

Response to Reviewer comments

Response to Reviewer 1

General Comments

In this paper, the authors investigated changes in soil characteristics and water flow through time by examining a chronosequence of soils from a retreating glacier. The study is very thorough, detailed, and makes conclusions that I think are novel and interesting to the community. The paper is mostly very well written and structured, but I have a few areas of concern and/or need for clarification, detailed below.

Response to General Comments

The authors would like to thank the reviewer for spending his/her time to review and make valuable comments to improve our manuscript. We will address these comments and suggestions below.

Specific Comments Issue 1:

Hypotheses. I think the hypotheses in lines 9-13 on page 3 could be improved or re-stated as research questions. In general, I think they are a bit vague for hypotheses. For example in (1), what does “change” mean?, in (2) what does “more important” mean? And (3) what process is hypothesized to lead to a reduction in particle size and/or increase in porosity and/or increase in subsurface water storage? And for (3) should this be more than one question? It hits a few different predictions/questions.

I think the wording used when addressing the hypotheses in the conclusion is also a bit strong. I think there’s an argument to be made that it is okay to say “confirmed” about a hypothesis, just being careful to avoid “proved” but it gave me pause. I think the conclusion could benefit from a few statements identifying the uncertainty in the set up and analysis and then caching the “confirmation” of the hypotheses in those terms.

Response to Specific Comments Issue 1:

We agree and will specify and rephrase our hypotheses to:

More specifically, we test the hypotheses that (1) Vertical subsurface flow path types and vertical extent change through the millennia as: (2) The proportion of macropore flow will increase due to the development of biopores, (3) The soil develops from a homogeneously mixed material into a depth differentiated soil system, and (4) Physical weathering leads to a reduction in particle size and an increase in porosity.

Specific Comments Issue 2:

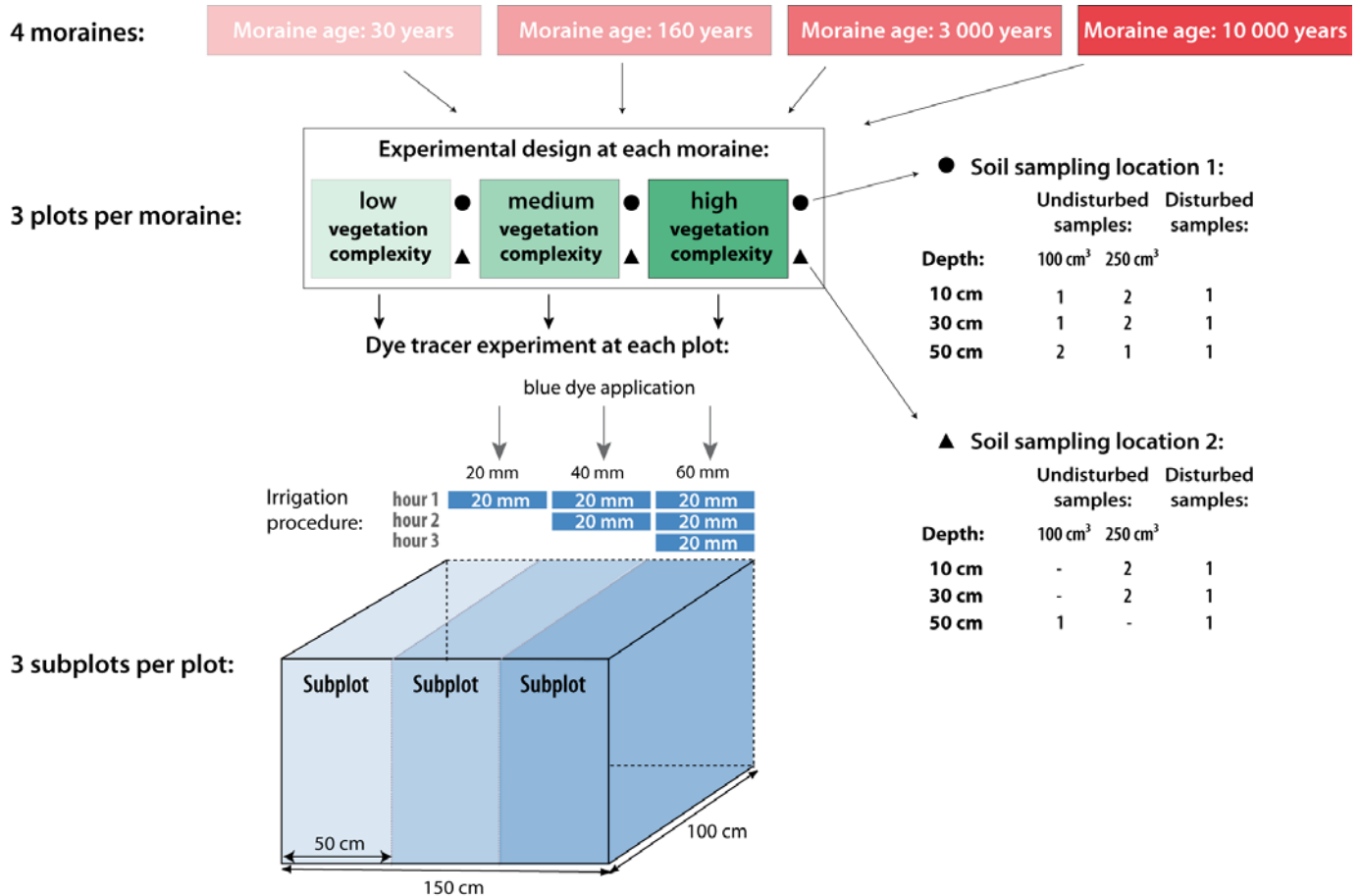
Description of the study design. I had to read through the methods several times, taking notes and adding up samples from “plots” and “subplots” trying to be sure I understood where the data was coming from. I think the section would benefit from a paragraph in 2.2 that makes very clear: how many plots are there in each moraine? How far away are they from each other? (can this also be shown in Figure 1?) are there subplots in every plot or just the dye application plots? I realize this information is all included in the paper, but it’s scattered throughout the methods so some piecing together was required for me to figure it out.

