ANSWERS to the review #1

Determining the drivers for snow gliding by Fromm et al.

Reviewer comments and questions are black and answers are green.

The authors present the analyses made on data gathered in an experimental test site for snow gliding, in order to find the most significant drivers for such phenomenon. What is interesting is that, beside the more classical snow and weather variables, they consider as drivers also soil and vegetation.

The topic can be of interest for the readers of NHESS. The paper is worth to be published but only after, I think, major revisions.

In particular, my main concern is about the chosen method for selecting the data to be used for the statistical analyses. The choice might imply some uncertainty in the results which is not discussed in the manuscript. Due to this, at the moment I would like to highlight this fact, without entering too much into other details. Therefore, in the following I report my general comments to the authors and not an exhaustive list of specific comments. I am willing to hear the response of the authors, in order to make a fruitful discussion about this interesting topic and hopefully be helpful in publishing their manuscript.

General comments to the authors:

The manuscript is well written and introduces clearly the argument. The Introduction is very well written.

My main concern is related to the choice of the data used for the analyses and the possible consequences of this choice on the results. You state that "*In about 0.5 % of the data entries snow gliding was recorded. The data set was reduced by randomly selecting data entries without displacements. This satisfies that equal amount of 0 and 1 for snow gliding which are used for the multiple logistic regression.*" (pag. 5, lines 12-14). As in the period of "no gliding" the other parameters (used as independent variables) were very variable (Fig. 2), I think that the results of your analyses might be very different if another random subsample of "no gliding" data was chosen. I think you should try to address this fact, discussing the uncertainty related to the results. Did you try with different subsets?

We agree that randomly selecting sub-samples cause variations of the coefficients exp(β). Therefore, we performed bootstrapping to demonstrate the consequences (100 times). An additional paragraph in sub-section 2.3 explains the approach. In table 3 the range of value B is shown by implementing the lower and upper limits of B.

You should also indicate the number of data in your dataset: 0.5% corresponds to N = ?

This part was slightly modified due to the requested bootstrap analysis and the numbers are now provided: "The samples with snow gliding were subsequently weighted. This satisfies that equal amount of 0 and 1 for snow gliding which are used for the multiple logistic regressions (period I: n = 1164096; period II: n = 1340425)."

Something unclear is also what is the "snow glide rate" that you used as dependent variable? It seems that it takes the value 1 or 0 if there was or not displacement. If this is the case, I would not call it glide rate which includes something related to time (30 min, hourly, daily ?).

Displacements of glide shoes originate electrical pulses which are recorded. A pulse is produced by a rotary switch when the glide shoe moves 2.6 mm.
All remaining data (temperature, moisture etc.) are registered in intervals of 10 minutes. Therefore, the snow displacement is calculated for these 10 minute intervals (in millimeter per 10 minutes) for each glide shoe. We will improve the wording in the revised version of the manuscript to avoid confusion.

Specific comments:

In the Introduction, I think that lines 14-16 (pag. 2) are not needed. Without these lines the section naturally flows to the goal of the manuscript (pag. 2, lines 17-25), where the importance of vegetation appears and is introduced just before (lines 11-13). Lines 14-16 could be little modified and moved to section 2.2.2 (pag. 4).

The lines 14-16 (pag. 2) are deleted. A is added sentence in section 2.2.2 which indicates that the SMA sensor was already used in a study concerning the triggering of wet-snow avalanches.

Table 1 already presents some results. I would move it in section 3. Moreover, in the caption of Table 1 you write "*… For each land-use type the glide distance and all…*", but no glide distance is given.

Table 1 is moved to section 3 in a new sub-section 3.1. as proposed.

We added a row in Table 1 named "glide distances".

At the end of section 2.2.3 (pag. 4, line 30) there is a part that should belong to the result section. I would move this part in a new subsection of section 3 related to topography and vegetation. Also Table 1 and the figure of the Appendix should be moved in this new section. I would also make this figure distinguishing between abandoned and pasture areas. Though it is not the main goal of the manuscript, showing the difference of the vegetation types in the two different plots would anyhow provide useful information for discussion.

A new sub-section 3.1. "Topography and vegetation" is added. It contains Table 1 which is moved from section 2.2.3. and the figure from the appendix with the histograms of topographic properties and vegetation characteristics. Now, we distinguish between abandoned and pasture areas. Hence, the figure numbering is adjusted.

Still in section 2.2.3 you write "*The stagnation depth was below 0.5 m, except in one case, indicating a smooth location of that glide shoe.*" (pag. 4, line 32). Apart from this statement, concerning the roughness of the site, you show in Table 1 values for "vegetation roughness" in the pasture and abandoned areas… how did you determine these values? Is this parameter related to stagnation depth? Please describe this or refer to literature.

Sorry for this confusion. The static friction coefficient is the measure for roughness of the vegetation and calculated according to Leitinger et al. (2008). We have deleted "vegetation roughness" from Tab. 1 and added description how we determined the static friction coefficient.

Pag. 5, lines 23-24. Was the division in period I and II done according to a general rule or to the registered data in your study site? Dreier et al. (2016) and Ceaglio et al. (2017) explicitly write that their choices were based on the specific snow and weather conditions of their study sites. Please, give a reason for your choice, even if kind of expert-based.

Major snow gliding was observed in autumn (at the beginning of the winter snowpack) and in spring (during intense melting). We decided to separate the two periods. Therefore, the decision is expert-based.

In section 3. Results, I would eliminate the first subsection "Time series" and just begin the section with "*The time series…*", then make the more specific subsections 3.2 and 3.3 after the new subsection on topography and vegetation.

We followed these suggestions and removed the sub-title "Time series". The new subsection 3.1 contain Tab. 1 which gives an overview of the conditions and characterizes the test site.

In section 3.2 (pag. 6, line 9) you give values for the overall mean glide distance which I cannot find in Fig. 2. What are the values 185.9 and 361.8 mm? In Fig. 2 the black lines should represent the same values at the end of the period, right? Do I miss something? Please, check and explain well this… I would also write somewhere what a "click" in the measuring device for glide distance corresponds to. In Leitinger et al. (2008), which you refer to in section 2.2.1, it seems that it corresponds to 2.6 mm. Is this right?

The glide distances are correct now. The end of the time series used in this study is the end of May (Fig. 2). In the previous manuscript we used the latest data entry in logger from June when we removed the devices from the field.

In order to avoid duplications in the manuscript, the first line in sub-section 3.2 (snow gliding) is removed. The glide distances of pastures and abandoned areas are integrated in Tab. 1.

The information that one pulse represents a glide distance of 2.6 mm is added in sub-section 2.2.1.

At pag. 6, lines 1-3 you write something that is not represented in Fig. 2. The soil moisture at 10 cm (green line) in the abandoned area is around 15 %, not zero as you write here. Please check this.

This was an error. We used the wrong column, first. The text is modified.

Caption of Fig. 2 is incomplete. You show also snow glide distance… for which it is needed to write what it is the black line and the grey area around that line.

The black line represents the mean glide distance. The gray area indicates the range between the minimum and maximum values. Now, this information is added in the legend.

In the boxplot of Fig. 3, did you use the whole dataset or again only the subset which were used in the logistic regression? This is not clear.

The whole data set was used for the box plots. In order to communicate that to the reader we expanded the introducing sentence to the histograms: "The boxplots for the complete data set …"

And again it is not clear to me how you chose the parameters for the box plots and the Whitney–Mann Utest. In the caption of Table 2 your write "… (*bold = most relevant variables, indicated by a large difference from 1).*", but then some of the values are not much far from 1 (for ex. soil moisture at 1.5 cm) !?!?

Table 2 is revised and extended: bold = most relevant variables, indicated by a difference >0.05 from 1. Bootstrapping is applied and the results are based on 100 bootstrap samples.

At pag. 8 the discussion on snow gliding and vegetation properties is very interesting, but it is strange that some *p* values appear here for the first time without being presented before… did you do some correlation analyses? Why don't you present all the results of the correlation analyses in the results section and then discuss them here?

The Whitney-Mann U-test and its corresponding p values are now introduced in the methods section. The correlation matrix is added in the appendix.

ANSWERS to the review #2

«Determining the drivers for snow gliding» (Fromm et al.)

Reviewer comments and questions are black and answers are blue.

General comments:

The manuscript aims at determining the drivers for snow gliding under the effect of changing soil moisture conditions (also in relation development vs. decline of snowpack) and vegetation characteristics. The authors found that soil moisture at the soil surface (1st Part of winter) and soil moisture 1.5 cm below the soil (2nd part of winter) were the most important variables. They found also important vegetation effects. The presented work fills thus important research gaps and has the potential to be a valuable contribution to the state of research on snow gliding processes. I see however several points which should be improved before publishing in NHSS, most importantly:

1. The story of the manuscript should be focused more towards answering the three research questions and towards the main conclusions (which are not yet so clear for me). Two of the three research questions are dealing with vegetation effects on snow gliding. So, this topic should be introduced and discussed better in the light of previous work and implications for land-use management.

Thank you for this comment. We now introduced especially the state-of-the-art and gap of knowledge regarding the vegetation effects on snow gliding in the Introduction section. The results are discussed better and implications for land-use management are presented in the discussion section.

2. Some methodological aspects should be clarified (see also specific comments). Generally , the methods used in this work have been conducted carefully, but they partly fail at disentangling potentially confounding variables. Surprisingly significant results (e.g. effects of lichens and mosses on snow gliding) should thus be better checked for interactions with other variables or at least carefully discussed before publishing.

We now address this topic (as indicated in the specific comments) by stating the influence and relevance of confounding variables. By both checking and discussing this topic we clarify the mentioned methodological aspects.

3. The form and presentation of the manuscript could be improved in different ways (see also specific comments). Some parts of the text is not yet nicely structured in topical paragraphs. Some sections could be shortened without a loss of relevant information towards the main conclusions. Some captions to figures and tables are not 100% clear. The English language would deserve an additional check.

We improved the structure of the manuscript. A new sub-section "Topography and vegetation" is created in section 3 (results). It contains Table 1 which is moved from section 2.2.3. and the figure from the appendix with the histograms of topographic properties and vegetation characteristics. Now, we distinguish between abandoned and pasture areas. Hence, the figure numbering is adjusted. Furthermore, the headline of sub-section "Time series" is removed (section 3).

Some captions of figures and tables are written in more detail.

The manuscript has been professionally proofread to ensure correct grammar and spelling.

Specific comments:

For a reviewer it would be helpful to have continuous line numbers in order to refer in the review to a specific text.

The template from NHESS was used for the submission of the manuscript. We kindly ask the editor to forward this suggestion to *Copernicus Publications*.

Page 1, l. 16. Abstract: was it really the lower phytomass of mosses that had a negative influence on snow gliding or was it not just the lower canopy height of these sites, which was related to phytomass of mosses?

Thank you for this comment. You are right! Not the lower phytomass of mosses reduces the snow gliding, but the simultaneously increased canopy height. We introduced this point now in the Abstract.

P1, l. 17-18. Did a higher phytomass of dwarf shrubs really reduce snow gliding? According to table 2 I see that exp (B) for this variable is very close to 1 for the 1st period and not given for the 2nd period.

