR	15	9.62%	4.17%
SKR	14	13.51%	4.77%

Surface velocity

The highest velocities occur at the steep parts of the tongues of rock glaciers RKR and AHK with values of up to 3 m/a. These values are comparable to those given by several authors (e.g., Schneider & Schneider 2001, Hausmann et al. 2007a). At OGR, the fastest moving part of the rock glacier is the tongue of the smaller, southern rock glacier, which reaches velocities over 1.5 m/a. Big portions of the composite rock glacier seem to move slower, with values below 0.5 m/a. At SKR, surface velocities are very low in general. Only the steepest part of the smaller rock glacier reaches values of over 0.6 m/a, while the bigger, spatula-shaped rock glacier shows no clear movement at all. This could be expected due to the relatively flat topography of the area; unfortunately there are no other measurements available to validate the results.

Table 2. Average cover (Cov.) and frequency (Fr.) of all species in the different study areas and combined for all areas in percent.

Study area	**AHK**		**OGR**		**RKR**		**SKR**		**All**	
Species	Cov.	Fr.	*Cov.*	*Fr.*	Cov.	Fr.	Cov.	Fr.	Cov.	Fr.
Poa laxa	0.7	20	*1.69*	*44*	1.08	32	0.85	34	0.86	32
Cerastium uniflorum	1.28	26	*0.81*	*17*	0.72	28	0.83	14	0.73	21
Saxifraga bryoides	0.02	1.3	*0.01*	*0.6*	0.6	25	1.31	26	0.39	11
Oxyria digyna	0.42	0.6	*0.16*	*4.4*	0.45	17	0.28	11	0.26	7
Leucanthemopsis alpina	0.38	10	*0.58*	*11*	0.09	4.6	0.16	6	0.24	8.5
Minuartia sedoides	0	0	*1.02*	*29*	0	0	0	0	0.2	8.5
Geum reptans	0.02	1.3	*0.28*	*9*	0.12	7	0.11	6	0.11	5
Taraxacum alpinum	0	0	*0*	*0*	0	0	0.25	6	0.05	1.3
Sedum alpestre	0.2	4.5	*0.04*	*1.9*	0	0	0.3	2.7	0.05	2.4
Rhododendron ferrugineum	0	0	*0*	*0*	0.24	3.6	0	0	0.05	0.7
Veronica alpina	0	0	*0.18*	*5*	0	0	0	0	0.04	1.5
Senecio incanus	0	0	*0.15*	*6*	0.01	1.8	0	0	0.03	2
Saxifraga spec.	0.09	2	*0.01*	*0.6*	0	0	0	0	0.02	0.7
Salix retusa	0	0	*0.04*	*1.2*	0.04	0.9	0	0	0.02	0.5
Poa alpina	0	0	*0*	*0*	0.06	1.8	0.04	1.8	0.02	0.7
Erigon uniflorus	0	0	*0*	*0*	0	0	0.09	2.7	0.02	0.5
Doronicum clusii	0	0	*0.06*	*1.8*	0.04	1.8	0	0	0.02	0.7
Campanula barbata	0	0	*0.02*	*0.6*	0.04	0.9	0	0	0.02	0.4
Loiseleuria procumbens	0	0	*0.3*	*1.9*	0	0	0.3	1.9	0.01	1.1
Linaria alpina	0	0	*0*	*0*	0	0	0.03	2.7	0.01	0.5
Carex curvula	0	0	*0*	*0*	0.03	0.9	0	0	0.01	0.5
Androsace alpina	0.06	0.6	*0*	*0*	0.01	0.9	0	0	0.01	0.4
Artemisia mutellina	0	0	*0*	*0*	0	0	0.01	1.8	0	0.2

Discussion

While very high surface movement certainly prevents plant growth, vegetation seems to tolerate much higher intensities of surface movement than was previously assumed. The most species and the highest values for vegetation cover were found in squares with relatively low surface velocity, but vegetation covers of up to 20% were found in several squares with surface velocities of about 2 m/a (see Fig. 5). The only squares in which no vascular plants at all were found were those with velocity of over 2.8 m/a.

These results contradict the findings of Cannone & Gerdol (2003) and Burga et al. (2004). Cannone & Gerdol (2003) state that vascular species tolerate surface movement only up to a velocity of 0.35 m/a, with *Geum reptans* and *Cerastium uniflorum* being the species most resistant to stress induced by surface movement. However, Burga et al. (2004) give 0.3 m/a as the maximum surface movement value that is tolerated by vascular plants. Caccianiga et al. (2011) proved that several species, such as *Linaria alpina*, tolerated much higher velocities on the debris-covered Miage glacier.

The relationship of total vegetation cover to surface movement was analyzed for all mapped squares. The values for total vegetation cover do not clearly correlate with those for surface movement (see Fig. 5), but total vegetation cover is related to the percentage of fine-grained material (see Figs. 6 and 7). This correlation is noticeable for all squares (R^2= 0.43), but it gets better if squares with values for surface velocity exceeding a certain level are removed (Fig. 7).

The correlation gets much better if squares with a surface velocity of over 1.5 m/a are excluded (R^2=0.70), but it improves only slightly if more squares are removed from the comparison (e.g., R^2=0.75 if all squares with surface velocities of over 0.17 m/a are excluded). Nearly all squares with high percentages of fine-grained material (over 40%), which show no or very little vegetation cover, fall within the range of surface velocities above 1.5 m/a (see Fig. 6).