Response to Specific Comments Issue 2:

We agree with this comment and will restructure this paragraph on the plot selection, soil sampling and subdivision of the plots during the irrigation experiment to make it more clear that at each moraine three experimental plots were selected, which differ in vegetation complexity (low, medium, high) and that sets of soil samples were taken close to each of these three plots, but are presented as a single set

for the entire moraine. For the irrigation experiments each plot was further divided into three subplots for the application of three individual irrigation amounts. Also the image analysis was done individually for each of the subplots. We will also make it clear in the caption of Figure 1 that we here show only one of the 3 plots per moraine.

It is difficult to provide an overview of the plot locations at all moraines, since the plots were located several meters (10-100m) apart. But we will include this information in the text. To clarify the study design further, we will include a sketch that visualizes the experimental design of the field campaign and contains the information about the plot selection and subdivision as well as the soil sampling scheme (see below).



Specific Comments Issue 3:

Heterogeneity. I think it'd be good to have more discussion about the heterogeneity in these moraines, then how that heterogeneity was addressed in the study design and how it affects the interpretation of the results. Would you expect these moraines to be pretty homogeneous? If not, how were the heterogeneities accounted for, and how likely is it that the results might be different if the sites were placed differently?

Response to Specific Comments Issue 3:

We agree with this comment and will add at the end of the Discussion of the Evolution of soil texture and structure the following paragraph to address this issue:

It is well known that soil properties are spatially heterogeneous [Bevington et al. (2016) Hu et al. (2008)]. As it was not possible to account for this variability with a large sample size, i.e. with a large number of experiments, we decided to take a different approach: Assuming that vegetation cover and subsurface

flow paths are strongly linked, we took the variability in vegetation cover as a proxy and used it in an attempt to bracket this variability: per moraine three locations that differ in their vegetation complexity (low, medium, high) were chosen for soil sampling and the dye tracer experiments. The analysis of the structural soil properties shows that there is a slight increase in spatial heterogeneity with age, especially in the top soil (increase in interquartile range in Fig. 4), but also individual depths at different age classes show occasionally a higher heterogeneity.

The flow path analysis differentiated according to the vegetation complexity showed no systematic influence of the complexity level on the results. Heterogeneities within the individual experimental subplots were considered by averaging the volume density and surface area density profiles of the five vertical profiles per subplot. We therefore assume that the results of the flow path analysis are representative and account for the heterogeneity of the moraines.

Specific Comments Issue 4:

Discussion structure. This discussion does a good job of putting the findings of the paper in context with previous work, but could you also add some information about how these changes are happening? Having processes tied to the changes would be really helpful for applying the findings here to other places. There is a bit of discussion about this with regards to vegetation and flowpaths, but not so much with the texture and structure. Additionally, in the first part of the discussion findings are sort of point-by-point related to previous literature. I wonder if the readability of the section might be improved by restructuring a bit to talk about how some of the changes in texture and structure happen together rather than breaking them all into separate paragraphs. There are a lot of findings here, and I realize that makes it kind of hard to present them concisely, so it's just a suggestion. But maybe similar processes are leading to the changes observed, and discussing those processes and the results may help.

Response to Specific Comments Issue 4:

We agree with this comment and will add a paragraph on the processes affecting the soil texture and structure:

A high fraction of silt is very common for soils in mountain areas (Ellis, 1992). Physical weathering due to high fluctuations between day and night temperature and freezing cycles (Birse, 1980) leads to a reduction in grain size, without changing the particle mineralogy (Ellis, 1992).

The break down in grain size also influences the bulk density and porosity of the soil. Whereas sandy soils have a high bulk density, the breakdown of particles leads to an increase in total pore space (porosity) and thus to a reduction in bulk density. Soils enriched in organic matter content also have a lower bulk density [Neris et al. (2012), Carey et al. (2007)].

We will also restructure the discussion to improve readability.

Technical Corrections

Page 6 Line 15 parameter should be plural

We agree

Page 6 Line 24 should "amount" be "number"?

We agree

Page 7 Line 6 I think the comma after "both" can be removed

We agree

Page 7 Lines 22 and 29 can you add a note explaining what you mean by disturbed and undisturbed? I assume the structure was preserved in the undisturbed sample...but they were both removed from the site, so they were definitely disturbed!

We will include clarifications in section 2.4 *Soil sampling and laboratory analysis* to point out that disturbed samples are samples taken without maintaining the natural soil structure and undisturbed samples were taken with sample rings to provide undisturbed cores which maintain the natural soil structure.

Page 16 Line 14 maybe “agree” would be better than “correspond”?

We agree

Page 18 Line 17 add “age” after “increasing moraine”

We agree

Page 18 Line 17 what is unstable flow?

Unstable flow occurs when wetting fronts start out as horizontal wetting fronts that, under certain conditions, break into fingers or preferential flow paths as the front moves downwards (Hendrickx, 2001) For clarification we will include the sentence and the reference.

Page 18 Line 27 maybe use a different word than “significantly” since it isn’t a statistical Comparison We agree

Page 18 Line 27 see = saw

We agree

Page 20 Line 12 remove “also”

We agree

Page 20 Line 33 remove “already”

We agree