Dear Editor,

We would like to thank you for giving us the opportunity to revise our manuscript. We have revised the manuscript entitled "Field observations of soil hydrological flow path evolution over 10 Millennia" in response to your and the reviewers' comments. Please find attached a revised version of this manuscript as well as a detailed list of our responses to these comments.

We are grateful to you and the reviewers for your interest in our paper and for the detailed evaluation, valuable suggestions, and recommendations. As you will see when examining our revision, the reviewers' comments and recommendations were considered seriously and thoroughly addressed in our revised paper. The four main changes that we have made are as follows:

1. We rephrased our hypothesis to be clear and more specific.
2. We improved the description of the methods.
3. We improved the structure of the discussion.
4. We corrected our terminology to preferential flow paths

Additionally, we have addressed all other comments and suggestions.

We further extended section 2.3. Image analysis by a processing step that was unintentionally not included in the first manuscript version. We therefore updated former Figure 2 (now Figure 3) and included the missing explanations in line 167 to 170:

Due to poor lighting conditions or a heterogeneous background color distribution in the soil caused by material transitions, small stones or organic matter, the image analysis software was not able to recognize all large dye stains as coherent objects. Thus, a manual correction of the images using the photographs was necessary (see Fig 3).

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 specified and rephrased our hypotheses in lines 75 to 80 to:

Therefore, this study addresses the occurrence and the evolution of preferential flow during the first 10000 years of landscape evolution in glacial moraines in the Swiss Alps. More specifically, we test the hypotheses that (1) Vertical subsurface flow path types and vertical extent of flow paths 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 restructured this paragraph on the plot selection, soil sampling and subdivision of the plots during the irrigation experiment.
To clarify the study design further, we split Figure 2 into two Figures. The updated Figure 2 shows an illustration of 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).