The results show that dwarf shrub coverage has a significant negative impact in period 2 (see also Table 2, exp (B) = 0.88).

P1, l. 24. The 3rd sentence « Höller summarized the findings.. » is in this from not necessary for the introduction of the research questions. Please just add the reference where it fits and contributes to the state of research.

The sentence was deleted.

P2, l. 11-16 – The paragraph on the role of vegetation is important for the understanding of the manuscript (2 of 3 research questions are dealing with vegetation effects). The paragraph would deserve thus some more attention in the introduction. In the current form the topic is just introduced by the statement that not much is known about vegetation effects (ignoring thus various publications on snow-glide vegetation effects) before the topic is again abruptly changed to LWC in the same paragraph.

We have expanded our reasoning regarding the vegetation effects on snow gliding in the Introduction section. The results are now discussed in this light and implications for land-use management are presented in the discussion section.

P2, l 20-25, research questions: the two first research questions make sense, but the 2nd research question is not really introduced in the preceding introduction. The 3rd question is also relevant, but is in my eyes not really answered here. The manuscript provides some information on the association between snow gliding with different plant types (eg. mosses or lichens), but I can't find information about the effect of different land-use types (e.g. pasture, abandoned land).

We rephrased the 3rd research question to be in line with our main findings and the analyses on different plant types (i.e. plant functional groups) on the snow gliding process. The 2nd research question is now introduced in the Introduction section.

Section 2.1: the test-site section is quite long and partly redundant with Fig. 1. Please avoid where possible paragraphs with only 1 sentence (in the whole manuscript). I would also reduce the number of listed plant species (because most readers of NHSS are probably not be familiar with them) and focus on the most characteristic and for snow gliding most relevant dwarf shrub and grass species (or vegetation types). It is not clear from the description of the study area if we have 2 or 3 treatments
(is abandoned and unusable the same treatment or not). And are slope angles and other topographical variables the same for the different categories?

We improved the description of our test-site and reduced the number of listed plant species to the most abundant ones. In the description of the study area as well as improved Fig. 1 we clarified the experimental setup and number of treatments.

Section 2.2.1: The description of the design of the distribution of the glide shoes is rather vague. How many glide shoes were distributed in pastures vs abandoned land and which other criteria were used to distribute them?

Table 1 as well as Fig. 1 contains the number of glide shoes in pastures (18) and abandoned areas (22).

No additional rules or criteria were applied to choose their locations. We added "… randomly selected places …" in sub-section 2.2.1.

Section 2.2.2: Some of the very technical information in this section could potentially be shortened without substantial loss of information.

The sub-section is shortened by removing sentences containing low information or sentences are reformulated.

p.4. line 21. Please replace « after Braun-Blanquet » with « according to Braun-Blanquet »

The suggestion has been implemented.

p5, line 12-14. I'm a bit confused by the statement that about 0.5% of the data entries contain snowgliding and the data set was reduced to have an equal number of snow gliding vs. no snow gliding. I agree that the numbers of 0 and 1 in a logistic model should be similar or at least in the same range, so the approach seems ok for me. But this would means that c. 90% of the data entries without gliding have been thrown away. Could you provide here numbers of data entries with and without snow gliding and the criteria used for this categorization.

We have now calculated the statistics via a bootstrapping and rephrased the whole section to clarify our methodical approach. 'In about 0.5 % of the data entries snow gliding was recorded. The samples with snow gliding were subsequently weighted. This satisfies that equal amount of 0 and 1 for snow gliding which are used for the multiple logistic regressions (period I: n = 1164096; period II: n = 1340425). A bootstrap is performed by randomly selecting a value, with replacement (i.e. a given value can be represented more than once in the sample). Each sample selected in this manner is used to calculate the regression coefficient B value. This is repeated 100 times, and the generated sample of *B* values is then used to estimate the standard error and the lower and upper 95% confidence interval. The bootstrapping approach is preferable to that presented by Gude et al. (2009).'

p. 6, line 8ff. Was slope angle not a relevant variable or was the variation in slope angle so small? I would have expected also a boxplot with snow-gliding vs. slope angle.

The mean and the standard deviation of the variable "slope angle" is shown in Tab. 1 and its relevance given in Tab. 2. We found that it is a significant variable for snow gliding, but its influence is low. Other studies with higher variations of the slope angels in their test sites investigated its role in more detail.

p. 6, line 26, replace "very significant" by "highly significant"

The suggestion has been implemented.

p. 6, line 29-30 (and elsewhere): please avoid where possible method description in the result section

The accuracy tables and the Whitney-Mann U-test (including p values) are now introduced in the methods section.

p. 7, line. 13-15. It is not necessary to repeat the objective of the study here. The objective should be clear from the introduction.

The sentence is deleted.

p. 7, line 18-19. It is for me a bit surprising that the phytomass of mosses has an influence on snow gliding. While I'm not surprised that you received a significant relationship, I expect mainly a confounding effect between phytomass of mosses and other variables which may have a more direct effect on snow gliding (also indicated on p. 8, line 10, relationship with canopy height). Such potentially confounding relationships are not easy to disentangle with multivariate logistic models alone. I would suggest to check additionally for such relationships or at least to discuss such a result (which is also repeated in the abstract) and potential confounding effects with other variables

Thank you for this comment. We have revised the entire manuscript to clarify such relationships and have inserted a correlation matrix (Appendix) to support our statements.

p8, l8: snow gliding or snow sliding?

This typing error was corrected in the whole manuscript.

P8, l. 9 ff. similar case like

Table 1: do the abandoned areas include "unusuable land"? And was there actually a difference in snow gliding for the different land-use types? Do the results of this study confirm earlier studies (e.g. by Leitinger, Tasser et al. ?)

There is no significant difference between the abandoned areas and "unusable land". Both sites are currently not managed, but we do not know for sure from one site whether it was used in former times. Therefore we have introduced this subdivision; however, we have deleted the term 'unusable land' in order to avoid confusion.
The results confirm earlier studies (see Discussion section).

Table 3: the content of the contingency table is interesting but should be better explained in the table caption. The model for period 1 was obviously better than for period 2, which can be interpreted quite well with differences in relevant variables for both periods

The table caption is extended. And the percentage for each class is given now. This facilitates the interpretation.

Fig. 3: The description of the figure could be clearer. In the first graph on the left, the y-axis is water content, but there is also a boxplot on soil moisture in the same graph. And what do the A, B, AA, BB mean?

The label in Fig. 3a (now Fig. 4a) is modified. “Boxplots of the most relevant variables in period I and period II (selected according to Tab. 2). Differences between the groups are given by different letters and were determined by Whitney–Mann U-test.”

Determining the drivers for snow gliding

Reinhard Fromm[1], Sonja Baumgärtner[2], Georg Leitinger[2], Erich Tasser[3], Peter Höller[1]

[1]Federal Research and Training Centre for Forests, Natural Hazards and Landscape – BFW, Department of Natural Hazards, Innsbruck, 6020, Austria
[2]Institute of Ecology, University of Innsbruck, Innsbruck, 6020, Austria
[3]Institute for Alpine Environment, Eurac research, Bozen, 39100, Italy

Correspondence to: Reinhard Fromm (reinhard.fromm@bfw.gv.at)

Abstract. Snow gliding is a key factor for snow glide avalanche formation and soil erosion. This study considers atmospheric and snow variables, vegetation characteristics, and soil properties, and determines their relevance for snow gliding at a test site (Wildkogel, Upper Pinzgau, Austria) during winter 2014/15. The time-dependent data were collected at a high temporal resolution. In addition to conventional sensors a 'snow melt analyzer' was used.

The analysis shows that the soil ~~moisture at~~temperature 10 cm below the ~~soil~~ surface, the phytomass of mosses, the liquid water content in the snowpack, and the static friction coefficient of the glide shoes had ~~the largest~~significant influence on snow gliding during the ~~first part of the~~whole winter. In the first period (October to January~~). The soil moisture 1.5 cm below)~~ the soil moisture at the surface ~~was~~and 1.5cm below the surface and the length of the slope uphill the glide shoes affected the snow gliding, too. In the second ~~important variable in the first part of the winter, and the most important variable in the second part of the winter~~period (February to May~~). A negative~~) the soil temperature at the surface, the soil moisture 10cm below the surface, and the slope angle had additional influence on snow gliding ~~had the phytomass of mosses in autumn and spring~~. The role of the vegetation in the snow glide process is determined by the influence on the static friction coefficient caused by ~~lower canopy heights at these sites. Furthermore, a higher portion of dwarf shrub phytomass reduces snow gliding, because~~ its ~~rigid structure can transfer forces~~composition and characteristics and that moss-rich and short-stemmed canopies seem to be more interconnected with the snowpack.

Additional to the soil~~.~~

~~Further~~ and snow properties, the topography and the vegetation characteristics, further investigations may be focused on the freezing and melting processes in the uppermost soil layers, and at the soil surface.

1 Introduction

Deposited snow on the ground is in motion caused by gravity, external forces, or metamorphism. The movement inside the snowpack is called creeping, and the sliding of the entire snowpack on ~~a slope is~~an inclined ground surface is referred as snow gliding (In der Gand and Zupancic, 1966).~~ Höller (2013) summarized the findings concerning snow gliding and glide snow avalanches in chronological order.~~ Snow gliding is favored by a smooth ground surface and a lowermost layer of wet snow (In der Gand and Zupancic, 1966). Once the glide motion turns into an avalanche movement, the process is called a glide avalanche (UNESCO, 1981).

The presence of liquid water at the bottom of the snowpack is a basic requirement for snow gliding (In der Gand, 1954; Lackinger, 1988; McClung et al., 1994; Mitterer and Schweizer, 2013). Several sources exist to provide liquid water to this location (Ceaglio et al., 2012; Ceaglio et al., 2017; Mitterer and Schweizer, 2012). Rain on the snow surface, as well as melting snow near to the surface (Koh and Jordan, 1995), can percolate the isothermal snowpack. Geothermal heat flux can provide energy to melt snow at the bottom of the snowpack (McClung and Clarke, 1987). The suction head can lift water (Mitterer and Schweizer, 2012; Ceaglio et al., 2017) which is produced by melting ice stored in the soil or it can be advected through channels in the soil (ground water outflow).

In addition to the presence of liquid water at the bottom of the snowpack, further variables influence the intensity of snow gliding. Therefore, air temperature can be used to classify the glide snow avalanches into warm-temperature events and cold-temperature events (Clarke and McClung, 1999). The viscosity of snow depends on the snow temperature (Loth et al., 1993; Morris, 1994) and snow water content (Mitterer and Schweizer, 2012; McClung and Clarke, 1987). The slope angle, the micro relief, and the hydrological properties of the slope influence the glide velocity (Ceaglio et al., 2017; McClung and Schaerer, 1999; Margreth, 2007). Friction originated by the vegetation depends on its composition and height (Höller et al., 2009). Both the vegetation and the micro relief depend on the land use, which is an input for snow glide modeling (Leitinger et al., 2008; Maggioni et al., 2016).