Therefore, we conclude that vegetation cover is at first regulated by the availability of fine-grained material, as long as the surface velocity is below a threshold of 1.5 m/a. If this threshold is exceeded, vegetation cover is heavily influenced by surface instability and therefore shows much lower values in relation to the fine-grained material. Below this threshold, vegetation seems to tolerate movement reasonably well, and its occurrence is mainly related to the percentage of fine-grained material.

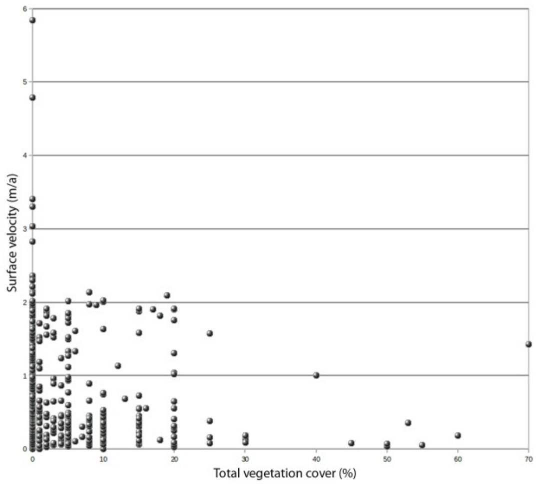

Figure 5. Relation of vegetation cover and surface velocity.

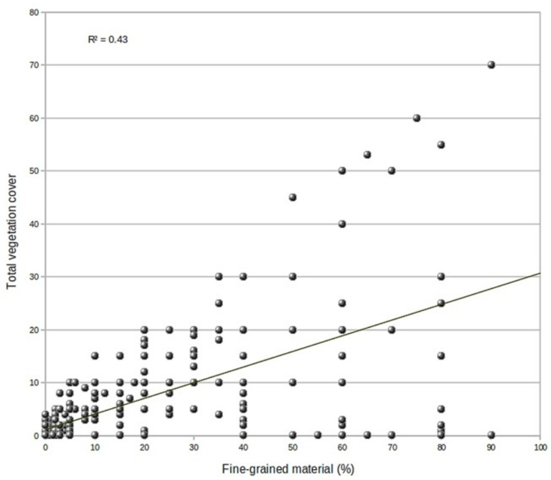

Figure 6. Relation of total vegetation cover and fine-grained material for all squares.

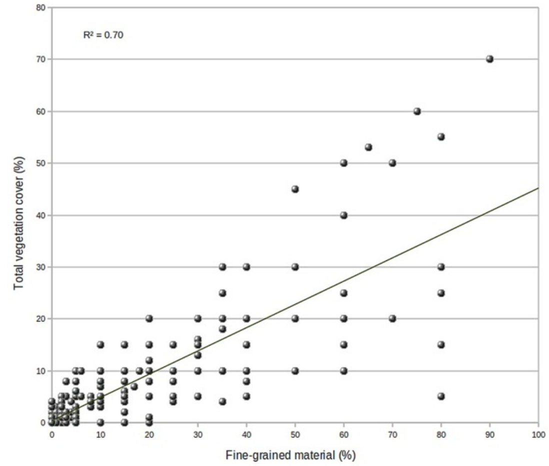

Figure 7. Relation of vegetation cover and fine-grained material for squares with surface movement below 4.5 m during three years.

Conclusions

Analysis of vegetation showed that all species that occur on the rock glaciers in all study areas have also been found on other rock glaciers in the Alps (Cannone & Gerdol 2003, Burga et al. 2004). Especially *Cerastium uniflorum* and *Saxifraga bryoides*, and to a lesser extent *Geum reptans* and *Loiseleuria procumbens,* occurred frequently on all botanically investigated rock glaciers. Of course, these are widespread alpine plants, but they can be assumed to be well-suited to the stress caused by environments as extreme as active rock glaciers. As expected due to the transect-approach, fewer different species were found than in other studies. On the other hand, the complete rock glacier surfaces could be covered, even in a less detailed way, while the majority of other studies focus on the easily accessible rock glacier tongues. This might also be the reason for the relatively low total vegetation cover in comparison to other studies.

The comparison of calculated surface velocities with the data acquired during the field campaign showed interesting results. Relatively high vegetation covers (up to 20%) were mapped in areas with surface movement rates of over 1.5 m/a and scarce vegetation even in areas with surface velocity exceeding 2.5 m/a.

The relationship between vegetation cover and the percentage of fine-grained substrate is also dependent on surface velocity. A threshold of 1.5 m/a for surface velocity could be defined. Below this threshold, the vegetation cover is mainly dependent on the availability of fine-grained material, while it is heavily affected by surface instability if the surface velocity exceeds the threshold. Of course, it has to be kept in mind that other factors can influence plant growth if not hindered by surface instability or the lack of fine-grained substrate. Topographic parameters such as elevation, aspect, and slope have been tested as well, but no clear correlation between them and the total vegetation cover was found. For other parameters, such as air temperature and water availability, no data were available for the investigated areas. Further research and data would be required to answer the remaining questions.

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