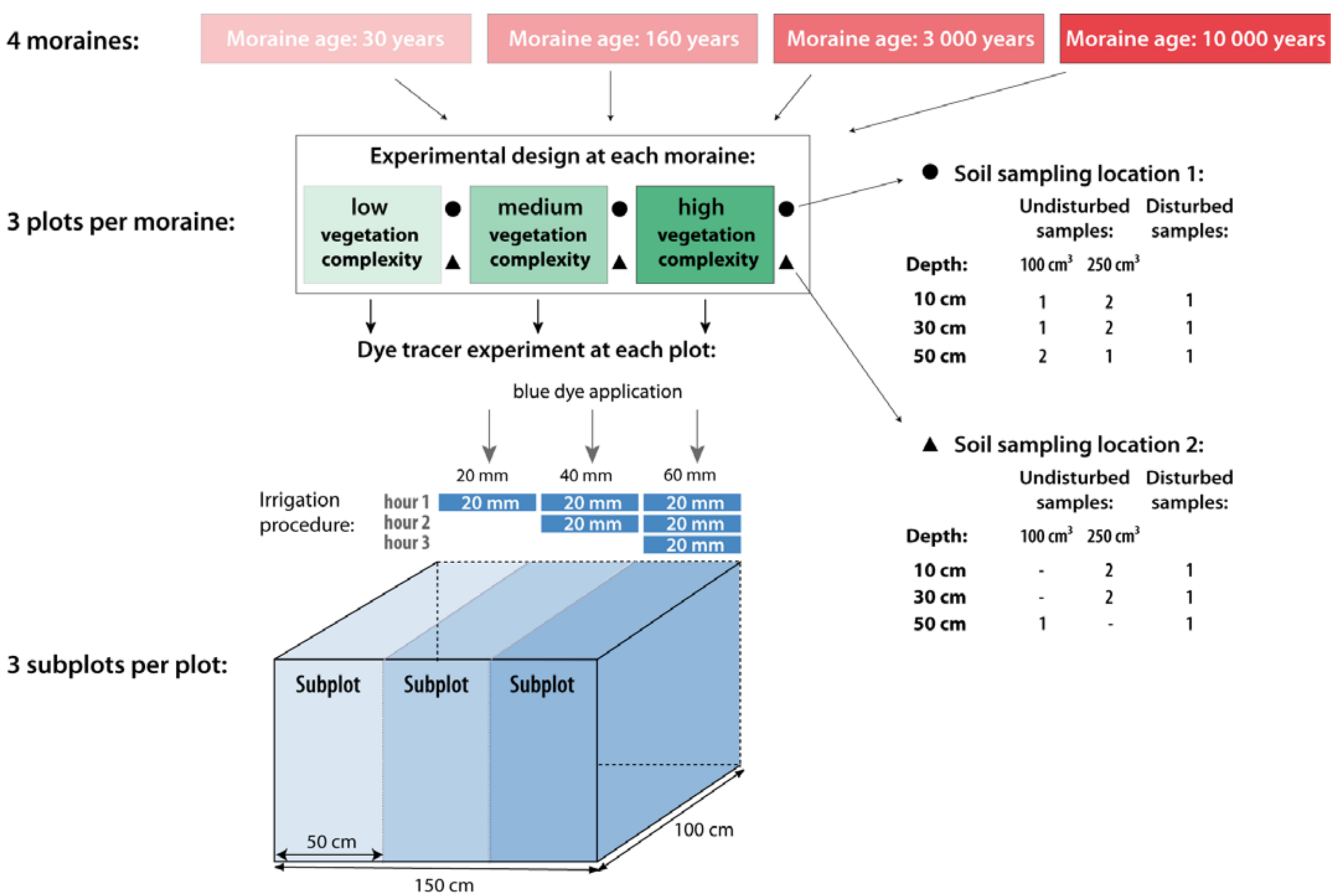


Figure 2: Illustration of the experimental design and soil sampling scheme at each moraine.

We also made it clear in the caption of Figure 1 that we here show only one of the 3 plots per moraine. New caption text in Figure 1: *Location (left) and surface cover (right) of the four selected proglacial moraines of the Stein glacier. White circles show locations of one of the three brilliant blue experiment* *plots per age class. Photo of location is provided by Google (n.d.). Photos of the 30, 160, and 10 000-year-old moraine were taken after the brilliant blue experiment (photos taken by F. Lustenberger).*

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 in Line 131:
The distances between the three study plots at each moraine ranged from 10 to 100 m.

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 added at the end of the Discussion of the evolution of soil texture and structure the following paragraph from line 412 to 424 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 ranges for all properties in the top layer in *Fig. 6), but occasionally also individual depths show a higher heterogeneity, irrespective of age.*
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 taken into account by averaging the volume density and surface area density across the five vertical profiles per subplot instead of relying on individual profiles. We therefore assume that the results of the flow path analysis are sufficiently representative to investigate their evolution across the chronosequence. .

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 and restructured the discussion to improve readability. Instead of going through the soil physical characteristics one by one we are now discussing the different development stages jointly in all their characteristics.

We also added a paragraph on the processes affecting the soil texture and structure in Line 382 to 384:
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).

And in Line 356 to 362:
After 160 years of soil development the porosity in the top layer increased and bulk density decreased. In general, these changes could be linked to changes in grain sizes, as the breakdown of particles leads to an increase in total pore space (porosity) and thus to a reduction in bulk density (Arvidsson, 1998). However, since changes in grain sizes were only marginal, the vegetation development, which includes an increase in root activities, litter accumulation, and biological activities in the root zone, is likely the main cause for changes in bulk density and porosity [Neris et al. (2012), Carey et al. (2007)].

Technical Corrections
Page 6 Line 15 parameter should be plural
We agree and included the correction (see Line 172)
Page 6 Line 24 should "amount" be "number"?
We agree and included the correction (see Line 179)
Page 7 Line 6 I think the comma after "both" can be removed
We agree and included the correction (see Line 198)
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 included 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:

See Lines 213-214: *For grain size analysis, two disturbed bulk soil samples per depth were taken at 10, 30, and 50 cm depth at each plot.*

And Lines 224-225: *For the analysis of the structural parameters soil samples were taken with sample rings to provide undisturbed cores which preserve the natural soil structure.*

Page 16 Line 14 maybe “agree” would be better than “correspond”?
We agree and included the correction (see Line 379)
Page 18 Line 17 add “age” after “increasing moraine”
We agree and included the correction (see Line 458)
Page 18 Line 17 what is unstable flow?
We agree and included a further explanation in line 459 to 4608:
Thus, we conclude that hydrophobicity of the organic top layer has a big impact on infiltration and the initiation of unstable flow. Unstable flow occurs when horizontal wetting fronts break into fingers or preferential flow paths during the downward movement (Hendrickx and Flury, 2001).

Page 18 Line 27 maybe use a different word than “significantly” since it isn’t a statistical Comparison and Page 18 Line 27 see = saw

We agree and included the correction (see Line 473):
At the oldest moraine, we saw a distinctly shallower infiltration depth.
Page 20 Line 12 remove “also”
We agree and included the correction (see Line 506)
Page 20 Line 33 remove “already”
We agree and included the correction (see Line 530)

Response to Reviewer 2, Nicholas Jarvis

General Comments

This paper presents the results of dye tracing experiments showing how the mechanisms of preferential flow (PF) change with soil development in alpine moraines exposed by glacial retreat. This work culminates in a very nice schematic diagram (Figure 9) that summarizes and illustrates the main findings. The main strength of the paper is that the study of PF from this kind of pedological perspective is still really quite novel.