~~Up to now~~Ancey and Bain (2015) summarized the knowledge concerning the formation of snow glide avalanches and its impact on obstacles in the path. They concluded that meteorological conditions and topographic features causing snow gliding are well known, but the mechanisms are poorly understood. However, the role of the vegetation ~~has~~and the soil conditions have not been considered in very much detail in previous studies~~. Although~~ which is also indicated by (Höller, 2014) who stated that the conditions at the snow-soil interface have to be investigated most notably. Even though Leitinger et al. (2008) established a measure for vegetation roughness (i.e. surface roughness) and showed that this factor has a significant influence on snow-glide distances, detailed consideration of the soil-vegetation system in the snow-glide process is missing. Although the impact of global change on land cover was mainly due to socio-economic drivers (Tasser et al., 2017), future impact of changing climate will accelerate changes in vegetation composition and vegetation roughness. Hence, studies on causal links and quantitative impacts are especially crucial for snow-gliding and related processes. Besides measures to simplify the complex interactions of vegetation roughness at the snow-ground interface (i.e. surface roughness, Leitinger et al., 2008), the influence of vegetation composition and liquid water to the interlocking of the soil-vegetation-snow continuum is widely unknown.

~~Mitterer et al. (2011) measured the liquid water content (LWC) in the snowpack with the SnowPower sensor (Stähli et al., 2004) and used the acquired data in the context of the triggering of wet-snow avalanches. They modeled the LWC of the snowpack and used the measurements for verification. However, no snow glide data were used in their study.~~

This study specifically addresses the role of the soil-vegetation system on snow gliding, with an elaborate experimental setup. The focus was on the presence of liquid water in the snowpack, on the vegetation, the soil surface, and in the upmost soil layers, as well as vegetation composition and its consequence on snow gliding. Therefore, these key questions are addressed:

- Which variables in the soil-vegetation system, the snowpack, and the lowest atmospheric boundary layer have considerable influence on snow gliding?
- Is it appropriate to distinguish between processes at the beginning of the winter (development of the snowpack) and the late winter (decline of the snowpack)?
- ~~Is it possible to identify the effect of differences between vegetation types (dwarf shrubs and pastures) on the soil surface moisture?~~
- How does vegetation composition influence the snow gliding process?

2 Experimental test site and methods

2.1 Test site

The study site is located on the orographic left, south-facing slope of the upper Pinzgau Valley. From the geological point of view, it is a very homogenous area made up mainly of paragneiss and mica schist. This siliceous bedrock is responsible for the presence of cambisols on the pastures. The abandoned and unused areas are mostly based on cambic podzols. The climate at the Wildkogel can be characterized as a subalpine European climate. Long-term average annual rainfall (at 1973 m a.s.l., Schmittenhöhe) amounts to 1501 mm, with the highest monthly precipitations falling in June and August (175–200 mm per month). Long-term average annual temperature is 1.9°C, with the highest monthly average in August at around 10°C. These low temperatures, high precipitation, and the long period of snow cover impose limits on the vegetation period. The investigated slope faces SSE, with slope angles from 20° to 37°.

The area is characterized by pastures and abandoned ~~pastures/unusable~~ areas in the immediate vicinity (Baumgärtner, 2016). This situation allowed a comparative approach to be used (Fig. ~~1, Tab.~~ 1).

The pasture is stocked with cattle between the end of June and the beginning of September. This area is dominated by grasses and has been classified as Sieversio montanae–Nardetum strictae subassociation typicum (Lüth et al., 2011~~). The characteristic species are~~) with the matgrass (*Nardus stricta*~~, Geum montanum, Carex pallescens, Hieracium hoppeanum, Phyteuma hemisphaericum, and Scorzoneroides helvetica.~~) as dominant species. Management of the abandoned area ceased about 10 years ago. The predominant species of the area are dwarf shrubs ~~of the species~~(e.g. *Vaccinium myrtillus, V. vitis–idaea,* ~~V. uliginosum, Rhododendron ferrugineum,~~ *Calluna vulgaris*~~, and Arctostaphylos uva ursi. Other important species of this vegetation type (Caricetum sempervirentis with dwarf shrubs) are~~) and the evergreen sedge (*Carex sempervirens*~~, Avenella flexuosa, and Juncus trifidus. In the unused area the vegetation is similar to the abandoned area, with a higher coverage of grasses and herbs (>50 %).~~).

~~<< proposed position for Figure 1 >>~~

2.2 Measurements and methods

2.2.1 Snow gliding

Snow gliding was measured with glide shoes (In der Gand and Zupancic, 1966). The glide shoes were connected to a drum with a wire. Its displacements generated rotations. A rotary switch generated pulses which were counted by HOBO H6 logger units. The date and time of each pulse was stored. One pulse represents a glide distance of 2.6 mm. A detailed description is given by Leitinger et al. (2008). Forty devices (Fig. 1) were installed at randomly selected places with different land use, topographic conditions, and vegetation characteristics in October 2014 (Baumgärtner, 2016).

The initial force required to displace each shoe was measured with a tension spring balance (Pesola Medio 1000 g). The static friction coefficients for all glide shoes were calculated as the ratio of the initial forces and the normal forces. They represent the influence of different vegetation types and different land uses on snow gliding (Leitinger et al., 2008).

2.2.2 Meteorology and related snow and soil properties

An automatic weather station recorded air temperature, air humidity (Rotronic MP103), snow depth (Sommer UHZ8), snow temperatures (Sommer AD592c; 0, 5, 50, 100 cm), and global radiation (Schenk 8101). It was located at the test site. The data were stored at intervals of 10 minutes by a data logger.

At the meteorological station a snow melt analyzer (SMA, Sommer) was available. ~~The SMA is a further development of the SnowPower device.~~ It measures the dielectric coefficients with a time-domain reflectometer, using two frequencies along a flat band cable. ~~Ice and water show significant differences in their~~The different dielectric properties~~, which is~~ of water and ice are used to ~~calculate~~determine the volume fractions of the LWC and the ice content (Stähli et al., 2004). The flat band cable was mounted 5 cm above the soil surface. It was aligned parallel to the surface and orientated along the fall line. The acquisitions were recorded by a data logger in 10 minute intervals. Data entries were removed ~~if~~in case that the snow depth was less than 5 cm~~, because in such cases the flat band cable of the SMA and the snow temperature sensor at 5 cm height was outside the snowpack.~~.

Soil temperatures (Pt-100) and soil moistures (Decagon, ECHO®) were measured at four levels (0, 1.5, 5, 10 cm) in the pastures and the abandoned area. The data were stored at intervals of 5 minutes by a data logger (HOBO® Microstation).

2.2.3 Topographic features and vegetation characteristics

In order to consider the micro-relief close to the snow glide shoes, topographic features were noted at each glide shoe~~ (Tab. 1)~~. The slope angle was measured directly by each glide shoe, as well as one meter uphill and one meter downhill. Along the fall line the distances where the micro relief changed were measured (uphill and downhill). The amplitudes (A) and the wavelength (λ) of the micro relief were determined. For that purpose, an elastic aluminum pole (length 2 m) was used, which was matched to the ground surface and resulted in a deformation of the slope. With these data, the stagnation depths were calculated according to Salm (1977) for each glide shoe position.

~~<< proposed position of table 1 >>~~

~~A scientific~~The parameter *static friction coefficient* was determined to estimate the roughness of the vegetation. For calculation, the weight of the glide shoe and the force needed to move the glide shoe on the vegetation surface was measured (Leitinger et al., 2008). A vegetation inventory of each snow gliding measurement plot was made by a simplified phytosociological survey, ~~after~~according to Braun-Blanquet (1964). This involves analyzing the degree to which the important plant species are present at the position of the snow-glide shoes.

To determine phytomass pools at the sites, production analyses were carried out at the beginning of the vegetation period (end of May). Within a harvest frame (size 900 cm²), all above-ground stands were harvested destructively. The experiment consisted of 18 and 22 replicate plots for the pasture and the abandoned/agricultural unused area, respectively.

Knowledge of the absolute amounts of the different functional groups are important in order to assess qualitative vegetation composition and the resulting effects on snow gliding (Newesely et al., 2000; Leitinger et al., 2008). Therefore, the harvested phytomass was divided into ~~several~~the following plant functional groups: grass, herbs, dwarf shrubs, lichens, and mosses. The phytomasses were then oven-dried~~ in an oven~~ at 80°C until they reached a constant weight, determined as the dry weight.

~~The frequency distributions of vegetation characteristics are L-shaped for all vegetation types (see appendix). This indicates that no vegetation type is dominant at the test site. The prevailing slope angle is in the class which ranges from 30 to 35°. The stagnation depth was below 0.5 m, except in one case, indicating a smooth location of that glide shoe. The friction force was low, and in the majority of the cases very low. The frequency distribution of the canopy heights was between 0.01 m and 0.08 m – higher values were less frequent. The distribution of the slope lengths above and below the glide shoes were equally shaped. The distribution of the slope angles below the glide shoes had a maximum at 30°.~~

2.3 Data interpretation and statistical methods

In order to identify the magnitude of the influence of the variables, the snow glide rate is defined as the dependent variable. All other variables are interpreted as independent variables. ~~Because~~Since snow gliding in the data set is a binary piece of information for each time step, multiple logistic regression was used to determine the relevant variables (Wilks, 1995). The magnitude of the regression parameters can be used to describe their influence on the dependent variable.

The number of independent variables should be reduced to avoid overfitting. This procedure is often called screening regression and was established by backward elimination (Wilks, 1995). The procedure starts with all potential predictors. At each step the least important predictor is removed until the termination criteria are reached (tolerance of the predictor >0.2 and variance inflation factor <10).~~ In about 0.5 % of the data entries snow gliding was recorded. The data set was reduced by randomly selecting data entries without displacements. This satisfies that equal amount of 0 and 1 for snow gliding which are used for the multiple logistic regression.~~

In about 0.5 % of the data entries snow gliding was recorded. ~~The logistic regression fits~~The samples with snow gliding were subsequently weighted. This satisfies that equal amount of 0 and 1 for snow gliding which are used for the multiple logistic regressions (period I: n = 1164096; period II: n = 1340425). A bootstrap is performed by randomly selecting a value, with replacement (i.e. a given value can be represented more than once in the sample). Each sample selected in this manner is used to calculate the regression coefficient B value. This is repeated 100 times, and the generated sample of *B* values is then used to estimate the standard error and the lower and upper 95% confidence interval. The bootstrapping approach is preferable to that presented by Gude et al. (2009).

The logistic regressions fit the parameters B for all variables. The magnitude of exp(B) is used to describe the intensity of its influence on snow gliding. If exp(B)>1 the effect is positive, which means that the probability of snow gliding rises with increasing values for the variable. Values below 1 have a negative effect, and the probability of snow gliding decreases if the values for the variable rises. exp(B)=1 indicates that the corresponding variable has no influence on snow gliding.

~~Caused by~~Due to the fact that liquid water at the snow-soil interface is a requirement for intense snow gliding (In der Gand and Zupancic, 1966) the measured soil moisture at 0 cm (soil surface) is analyzed in more detail. By using a multiple linear regression model, the regression coefficient was determined to identify the sign and the magnitude of the independent variables. ~~In order to~~To avoid overfitting, variables which correlate among themselves were excluded.