Nevertheless, the authors are not the first researchers to have taken this kind of pedological approach and it would strengthen the paper if some of this relevant earlier work could be mentioned in the Introduction. The authors could check out Quisenberry et al. (1993), Lin (2003), Cammaraat and Kooijman (2009) and Jarvis et al. (2102).

Another interesting and rather novel aspect of the paper is the demonstration of the importance of stones and rocks for generating and maintaining preferential flow. Maybe the authors could also cite Bogner et al. (2014), who demonstrated the same thing.

The paper is generally well written and presented and easy to read, although the language could be improved further by a native speaker. One minor concern is that the author's use of terminology related to PF is, at times, unnecessarily confusing. I have two other criticisms. First, the methods are not described in sufficient detail. Secondly, the authors could do a better job of discussing their results with respect to the fundamental processes causing the observed changes in flow patterns. These aspects are explained more fully in the following.

Response to General Comments

We thank the reviewer for spending his time to review and improve our manuscript. We will address all concerns and suggestions below.

We appreciate the references to further literature and included some of the references in line 82-84:

This sort of hydropedological approach (Lin 2003) that links pedon (Quisenberry et al., 1993), landscape (Cammeraat and Kooijman, 2009) and hydrologic processes studies is likely to open up new insights into the preferential flow phenomenon (Jarvis et al. 2102).

And in line 489 to 490 we included the sentence:

The tendency of higher rock contents to increase the number of flow paths was also found by Bogner et al. (2014).

Specific Comments Methods:

Methods: It was not clear to me what aspects of the vegetation cover were actually measured. For example, you use the term "mapped" on page 4 at line 15, but this is a rather vague. Do you have measurements of anything like above-ground biomass or was only species composition recorded? Please write this more explicitly. The description of vegetation complexity on page 5 at lines 2-4 is also not very helpful. Can you give a brief description here, maybe with an equation? The reader should not have to consult another paper (Musso et al.).

Response to Specific Comments:

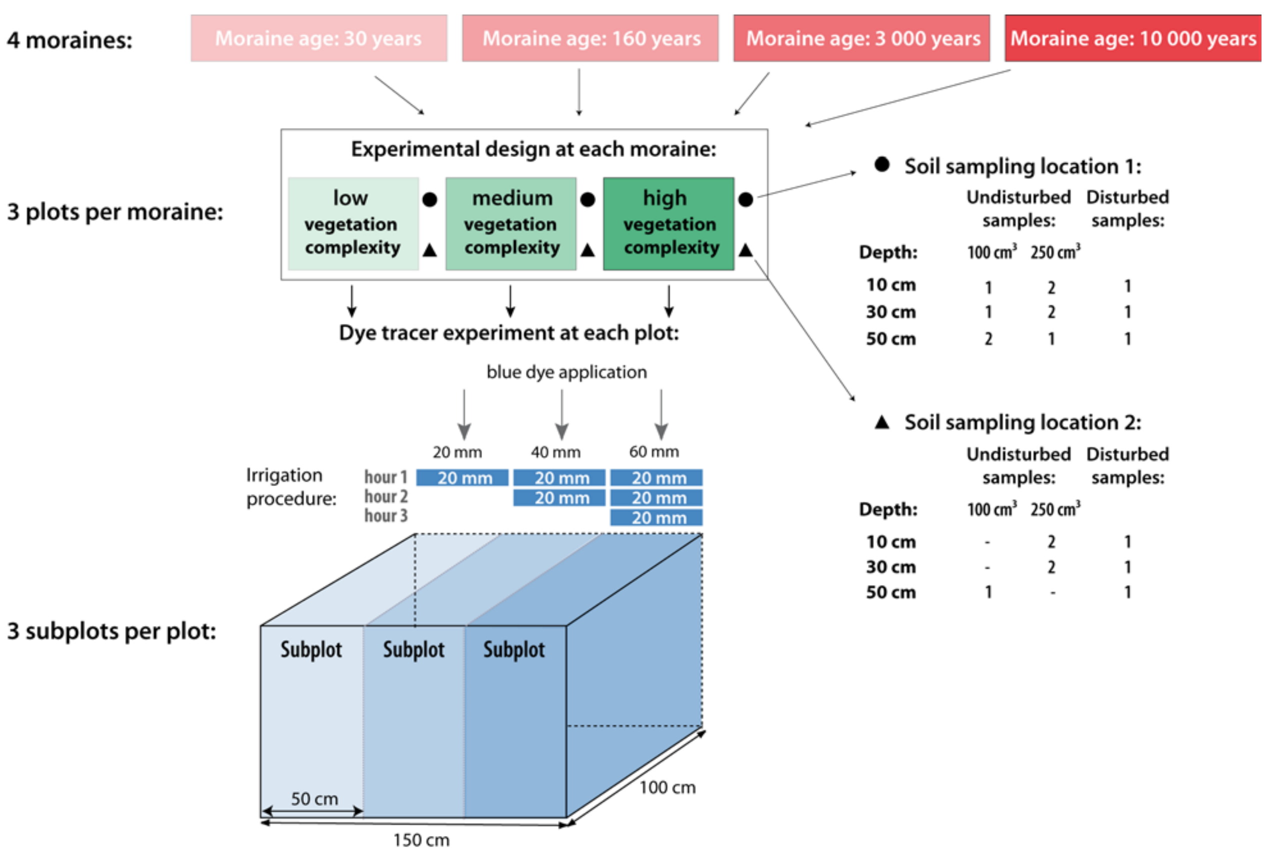
We agree with this suggestion and added this explanation in lines 125 to 130:

Three study plots were selected at each moraine, based on degree of vegetation complexity (low, medium and high complexity). Vegetation complexity is characterized by vegetation coverage, number of species and the plant functional diversity. The functional diversity is calculated based on specific leaf area, nitrogen content, leaf dry matter content, Raunkiaérs life form, seed mass, clonal growth organ, root type and growth form. The collection of *the required data and calculation of the vegetation complexity was done by the Geobotany Group of the University of Freiburg and is described in more detail in Maier et al. (2019).*

Please note that we moved this part from chapter 2.1 to chapter 2.2 Field experiments.

The description of the irrigation procedure on page 5 (lines 15-18) was quite difficult to Follow. It seems as if the irrigation pattern was different between the plots. Why was that? Perhaps a schematic figure might help to explain this.

Response to Specific Comments:
We agree with this comment and have clarified the procedure. We restructured the entire paragraph on plot selection 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). For the irrigation experiments each plot was further divided into three subplots for the application of three individual irrigation amounts.
We also split Figure 2 into two Figures and included an illustration of the dye tracer plot and the stepwise irrigation scheme into a separate Figure (now Figure 2) that shows the experimental set up of the field campaign in more detail:



Soil sampling location 1	Undisturbed samples: 100 cm³	Undisturbed samples: 250 cm³	Disturbed samples
10 cm	1	2	1
30 cm	1	2	1
50 cm	2	1	1

Soil sampling location 2	Undisturbed samples: 100 cm³	Undisturbed samples: 250 cm³	Disturbed samples
10 cm	-	2	1
30 cm	-	2	1
50 cm	1	-	1

Figure 2: Illustration of the experimental design and soil sampling scheme at each moraine.

We also updated the description of the irrigation procedure in lines 140 to 150 as follows:

The tracer was applied with a hand-operated sprayer connected to a battery powered pump which guaranteed a constant pressure for a uniform flow rate of 60 l/h. For a time-efficient irrigation of the *three subplots with three irrigation amounts (20, 40, and 60 mm) and an intensity of 20 mm/h, the irrigation procedure was divided into three steps. In the first step all three subplots were irrigated simultaneously for 60 minutes in a sequence of 5 minutes irrigation and 5 minutes break. This provides an application of 20 mm to all three subplots. After finishing the first step the first subplot was covered to avoid any additional water input. In a second step, the other two subplots were simultaneously irrigated for additional 60 min in a sequence of 5 min irrigation and 10 min breaks. This provides an application of additional 20 mm to the two remaining subplots. In the last step only the third subplot was irrigated for 60 min in a sequence of 2 min irrigation and 10 min breaks while the other two plots remained covered providing an additional 20 mm to this last remaining subplot. After the end of tracer application, the entire plot was covered to avoid any disturbance by natural rainfall.*

The method to classify the flow patterns into different groupings is described only very briefly (on pages 6/7) and it was also difficult to follow. To complement the text (e.g. at lines 28-30 on page 6), could you give an equation or perhaps include a schematic diagram (or both)? This procedure is quite central to the paper, so it is important to explain this carefully.