In order to consider the differences between the properties of a rising and a degrading snowpack, the data set was divided into two sub-periods: period I from October to January, and period II from February to May. For both periods accuracy tables are used to demonstrate how well the applied method is able to distinguishes between the two classes (gliding, no gliding). As score index the hit rate was used which is the fraction of correctly calculated data records and the sum of all data entries (Wilks, 1995).

The Whitney–Mann U-test is a nonparametric rank test (Schönwiese, 2000). It was used to determine the significance levels (p values) for selected variables.

The statistical analyses were accomplished with the software IBM SPSS Statistics (Version 21, IBM SPSS Statistics Software).

3 Results

~~3.1 Time series~~

The time series in Fig. ~~1~~2 give an overview of the investigated period. The snow cover season started in October 2014 and ended in late May 2015. It was interrupted twice: in November and in May. In period I the soil temperatures decreased until they reached values between 0°C and 1°C. During period II the soil temperatures were nearly constant until the snow melted. At the beginning of the winter (period I) snow gliding was recorded by all glide shoes. The LWC reached more than 4 % (volumetric percent). The soil moisture characteristics were different for pastures and abandoned areas. At the surface, the soil moisture was close to zero until March in the pastures ~~(Fig. 1). In contrast, this behavior was observed at 10 cm~~and in the abandoned area~~.~~ (Fig. 2).

At the beginning of period II, the measured LWC values were about 2.5 %. It raised during snow melting, indicated by a rapid decrease in snow height.

3.1 Topography and vegetation

An overview of the observations and measurements at the pastures and abandoned areas is given in Tab. 1.

The frequency distributions of vegetation characteristics are L-shaped for all vegetation types (Fig. 3). This indicates that no vegetation type is dominant at the test site. ~~<< proposed position of Figure 2 >>~~

The prevailing slope angle ranges from 25° to 35°. The stagnation depth was below 0.5 m, except in one case, indicating a smooth location of that glide shoe. The friction force was low, and in the majority of the cases very low. The frequency distribution of the canopy heights was between 0.01 m and 0.08 m – higher values were less frequent. The distribution of the slope lengths above and below the glide shoes were equally shaped. The distribution of the slope angles below the glide shoes had a maximum at 30°.

3.2 Snow gliding

~~The overall mean glide distance for pastures was 185.9 ± 30.6 mm and for the abandoned areas 361.8 ± 114.5 mm.~~
For period I the soil temperature at 10 cm was determined as the variable with the most influence on snow gliding, followed by the LWC (Tab. 2). Moderate influence was detected for soil moisture at ~~1.5~~0 cm and soil moisture at 1.5 cm. The soil temperature at 10 cm was the most important variable for period II.~~0 cm.~~ A strong negative influence is indicated for the phytomass of mosses and the static friction coefficient in both periods.
~~The soil temperature at 10 cm was the most important variable for period II. The soil moisture at 1.5 cm had a moderate influence. A negative influence was identified for the variables friction coefficient and mass of mosses.~~

~~<< proposed position of table 2 >>~~

The boxplots for the complete data set distinguish between snow gliding and no snow gliding for LWC and soil moisture at 1.5 cm (Fig. ~~3a~~4a), soil temperature at 10 cm (Fig. ~~2b~~4b), and the phytomass of mosses (Fig. ~~3c~~4c) for period I. The positive influence of the soil moisture at 1.5 cm and the soil temperature at 10 cm is obvious, as is the negative effect of the phytomass of mosses. The influence of LWC on snow gliding exists, but it is low.
~~Four variables show significant influence during~~In period II~~. The~~ the soil moisture at 1.5 cm (Fig. ~~3d~~4d), the soil temperature at 10 cm (Fig. ~~3e),~~4e), and the phytomass of mosses (Fig. ~~3f~~4f), and the static friction coefficient (Fig. ~~3g) all~~4g) affect the snow gliding.
~~The Whitney–Mann U-test is a nonparametric rank test (Schönwiese, 2000). It was used to determine the significance levels~~ The Whitney-Mann U-test shows for ~~the~~all selected variables ~~(Tab. 2; Fig. 3). The results were very significant~~high significance levels (p<0.001~~) for all of these variables.~~; Fig. 4).

~~<< proposed position of figure 3 >>~~

~~Accuracy tables can be used to demonstrate how well the applied method is able to distinguishes between the two classes (gliding, no gliding). The hit rate is the fraction of correctly calculated data records and the sum of all data entries (Wilks, 1995).~~ For period I the hit rate is ~~83.6~~85.4 %, and for period II it is ~~69.4~~66.0 % (Tab. 3).

~~<< proposed position of table 3 >>~~

3.3 Soil water content at 0 cm

The presence of liquid water at the bottom of the snowpack is a requirement for snow gliding (In der Gand, 1954; Mitterer and Schweizer, 2013). In order to determine the relevant variables and quantify their influence, a multiple linear regression was calculated for both the pastures and the abandoned area. The soil moisture at 0 cm was used as the dependent variable. The signs of the regression coefficients indicate a positive or a negative relationship (Tab. 4). The magnitude represents the intensity of its influence on the soil moisture at 0 cm. For both areas, the soil moisture at 10 cm is identified as the most important variable. Negative correlations were found for soil temperature at 10 cm and snow temperature at 5 cm. Atmospheric variables had a very low influence on the soil moisture at 0 cm.

~~<< proposed position of table 4 >>~~

4 Discussion and conclusions

~~The objective of this study was to investigate snow gliding by means of detailed consideration of the snow-vegetation-soil system.~~

Ceaglio et al. (2017) investigated the role of the soil in the context of snow gliding and the formation of glide cracks and avalanches. They concluded that the thermal and hydraulic processes in the soil have to be considered. ~~This~~Our study confirms that the soil moisture at the soil surface, and a few centimeters below the surface, are variables which influence the snow glide rates. Additionally, ~~it was~~we found that temperatures in the soil have a significant influence on snow gliding. Furthermore, the phytomass of mosses affects the snow glide rates at the test site.

Clarke and McClung (1999) introduced the terms cold-temperature events and warm-temperature events, which indicate a correlation of glide snow avalanches with air temperatures. Since glide snow avalanches did not occur at the study site, such classification is not useful here. However, to consider different processes during the development of the snowpack and the decline of the snowpack, two sub-periods were defined (period I: October–January; period II: February–May). The soil moisture and the soil temperature had a significant influence on snow gliding in both periods. ~~The LWC was only relevant in period I.~~ This indicates a lower viscosity of the moist snowpack and a water transport from the snowpack towards the soil surface. However, the LWC is not the predominant variable that explains the soil moisture at 0 cm~~.~~ (Tab. 4). Dreier et al. (2016) investigated the influence of meteorological parameters on snow glide avalanches and divided the winter season into two periods. They found that warm temperature events were mostly associated with a melting snow surface, and cold temperature events are linked with hydraulic process in the basal snow layers and the uppermost soil layers. It confirms the conclusions regarding glide distances presented here.

Some topographical factors also affect snow gliding. In particular, the static friction coefficient ~~in period II~~ has a negative effect on snow ~~sliding~~gliding. It seems that the friction is reduced by the vegetation, which was depressed by the weight of the snowpack~~, during period II.~~. This depends on the composition and the characteristics of the vegetation (Leitinger et al., 2008). At the test site it can be concluded that dwarf shrubs are more resistant against depression than pastures.

~~Furthermore, to a small extent, the stagnation depth, the slope angle, the slope angle above the glide shoes, and the friction had influence on snow gliding in various directions. The reason for the weak influence of these variables might be that their ranges are low at the test site. Therefore, the statistical analysis cannot identify a clear trend.~~

The results also show that the vegetation has a significant effect on snow ~~sliding~~gliding. Just the phytomass of mosses had a negative influence on snow gliding in both periods. The analyses of the vegetation composition have shown that a higher percentage of mosses exists at low canopy heights (p=-0.~~523~~52**). Moss-rich and short-stemmed canopies seem to be more interconnected with the snowpack, and thus contribute to a reduction in snow gliding. On the other hand, long-stemmed, grass-rich canopies can be easily felled, and they form an ideal gliding horizon. These findings are in accordance with ~~the findings~~those of Newesely et al. (2000) showing that the gliding distances are increasing from cut meadows to pastures to uncut or abandoned grasslands. Furthermore, a ~~higher~~canopy height is positively correlated with the proportion of dwarf shrub phytomass ~~reduces snow gliding.~~(p = -0.73***). The predominant dwarf shrub species in the study area are *Vaccinium sp.* and *Rhododendron ferrugineum*, and ~~so~~ are highly lignified and rigid dwarf shrubs. Such dwarf shrubs, as well as small trees, keep the ~~snow cover~~snowpack back and thus reduce snow ~~sliding~~gliding (see also Newesely et al., 2000; Leitinger et al., 2008). On the other side, the canopy height is negatively correlated with the phytomass of grasses (p = -0.61***) which promotes snow-gliding (Newesely et al., 2000).

~~Finally, in our study a higher cover of lichens corresponded with~~ Implications for agricultural land management (Tasser and Tappeiner, 2002) are given as the type of land-use (mowing, grazing), as well as the intensity of land-use (frequency of annual mowing, fertilisation, irrigation, number of grazing animals), lead to characteristic vegetation communities. Mowing and a low level of fertilisation greatly favour the growth of herbs and high growing grasses, while *Nardus stricta* spreads rapidly on meadows with low land-use intensities (usually mown once a year, not fertilised). After land abandonment, *Carex sp.* immediately spreads, forming the climax vegetation at the higher altitudes. Below the natural timberline, however, the proliferation of dwarf shrubs and subsequent a natural reforestation are taking place. Land-cover changes, especially the transitional forms between meadows of high land-use intensity and young forests may have crucial impact for the snow-gliding process (Newesely et al., 2000; Leitinger et al., 2008). If an adequate land-use intensity cannot be maintained, steep areas have to be reforested to shorten a critical time period of high snow-gliding activity.

~~lower snow glide rates. This, however, is probably not directly connected with the lichen cover itself, but with the simultaneous decrease in the grass cover. If the covering of the lichens increases, the covering of the grasses, which promotes snow-gliding (Newesely et al., 2000), is simultaneously reduced (p = -0.632***).~~

These investigations on snow gliding confirmed findings from previous studies, and extended them by considering variables describing the vegetation. It seems that the use of soil moisture sensors makes sense for further investigation, which may be focused on the hydraulic processes close to the soil surface. However, upcoming measurement problems of the uppermost partially frozen soil layers must be considered.

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Table 1: Key characteristics of pastures and abandoned/agricultural unused areas. For each land-use type the glide distance and all topographic and vegetation factors are given (mean ± s.e.).

Land use	**Pasture**	**Abandoned area**
N	18	22
static friction coefficient ( )*	0.0 ± 0.0	0.1 ± 0.0
stagnation depth (cm)	16.0 ± 3.6	10.2 ± 4.9
slope inclination (°)	25.0 ± 1.2	31.7 ± 1.1
slope inclination uphill (°)	25.0 ± 1.1	29.7 ± 1.6
slope inclination downhill (°)	31.8 ± 2.5	30.2 ± 1.7
slope length uphill (m)	2.7 ± 0.6	1.7 ± 0.4
slope length downhill (m)	4.6 ± 0.4	4.2 ± 0.4
slope orientation (°)	190.0 ± 0.0	186.6 ± 1.9
~~initial force (g)~~	~~101.7 ± 7.8~~	~~147.7 ± 11.9~~
~~vegetation roughness (g)~~	~~10.6 ± 4.3~~	~~21.4 ± 9.1~~
canopy height (cm)	2.8 ± 0.3	3.7 ± 0.3
cover of dwarf shrubs (%)	7.6 ± 1.8	43.0 ± 6.3
cover of grasses (%)	28.9 ± 3.5	4.7 ± 0.9
cover of herbs (%)	0.6 ± 0.1	0.4 ± 0.1
cover of lichens (%)	0.4 ± 0.1	9.4 ± 1.6
cover of mosses (%)	0.3 ± 0.1	0.3 ± 0.1
phytomass of dwarf shrubs (g m^{-2})	179.7 ± 28.7	739.0 ± 49.7
phytomass of grasses (g m^{-2})	870.9 ± 24.1	156.6 ± 43.8
phytomass of herbs (g m^{-2})	27.7 ± 6.1	26.5 ± 13.9
phytomass of lichens (g m^{-2})	18.0 ± 5.8	178.0 ± 33.9
phytomass of mosses (g m^{-2})	14.8 ± 4.1	6.0 ± 2.0
glide distance (mm)	144.8 ± 67.1	161.1 ± 89.9

Table 2. Significant parameters without multi-collinearity and exp(B) of two logistic linear regressions for both periods with snow gliding as dependent variable. If exp(B)<1 then the correlation is negative, if exp(B)>1 then it is positive (bold = most relevant variables, indicated by a ~~**large difference from 1).**~~difference >0.05 from 1). Bootstrap results are based on 100 bootstrap samples. B = regression coefficient B, s.e. = standard error, exp(B) = odds ratio

	Without multi-collinearity		Period I						Period II					
	Tolerance of the predictor	Variance inflation	exp(B)	sig.	B	s.e.	upper	lower	exp(B)	sig.	B	s.e.	upper	lower
soil temperature 0 cm	0.505.731	1.981368	-1.015	0.000-	-.015	-.001	.013	.017	.809	0.000	-.212	.003	-.218	-.207
soil temperature 10 cm	0.525.492	1.9032.031	1.639788	0.000	4.581.448	.002	.577	.586	1.352	0.000	.301	.004	.294	.309
soil moisture 0 cm	0.386.355	2.591819	1.117242	0.000	-.216	-.002	.212	.220	.907	0.000	-.097	.001	-.098	-.096
soil moisture 1.5 cm	0.277.196	3.6065.102	1.076061	0.000	.059	.001	.057	.061	1.041044	0.000	.043	.001	.041	.044
soil moisture 110 cm	.267	3.749	.991	0.248000	4.026-.009	-.001	--.011	--.007	-1.110	0.000	.104	.001	.103	.105
snow temperature 0 cm	0.388	2.575	1.091	0.000	-	-								
snow height	0.532.495	2.021	1.878013	0.000	.013	.000	.013	.013	1.006002	0.000	-.002	-.000	.001	.002
LWC	0.522.421	2.376	1.916390	0.000	.329	.003	.323	.335	1.405078	0.000	-.075	-.002	.070	.078
air temperature	.353	2.836	1.035	0.289000	3.455.034	-.001	-.032	-.037	-.981	0.000	-.019	.001	-.020	-.018
relative humidity	0.542.554	1.845804	1.006009	0.000	-.009	-.000	.008	.009	1.002	0.000	.002	.000	.002	.002
global radiation	0.876.867	1.141153	-1.001	-0.000	.001	.000	.001	.001	1.001	0.012000	.001	.000	.001	.001
static friction coefficient	0.296.807	3.3731.239	.448-	-0.000	0.060-.802	.0330.000	-.873	-.731	.321	0.000	-1.137	.023	-1.177	-1.078
stagnation depth	0.392.395	2.553529	1.008.998	0.000	1.017-.002	0.000	-.002	-.001	.995	0.000	-.005	.000	-.006	-.005
slope angle	0.609.630	1.643587	1.026016	0.000	.0161.035	0.001	.015	.018	1.060	0.000	.058	.000	.058	.059
slope angle 1 m uphill	0.693.721	1.442387	0.881.998	0.000	--.002	-.001	-.003	-.001	.983	0.000	-.017	.000	-.018	-.017
slope angle 1 m downhill	0.787.809	1.270236	-1.000	-0.000	-.000	-.000	.000	.001	.994	0.000	-.006	.000	-.007	-.006
slope length uphill	0.538.631	1.860584	-.827	-0.000	--.190	-.002	-.194	-.186	1.035	0.000	.035	.001	.032	.037
slope length downhill	0.784.790	1.276266	-1.008	-0.000	-.008	-.002	.005	.012	.955	0.000	-.046	.001	-.048	-.044
friction force drum	0.378.392	2.644553	1.009	0.000	1.009	0.000	.009	.009	.999	0.000	-.001	.000	-.001	-.001

friction force field	0.311	3.213	0.996		0.000	-		-						
Phytomassphytomass of dwarf shrubs	0.527.547	1.898828	.9880.994	0.000	--.012	-.000	-.013	-.012	.995	0.000	-.005	.000	-.005	-.005
phytomass of mosses	0.250.752	1.330	**.618**	**0.000**	**-.482**	4**.008**	**0.425-.497**	**-.4640.000**	**0.462.355**	**0.000**	**-1.037**	**.006**	**-1.049**	**-1.024**
cover of lichen	0.516.583	1.939715	0.993.985	0.027000	0-.016.988	0.039.000	-.016	-.015	.980	0.000	-.020	.000	-.021	-.020
cover of moss	0.229	4.367	1.209		0.000	-		-						

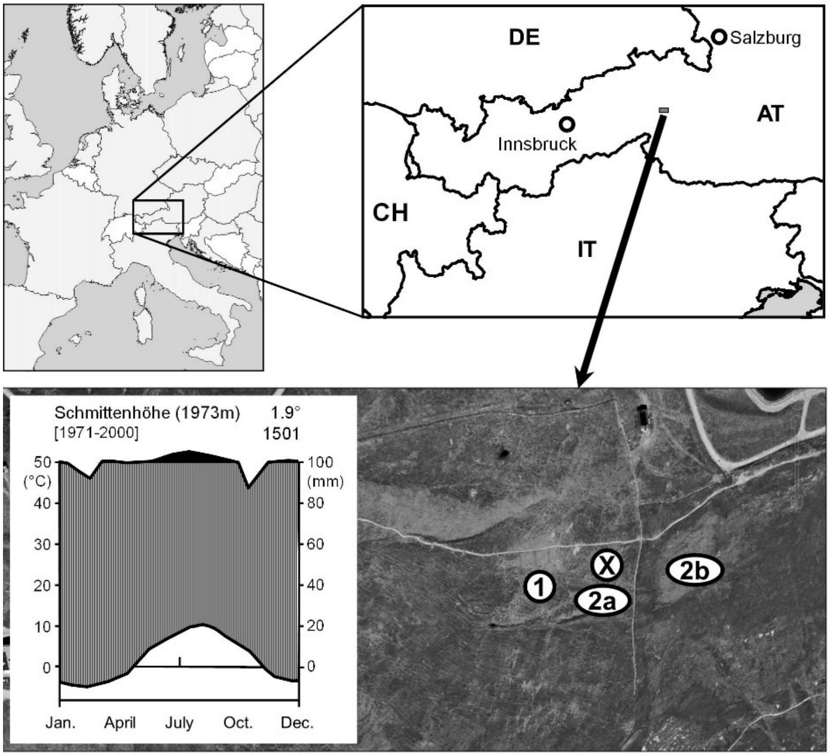
Table 3. Contingency table for both periods as a result of the logistic regression.

		Snow gliding observed					
		Period I			Period II		
		yes	no	Percentage Correct	yes	no	Percentage Correct
Snow gliding	yes	~~3683~~483565	~~85~~499587	~~559~~82.9	~~242~~449104	221001	67.0
	no	~~528~~70490	~~3342~~510454	~~259~~87.9	~~578~~235200	435120	64.9
Overall Percentage				85.4			66.0

Table 4. Regression coefficients of the multiple linear regression, with soil moisture 0 cm as dependent variable.

	Regression coefficients	
	Abandoned area	Pastures
soil temperature 0 cm	-0.048	-
soil temperature 10 cm	-0.276	-0.230
soil moisture 5 cm	-	0.342
soil moisture 10 cm	**0.770**	**0.431**
snow temperature 0 cm	0.189	0.234
snow temperature 5 cm	-0.044	-0.129
snow height	0.186	-0.010
LWC	0.124	0.117
air temperature	0.095	0.097
relative humidity	0.103	0.027
global radiation	-0.012	-0.033

R^2	0.878	0.712


DE
Salzburg
AT
Innsbruck
CH
IT
Schmittenhöhe (1973m)
1.9°
[1971-2000]
1501
50
(°C)
40
30
20
10
0
100
(mm)
80
60
40
20
0
Jan.
April
July
Oct.
Dec.
1
X
2a
2b