Response to Specific Comments:

We agree with your suggestion and included a ternary diagram after Weiler (2001) (see below) that shows which flow type is assigned to which proportions of the 3 stained path width classes in terms of volume density in Line 191:

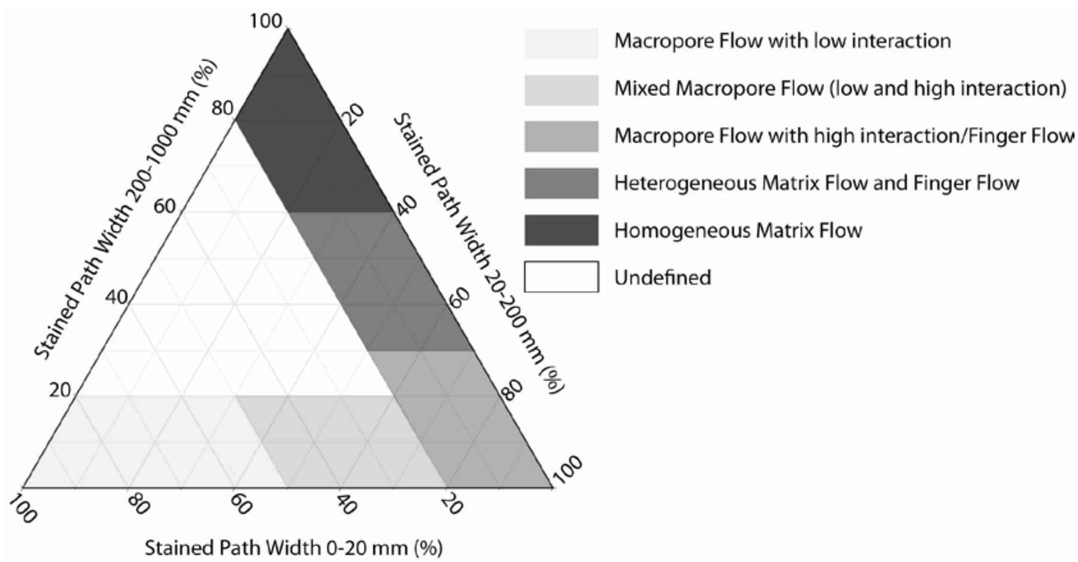


Figure 4 Flow type classification based on the proportion of the three stained path width classes: ternary diagram after Weiler (2001).

The description of the particle size analysis on page 7 makes no mention of the gravel/stone fraction (>2 mm). Did you measure the content of stones/gravel? I know this is very difficult in stony soils, so it is understandable if you didn't, but I think this should be stated.

Response to Specific Comments:
We added information about the measured gravel/stone fraction >2mm as a subfigure to the display of the soil texture results in Line 252:

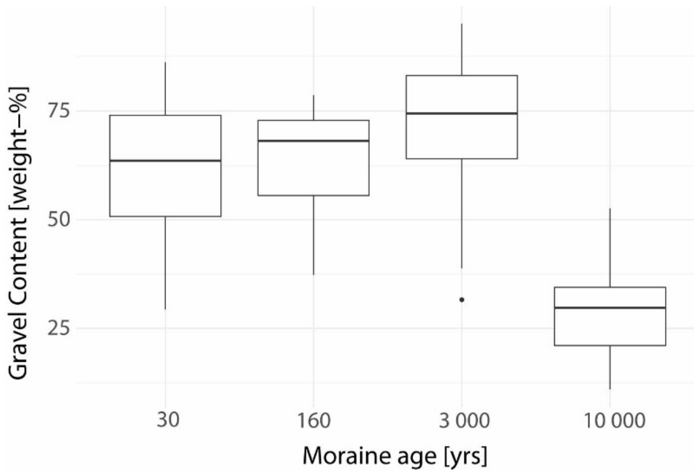


Figure 5. (a) Profile averaged grain size fractions for the four moraines. Fractions are percentages of the fine earth fraction (< 2 mm). (b) Profile averaged gravel content (> 2mm) calculated as the percentage of the entire sample weight. Each average is based on 18 samples.

We also updated section 2.4 Soil sampling and laboratory analysis by the method used for the stone and gravel content measurements in line 220-223:
Grain size fractions of particles < 2 mm were calculated as weight percentages of total weight of particles <2mm, thus excluding gravel and stones to avoid that single larger stones shift or dominate the distribution. The gravel and stone fraction was calculated separately as a weight percentage of the entire soil sample.

The description of how bulk density and porosity were measured (page 7, lines 31-32) is quite vague. Can you describe more exactly (but still briefly) how you measured bulk density and (especially) porosity? It would be good to give some details, because the porosity values are extremely small in the young moraine and in the subsoils. I suppose this is because of the high stone content, but it could also be because air got trapped in the samples during saturation.

Response to Specific Comments:
We agree with this comment and included some further explanation on the methods used in line 229-233:

The porosity was determined in the lab using the water saturation method. For this method sample weights were recorded at saturation and after drying at 105 °C. For saturation, the samples were placed in a small basin. The water level in the basin was increased step wise by 1 cm per day. When the water level reached the top of the soil sample and the sample was fully saturated, the bottom of the sample was sealed and the weight at saturation was measured. Bulk density was determined by relating the dry mass after drying at 105 °C to the sample volume.