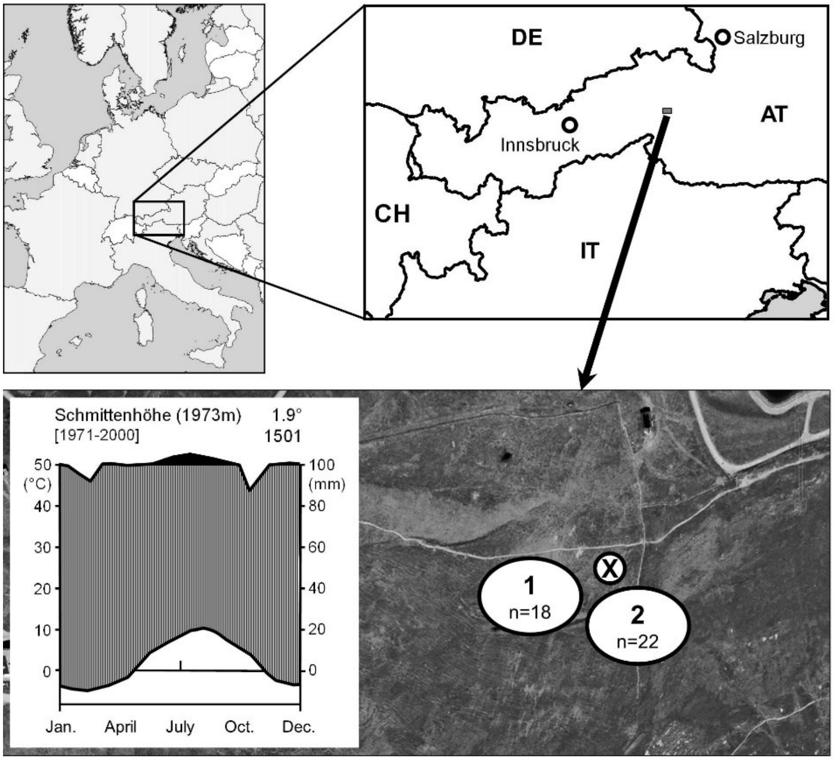
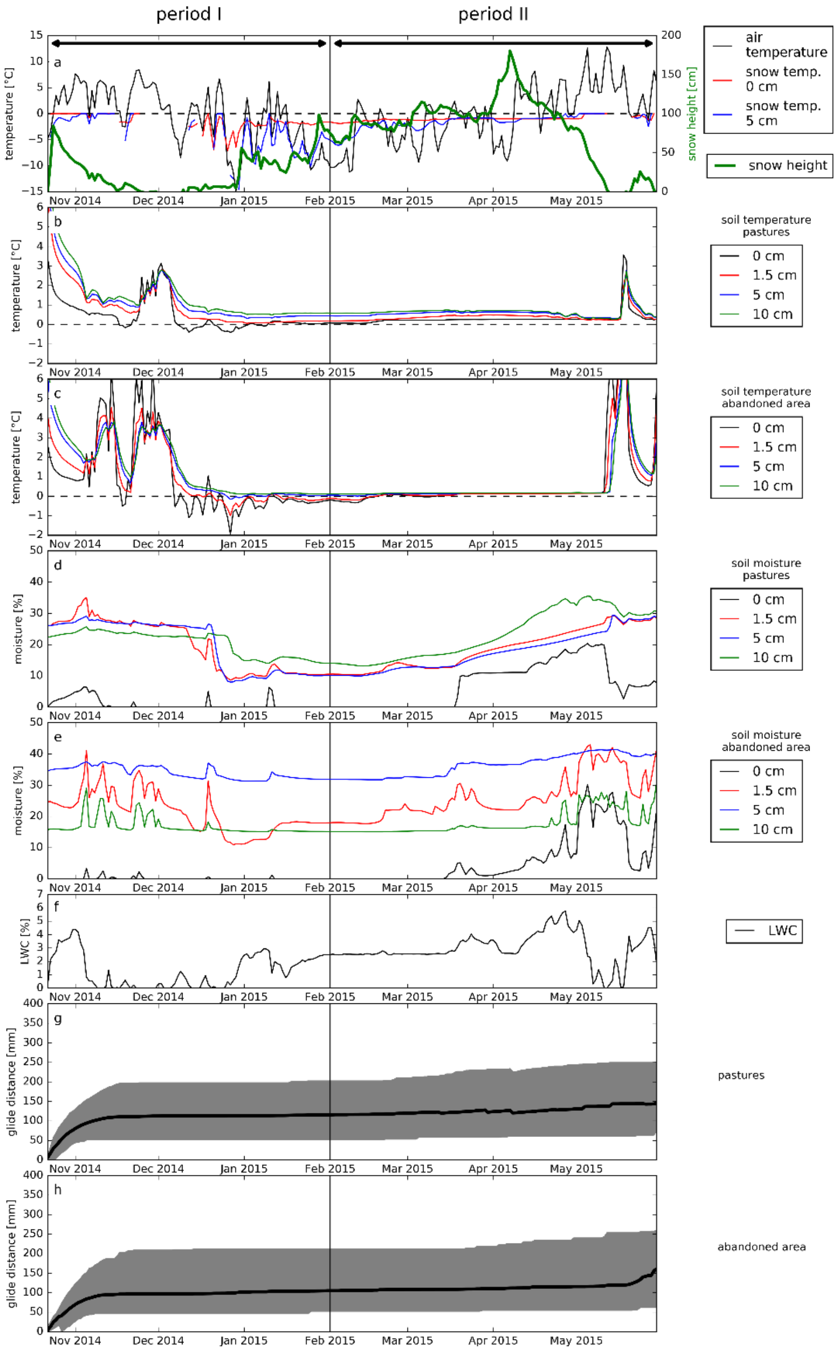


Figure 1. The study area, Wildkogel (Upper Pinzgau, Austria), is characterized by pastures (1), abandoned areas with high cover of dwarf shrubs (2a),) and abandoned areas with high cover of grasses (2b(2). X = automatic weather station. Original data for the climate diagram: www.zamg.ac.at.



period I
period II
a
b
c
d
e
f
g
h
temperature [°C]
snow height [cm]
moisture [%]
LWC [%]
glide distance [mm]
Nov 2014
Dec 2014
Jan 2015
Feb 2015
Mar 2015
Apr 2015
May 2015
air temperature
snow temp. 0 cm
snow temp. 5 cm
snow height
soil temperature pastures
0 cm
1.5 cm
5 cm
10 cm
soil temperature abandoned area
soil moisture pastures
soil moisture abandoned area
LWC
pastures
abandoned area

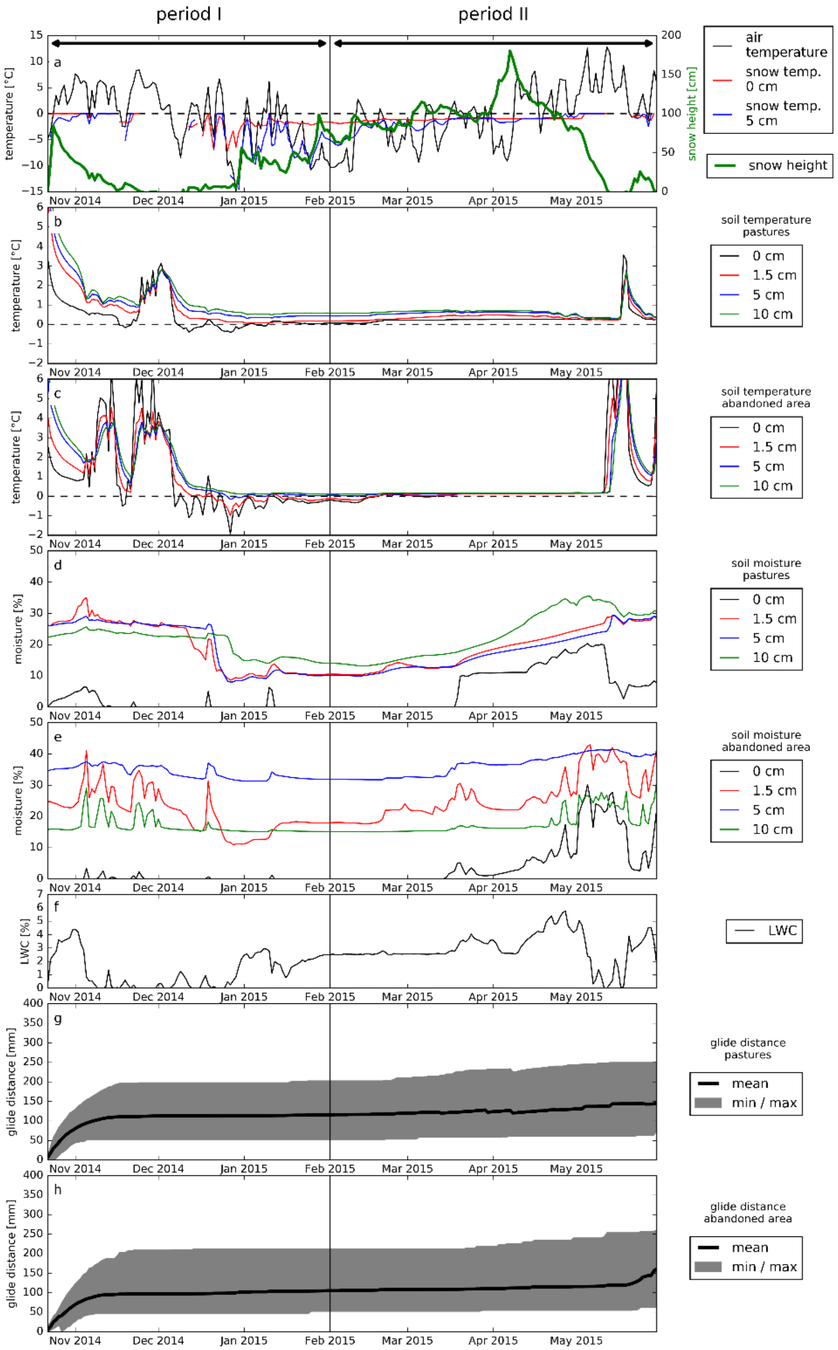
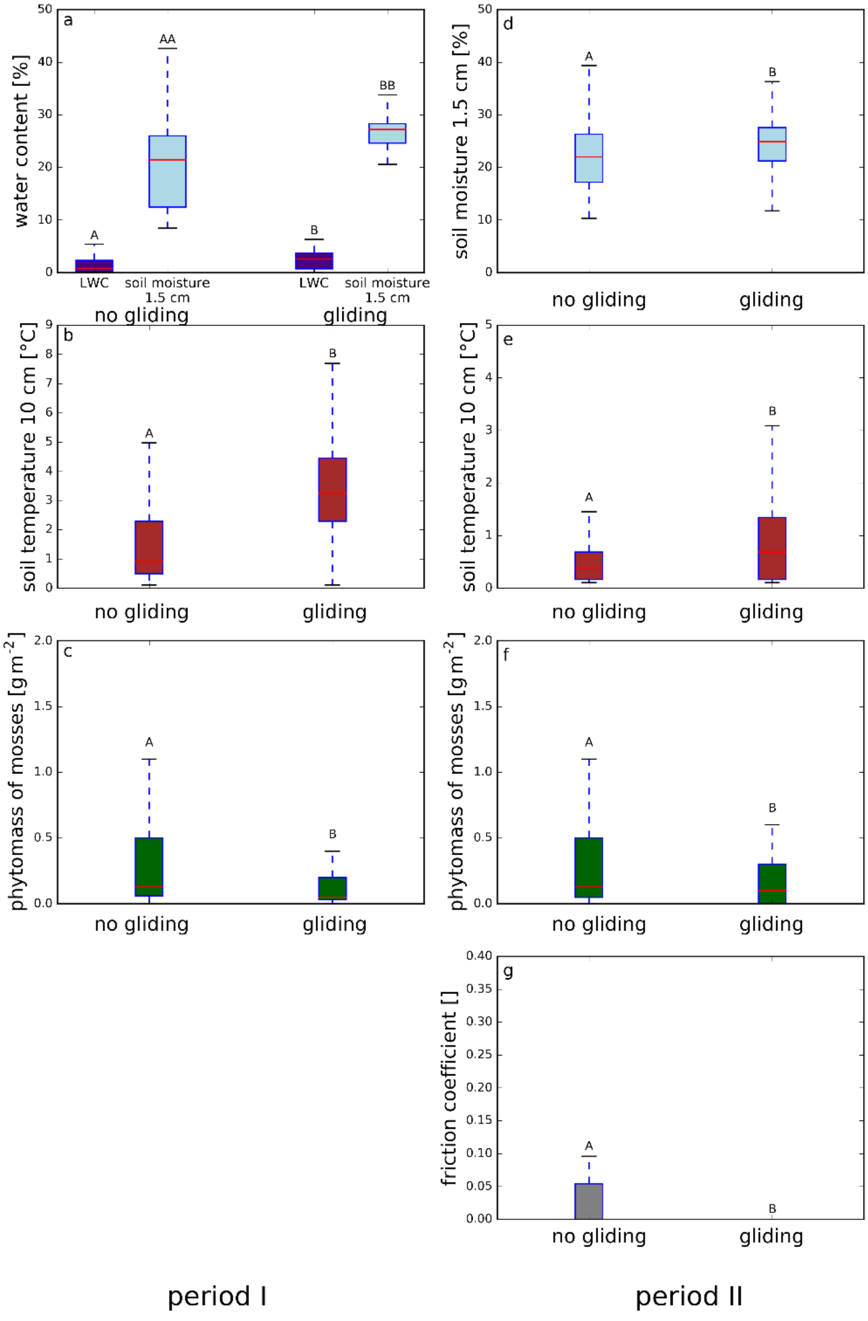

period I
period II
a
b
c
d
e
f
g
h
temperature [°C]
snow height [cm]
moisture [%]
LWC [%]
glide distance [mm]
Nov 2014
Dec 2014
Jan 2015
Feb 2015
Mar 2015
Apr 2015
May 2015
air temperature
snow temp. 0 cm
snow temp. 5 cm
snow height
soil temperature pastures
soil temperature abandoned area
soil moisture pastures
soil moisture abandoned area
0 cm
1.5 cm
5 cm
10 cm
LWC
glide distance pastures
glide distance abandoned area
mean
min / max