The authors do not report any measurements of soil organic matter content (SOM). This data should ideally be included in the paper, as the build-up of SOM over millennia due to the growth of vegetation seems to be a very important control on the observed changes in the flow patterns. If SOM was not measured, then I think it should be measured now and the results included in the paper (the analysis is quick and cheap).

Response to Specific Comments:
We have included the SOM data in the revised manuscript as an additional subfigure to the results of porosity and bulk density in Figure 6, Line 256:

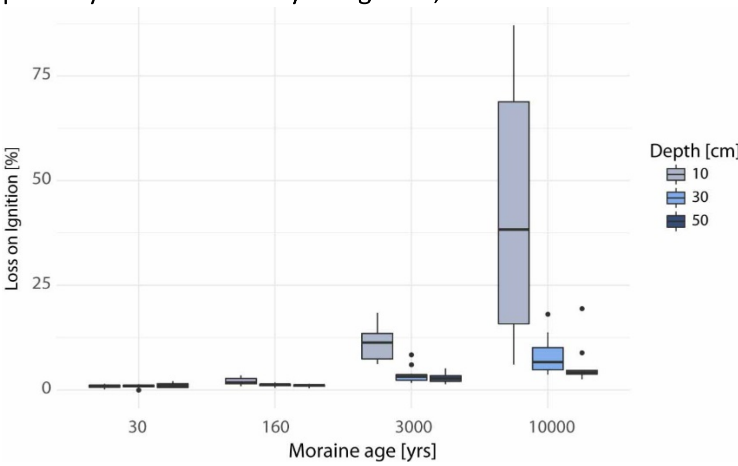


Figure 6. Evolution of soil porosity (a) bulk density (b) and loss on ignition (c) in 10, 30, and 50 cm depth.

We further updated section 2.4 Soil sampling and laboratory analysis by the method used for the estimation of Loss on Ignition in line 233 to 236:

The loss on ignition is a measure of the organic substance in the soil and describes the proportion of the organic substance that was oxidized during annealing for 24 hours at 550 °C. The loss on ignition was determined by drying sub-samples (4-6 g) for at least 24 hours at 105 °C and then at 550 °C. The ignition loss is then calculated by relating the weight loss after drying at 550 °C to the sample weight after drying at 105 °C.

We also updated the results section 3.1 soil texture and structural parameters by the description of the results of loss on ignition in line 264 to 271:

The loss on ignition, as a measure for the organic matter content, shows an increase throughout the first 10 millennia of soil development, which is most pronounced in the upper soil layer (see Fig. 6(c)). At the two youngest moraines the organic matter content is still very low (< 2 weight-%). At these two age classes the organic matter content is homogeneously distributed over the profile, with a slight tendency to higher values in the topsoil at the 160-year-old moraine. The 3000-year-old moraine shows a strong increase in organic matter content in the surface layer. At the oldest moraine the trend of increasing organic matter continues in all three depths. Here, the organic matter content in the topsoil makes up to two-thirds of the soil material. However, the organic matter content varies distinctly with a minimum of 6 weight-% and a maximum of 87 weight-%. In deeper depths, the organic content also increases compared to the 3 000 year old soil, but remains below 20 weight-%.

Specific Comments Processes:

Processes: Can you explain (e.g. on page 16, lines 9-17) why the texture becomes finer with age? Is it due to weathering or is it deposition of fine materials by wind, or maybe both (or something else)? The cause(s) might be obvious to the authors, but perhaps they will not be to all readers.

Response to Specific Comments:

We agree and included some further clarification in line 382-384:

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 process(es) operating to increase porosity and decrease bulk density should be explained better (e.g. on page 16, line 20, and lines 33-34). I presume that it is mostly related to a build-up of organic matter in the soil, which is supplied by the litter and roots of the increasingly dense vegetation cover and subsequently processed by soil micro-organisms and fauna, which ultimately results in a more open (aggregated) soil structure.

Response to Specific Comments:

We agree and included a sentence on that the linkage between the decrease in bulk density and vegetation development is caused by root activities, litter accumulation, and biological activities in the root zone in line 358-360:

However, since changes in grain sizes were only marginal, the dense vegetation development, which includes an increase in root activities, litter accumulation, and biological activities in the root zone, is likely the main cause for changes in bulk density and porosity [Neris et al. (2012), Carey et al. (2007)].

And in line 387-391:

The continuous increase in porosity and reduction in bulk density can be attributed to the continuing change in soil texture on the one hand and on the other hand to the pronounced vegetation development. Especially the latter with the resulting accumulation of soil organic matter (see Fig. 6(c)) and the growth of an even denser root network that is now over 35 cm deep, is the main cause for the pronounced changes in the top soil.

The authors associate the homogeneous flow patterns found in the young moraine with "gravity-driven" water flow (e.g. on page 15, line 2; page 18, line 2; page 20, line 21). This is rather misleading to my mind. Fundamentally, it must be the case that both gravity and capillarity were driving the infiltration process in all your experiments, because the soils were (presumably) initially quite dry. In fact, the authors do not really need to discuss whether gravity or capillarity dominated the flow patterns in the different moraines, but if they want to do so, then I think in reality, it is the opposite of what they write. Both macropore flow and finger flow are gravity-dominated processes, whereas a homogeneous flow pattern implies that capillarity was strong enough to prevent the development of any lateral non-equilibrium in soil water pressures. It is this lateral non-equilibrium in water pressures during flow that is a fundamental characteristic of PF.

Response to Specific Comments:

We removed the reference to gravity-driven flow. However, soils were generally quite wet during the entire field campaign as the total rainfall amount in this region is quite high and hence the soils never really dry out.

The coarse textured soil at the youngest moraine have a low water holding capacity and a high drainability. Therefore we updated our statements accordingly to the suggestions of the Reviewer in line 323-326:
Using the information in the volume density profiles and the stained path widths to characterize flow types (Weiler, 2001) we found a trend from a rather homogeneous flow pattern with matrix flow in a fast draining coarse textured soil at the youngest moraine to a more heterogeneous flow pattern with a mix of heterogeneous matrix flow and finger flow at both medium age moraines (Fig. 9).

And by removing line 442, and in line 513 to 515:

The derived flow types also support our hypothesis that vertical subsurface flow path types change through the millennia. Flow types change from homogeneous matrix flow in a fast draining coarse textured soil to a heterogeneous matrix and finger flow over the first 100-3 000 years.

Specific Comments Confusion over terminology:
Confusion over terminology: Considering the underlying physical mechanisms, there are three main types of PF (macropore flow, finger flow and heterogeneous flow) and this is indeed the basis of the classification system that the authors make use of in the paper.
However, the authors unnecessarily introduce some confusion at a couple of places in the paper by referring to another classification scheme, one that is not especially useful in my opinion:
i.) page 2 (lines 18/20): There is no good reason to distinguish crack flow from burrow flow (does burrow flow include flow in channels created by root decay?). These can all be lumped into macropore flow (as you do later). If you want to define some subgroups according to the origin of macropores, you should talk about flow in biopores (which includes both root and faunal channels) not burrow flow.

ii.) page 17, line 34: "In the clay layer, no significant macropores were identifiable, which is why it is assumed that the water is transported in cracks .....". Cracks are also macropores. You should replace the term macropores by biopores.

We agree with this comment and corrected our terminology accordingly in line 40-43:
They defined four types of preferential flow: crack flow, burrow flow (created by soil fauna), finger flow, and lateral flow along layer interfaces, where flow in burrows and cracks is also often classified as macropore flow. We will in the following distinguish flow in macropores according to their origin as crack flow and biopore flow, where the latter includes channels by activities of roots and soil fauna.

And in line 439-441:
In the clay layer, no significant biopores were identifiable, which is why it is assumed that the water is transported in cracks or along material interfaces.

Specific Comments Corrections:

1. The text at the end of the Introduction should be re-arranged. The hypotheses at lines 6-11 don't make much sense at the moment, because they are specific to the case of glacial moraines. It's not clear to the reader where these hypotheses come from. If you move this text to line 19 (after " … impacts water flow paths"), I think it will make more sense, especially if you add "… in glacial moraines in the Swiss Alps" after "… landscape evolution", and delete the last sentence in the first paragraph.

We agree and restructured the Introduction in accordingly in line 75-80.

2. Abstract, Line 1: you should delete "The presence or absence of …"

We agree and included the correction (see line 1)

3. page 3, line 1: add "volcanic" after "…younger"

We agree and included the correction (see line 57)

4. page 4, lines 15-16: delete "by the project partners … Germany"

We agree and included the correction (see line 112-113)

5. Page 7, line 10: maybe you could add "... and flow mechanisms" after "different properties"

We agree and included the correction (see line 202)

6. Page 8, line 1: add ".... moraines of differing …" after "four"

We agree and included the correction (see line 239)

7. Page 8, line 6: replace "the entire" by "all"

We agree and included the correction (see line 242)

8. Page 8, figure 3 caption: I presume that these results are % of the fine earth fraction (< 2mm). It would be good to state this here.

We agree and updated the caption of now Figure 5 accordingly:

(a) Profile averaged grain size fractions for the four moraines. Fractions are percentages of the fine earth fraction (< 2 mm). (b) Profile averaged gravel content (> 2mm) calculated as the percentage of the entire sample weight. Each average is based on 18 samples.