Figure 2. Time series of meteorological data, soil climate data, and snow properties.


a
water content [%]
LWC
soil moisture 1.5 cm
no gliding
gliding
A
AA
B
BB
b
soil temperature 10 cm [°C]
c
phytomass of mosses [g m-2]
d
soil moisture 1.5 cm [%]
e
f
g
friction coefficient []
period I
period II

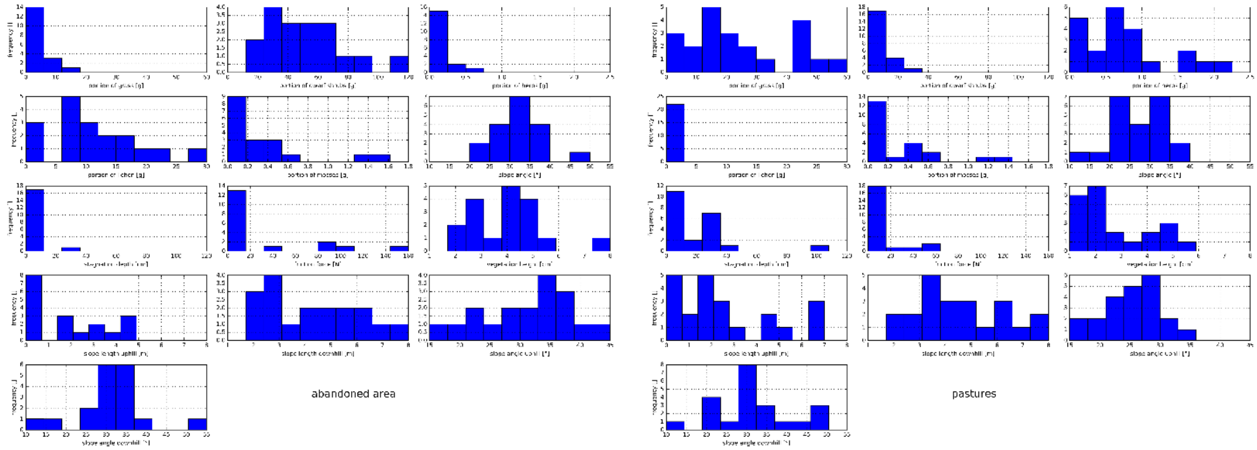


Figure 3. Histograms of topographic properties and vegetation characteristics at the glide shoes.

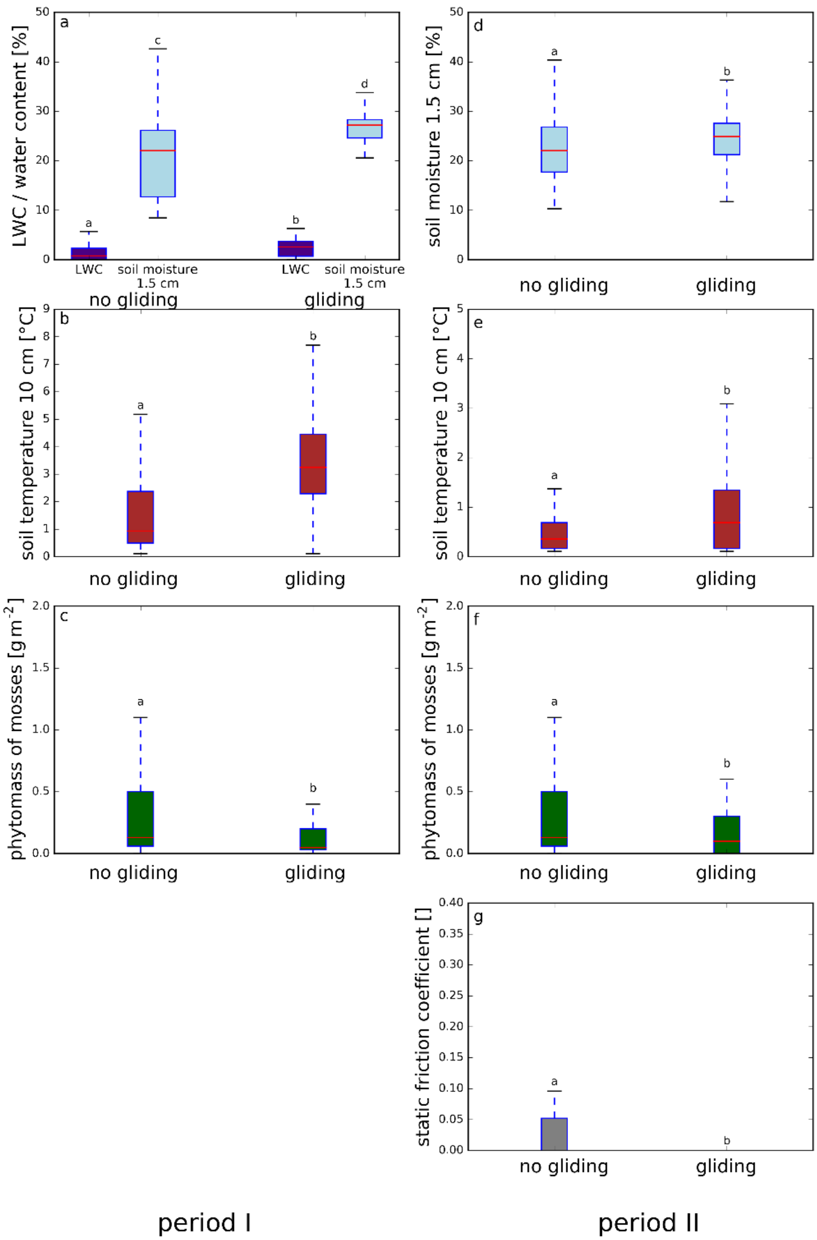
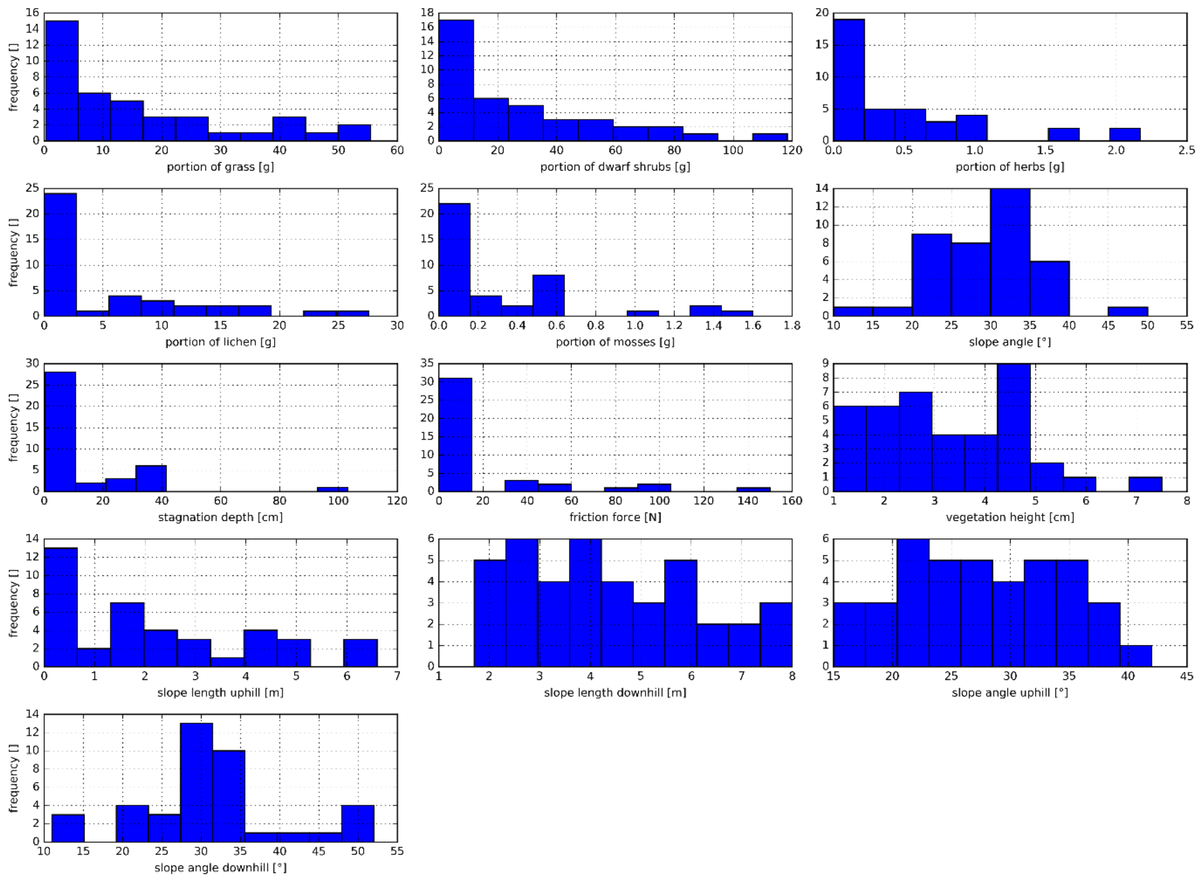


Figure 4. **Boxplots of the most relevant variables in period I and period II (selected according to Tab. 2).** **Differences between the groups are given by different letters and were determined by Whitney–Mann U-test.**

6 Appendix



5 Correlation matrix between all independent variables

	1	2	3	4	5	6	7	8	9	10	11	12	13
1 soil temperature 0 cm		0.90	0.69	0.59	0.04	0.25	0.10	0.31	0.54	-0.39	-0.39	-0.26	-0.38
2 soil temperature 1.5 cm	0.90		0.90	0.83	-0.01	0.32	0.16	0.35	0.39	-0.48	-0.40	-0.20	-0.39
3 soil temperature 5 cm	0.69	0.90		0.98	-0.04	0.36	0.22	0.36	0.22	-0.55	-0.39	-0.11	-0.36
4 soil temperature 10 cm	0.59	0.83	0.98		-0.07	0.36	0.23	0.35	0.15	-0.55	-0.37	-0.08	-0.34
5 soil moisture 0 cm	0.04	-0.01	-0.04	-0.07		0.60	0.09	0.73	0.43	-0.25	-0.22	0.04	-0.19
6 soil moisture 1.5 cm	0.25	0.32	0.36	0.36	0.60		0.75	0.52	0.40	-0.46	-0.29	0.04	-0.25
7 soil moisture 5 cm	0.10	0.16	0.22	0.23	0.09	0.75		-0.03	0.15	-0.10	.002*	0.10	0.02
8 soil moisture 10 cm	0.31	0.35	0.36	0.35	0.73	0.52	-0.03		0.36	-0.53	-0.36	0.03	-0.31
9 snow temperature 0 cm	0.54	0.39	0.22	0.15	0.43	0.40	0.15	0.36		-0.42	-0.57	-0.50	-0.58
10 snow height	-0.39	-0.48	-0.55	-0.55	-0.25	-0.46	-0.10	-0.53	-0.42		0.79	0.27	0.74
11 ice content	-0.39	-0.40	-0.39	-0.37	-0.22	-0.29	.002*	-0.36	-0.57	0.79		0.71	0.99

	14	15	16	17	18	19	20	21	22	23	24	25	26	
1 soil temperature 0 cm	0.27	0.09	0.05	0.00	0.00	0.09	0.05	0.00	-0.01	-.002*	-0.07	0.07	0.00	0
2 soil temperature 1.5 cm	0.23	0.20	0.02	0.01	-0.04	0.07	0.08	0.01	0.01	-0.01	-0.02	0.06	0.02	0
3 soil temperature 5 cm	0.15	0.28	0.00	0.01	-0.08	0.04	0.10	0.01	0.04	-0.01	0.04	0.04	0.03	0
4 soil temperature 10 cm	0.12	0.30	-0.01	0.01	-0.09	0.03	0.11	0.02	0.04	-0.01	0.06	0.03	0.03	0
5 soil moisture 0 cm	0.56	0.02	0.03	0.04	-0.01	0.14	0.12	-0.03	0.02	-0.06	-0.11	0.11	0.03	0
6 soil moisture 1.5 cm	0.53	0.19	0.02	-0.03	-0.03	-0.21	-0.08	-0.01	0.12	0.00	0.20	-0.22	-0.03	-0
7 soil moisture 5 cm	0.23	0.10	0.05	-0.09	0.04	-0.48	-0.32	0.02	0.16	0.05	0.36	-0.47	-0.11	-0
8 soil moisture 10 cm	0.52	0.16	0.03	0.08	-0.09	0.29	0.27	-0.05	-0.01	-0.07	-0.16	0.26	0.08	0
9 snow temperature 0 cm	0.51	-0.11	0.12	0.02	0.02	0.04	0.02	0.01	0.04	-0.04	-0.04	0.04	0.00	-0
10 snow height	-0.33	-0.24	0.05	-0.07	0.12	-0.12	-0.15	0.01	-0.02	0.04	-0.01	-0.13	-0.05	-0
11 ice content	-0.23	-0.11	0.09	-0.05	0.06	-0.10	-0.08	0.01	-0.01	0.06	0.03	-0.12	-0.02	-0

12 LWC	-0.26	-0.20	-0.11	-0.08	0.04	0.04	0.10	0.03	-0.50	0.27	0.71		0.78	0.00	0.02	0.08	-0.03	-.002*	-0.04	0.00	0.03	0.00	0.07	0.02	-0.04	0.00	0
13 snow density	-0.38	-0.39	-0.36	-0.34	-0.19	-0.25	0.02	-0.31	-0.58	0.74	0.99	0.78		-0.21	-0.09	0.09	-0.05	0.06	-0.10	-0.07	0.01	-0.01	0.07	0.03	-0.12	-0.02	-0
14 air temperature	0.27	0.23	0.15	0.12	0.56	0.53	0.23	0.52	0.51	-0.33	-0.23	0.00	-0.21		-0.41	0.23	0.02	0.03	0.04	0.06	-0.06	0.05	0.01	-0.03	0.01	-0.01	0
15 relative humidity	0.09	0.20	0.28	0.30	0.02	0.19	0.10	0.16	-0.11	-0.24	-0.11	0.02	-0.09	-0.41		-0.18	0.03	-0.06	0.02	0.04	0.02	-0.01	-0.04	0.03	0.03	0.07	0
16 global radiation	0.05	0.02	0.00	-0.01	0.03	0.02	0.05	0.03	0.12	0.05	0.09	0.08	0.09	0.23	-0.18		-0.01	0.01	0.01	-0.01	0.01	0.01	0.02	0.00	0.02	0.01	0
17 friction coefficient	0.00	0.01	0.01	0.01	0.04	-0.03	-0.09	0.08	0.02	-0.07	-0.05	-0.03	-0.05	0.02	0.03	-0.01		-0.21	-0.11	0.20	-0.03	0.21	-0.09	0.15	0.10	0.81	0
18 stagnation depth	0.00	-0.04	-0.08	-0.09	-0.01	-0.03	0.04	-0.09	0.02	0.12	0.06	-.002*	0.06	0.03	-0.06	0.01	-0.21		0.00	-0.30	-0.21	-0.06	0.06	-0.61	0.28	-0.24	-0
19 slope angle	0.09	0.07	0.04	0.03	0.14	-0.21	-0.48	0.29	0.04	-0.12	-0.10	-0.04	-0.10	0.04	0.02	0.01	-0.11	0.00		0.20	0.05	-0.38	0.06	-0.37	0.31	0.02	-0
20 slope angle 1 m uphill	0.05	0.08	0.10	0.11	0.12	-0.08	-0.32	0.27	0.02	-0.15	-0.08	0.00	-0.07	0.06	0.04	-0.01	0.20	-0.30	0.20		-0.02	0.11	-0.11	0.08	0.18	0.22	0
21 slope angle 1 m downhill	0.00	0.01	0.01	0.02	-0.03	-0.01	0.02	-0.05	0.01	0.01	0.01	0.03	0.01	-0.06	0.02	0.01	-0.03	-0.21	0.05	-0.02		0.15	0.01	-0.03	0.04	0.03	0
22 slope length uphill	-0.01	0.01	0.04	0.04	0.02	0.12	0.16	-0.01	0.04	-0.02	-0.01	0.00	-0.01	0.05	-0.01	0.01	0.21	-0.06	-0.38	0.11	0.15		-0.37	0.02	0.13	0.15	0
23 slope length downhill	-.002*	-0.01	-0.01	-0.01	-0.06	0.00	0.05	-0.07	-0.04	0.04	0.06	0.07	0.07	0.01	-0.04	0.02	-0.09	0.06	0.06	-0.11	0.01	-0.37		0.01	-0.08	-0.13	-0
24 exposition	-0.07	-0.02	0.04	0.06	-0.11	0.20	0.36	-0.16	-0.04	-0.01	0.03	0.02	0.03	-0.03	0.03	0.00	0.15	-0.61	-0.37	0.08	-0.03	0.02	0.01		-0.68	0.18	0
25 friction force drum	0.07	0.06	0.04	0.03	0.11	-0.22	-0.47	0.26	0.04	-0.13	-0.12	-0.04	-0.12	0.01	0.03	0.02	0.10	0.28	0.31	0.18	0.04	0.13	-0.08	-0.68		0.11	0
26 friction force field	0.00	0.02	0.03	0.03	0.03	-0.03	-0.11	0.08	0.00	-0.05	-0.02	0.00	-0.02	-0.01	0.07	0.01	0.81	-0.24	0.02	0.22	0.03	0.15	-0.13	0.18	0.11		0
27 canopy high	0.05	0.10	0.16	0.18	0.05	-0.05	-0.23	0.21	-0.01	-0.18	-0.08	0.04	-0.07	0.00	0.08	0.01	0.07	-0.45	-0.10	0.45	0.38	0.24	-0.09	0.28	0.13	0.17	
28 phytomass of dwarf shrubs	0.09	0.14	0.19	0.20	0.11	-0.12	-0.44	0.37	0.01	-0.28	-0.17	-0.02	-0.15	0.04	0.10	-0.01	0.23	-0.44	0.18	0.40	-0.05	0.06	-0.12	0.26	0.21	0.22	0
29 phytomass of grasses	-0.11	-0.12	-0.12	-0.12	-0.13	0.27	0.64	-0.40	0.01	0.23	0.17	0.07	0.16	-0.02	-0.09	0.03	-0.06	-0.02	-0.56	-0.31	0.27	0.41	0.09	0.23	-0.29	-0.04	-0
30 phytomass of herbs	-0.05	-0.09	-0.13	-0.14	-0.08	0.00	0.17	-0.22	-0.03	0.16	0.07	-0.02	0.06	-0.08	-0.04	0.01	-0.25	0.51	0.05	-0.33	0.01	-0.14	-0.01	-0.50	0.24	-0.27	-0
31 phytomass of lichens	0.06	0.08	0.09	0.09	0.08	-0.19	-0.46	0.27	0.01	-0.18	-0.12	-0.02	-0.11	0.01	0.07	-0.03	0.47	-0.43	0.13	0.31	0.15	-0.15	0.02	0.28	-0.03	0.43	0
32 phytomass of mosses	0.00	-.002*	0.00	0.00	-0.02	0.04	0.08	-0.05	0.00	0.00	-0.01	0.00	-0.01	0.00	-0.01	0.01	0.03	-0.27	0.05	0.00	-0.09	-0.13	0.15	0.28	-0.20	0.05	-0
33 cover of dwarf shrubs	0.13	0.16	0.18	0.18	0.20	-0.24	-0.69	0.50	0.05	-0.30	-0.21	-0.05	-0.19	0.08	0.08	-0.02	0.18	-0.31	0.43	0.51	-0.03	0.03	-0.18	-0.08	0.39	0.18	0
34 cover of grasses	-0.13	-0.15	-0.17	-0.17	-0.19	0.28	0.74	-0.51	-0.04	0.30	0.21	0.06	0.20	-0.06	-0.09	0.02	-0.22	0.33	-0.45	-0.52	-0.01	0.07	0.11	0.04	-0.35	-0.22	-0
35 cover of herbs	-0.02	-0.06	-0.10	-0.11	-0.04	-0.08	-0.02	-0.11	-0.02	0.10	0.03	-0.02	0.03	-0.06	-0.03	-.002*	-0.20	0.70	0.13	-0.18	-0.04	-0.18	0.00	-0.64	0.47	-0.23	-0
36 cover of lichens	0.05	0.07	0.08	0.08	0.05	-0.17	-0.39	0.21	-0.01	-0.14	-0.08	-0.01	-0.08	-0.01	0.06	-0.02	0.23	-0.38	0.18	0.25	0.17	-0.24	0.15	0.28	-0.13	0.25	0
37 cover of mosses	-0.04	-0.05	-0.05	-0.05	-0.08	0.11	0.26	-0.18	-0.02	0.07	0.03	-0.02	0.02	-0.04	-0.02	-0.01	-0.11	-0.05	0.00	-0.10	-0.11	-0.26	0.14	0.22	-0.35	-0.11	-0

~~Histograms of topographic properties and vegetation characteristics at the glide shoes.~~