9. Page 10, line 5: I don't think you should talk about hillslopes as you haven't mentioned anything about site topography. You could just replace "hillslope" here by "moraine"

We agree and included the correction (see line 276)

10. Page 12, line 7: This is ambiguous, but I think you mean: "For all four moraines, the volume density is largest in the top half of the soil profile"

This was a misunderstanding due to ambiguous wording, we did want to state that the youngest moraine has a higher volume density in the top half of the soil profile than all the other moraines. We replaced "The volume density in the top half of the soil profile is the highest of all ages (Figure 5)" with the sentence "*The youngest moraine has a higher volume density of flow paths in the top half of the soil profile than all other moraines*" in Line 289.

11. Page 13, line 2: interpreting dye tracing patterns can be tricky, since you only get a snapshot in time of a dynamic process. In this particular case, I think it's possible that even if the staining was homogeneous, it doesn't necessarily mean that PF didn't occur. PF could have occurred from the soil surface, but the signs of this may have been obliterated by the later (slower) downward movement of a uniform wetting front in the soil matrix. I am not saying that this is what happened (I'm confident that your interpretation is correct), but I think you could recognize this possibility.

We agree and have added a sentence to account for this in line 157-160:

Since dye tracer experiments only provide snapshots of flow patterns at 24 h after the irrigation, we cannot exclude the possibility that initial preferential flow paths were obliterated by a later downward movement of the infiltration front. However, as the probability for this special case is relatively low, we assume that these snapshots are a viable basis for the comparison of characteristic flow patterns along the moraine ages.

12. Page 16, lines 26-27: I don't understand how the decrease in bulk density in the first 160 years can be related to a change of particle sizes, since this was marginal. It must be primarily due to the increase in SOM content.

We agree that this sentence is misleading and updated the statement in line 356-362:

In general, these changes could be linked to changes in grainsizes, as the breakdown of particles leads to an increase in total pore space (porosity) and thus to a reduction in bulk density (Arvidsson, 1998). However, since changes in grain sizes were only marginal, the dense vegetation development, which includes an increase in root activities, litter accumulation, and biological activities in the root zone, is likely the main cause for changes in bulk density and porosity [Neris et al. (2012), Carey et al. (2007)].

13. Page 16, lines 26-34: there is no need to have separate discussions for porosity and bulk density, because they are very closely linked (via the particle density). You could simplify and shorten the text between lines 18 and 34: you only need to write that the increase of porosity and decrease of bulk density was presumably a result of organic matter build-up in the soil due to the development of a denser vegetation cover.

We agree and restructured the Discussion section accordingly.

14. Page 17, lines 2-3: it should be briefly explained (with a supporting reference) how the change in texture could affect bulk density. Presumably the finer particles fill the spaces between the coarser particles? However, I think that the effects of texture on bulk density are usually considered to be relatively small. I think that the increase in SOM content (and associated biological activity in the soil) must be the main reason for the decrease in bulk density.

We agree and included some further clarification in line 356-362:

In general, these changes could be linked to changes in particle sizes, as the breakdown of particles leads to an increase in total pore space (porosity) and thus to a reduction in bulk density (Arvidsson, 1998). However, since changes in grain sizes were only marginal, the dense vegetation development, which includes an increase in root activities, litter accumulation, and biological activities in the root zone, is likely the main cause for changes in bulk density and porosity [Neris et al. (2012), Carey et al. (2007)].

15. Page 17, line 20: "texture" in this context is quite a vague term. Was it clay content? Please be more explicit.

We agree and changed the sentence in line 407 – 410 to:

Saturated conductivity was found to be negatively correlated with the fraction of fine particles. The decrease in gravel content and the increase in silt seem to have an even a stronger effect on the saturated conductivity than the root network development (Maier et al., 2019).

16. Page 17, line 30: the coarse nature of the material must be important too?

We agree and included the correction (see line 436)

17. Page 18, line 27: replace "lower" by "shallower"

We agree and included the correction (see line 472)

18. Page 18, line 32: should be: "… cover was removed to decrease …"

We agree and included the correction (see line 477)

Field observations of soil hydrological flow path evolution over 10 Millennia

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Abstract. The presence or absence of preferential Preferential flow strongly controls water flow and transport in soils. It is ubiquitous, but difficult to characterize and predict. This study addresses the occurrence and the evolution of preferential flow during the evolution of landscapes, and here specifically during the evolution of hillslopes. We targeted a chronosequence of glacial moraines in the Swiss Alps to investigate how water flow paths evolve along with the soil forming processes. Dye tracer irrigation experiments with Brilliant Blue solution (4 g/l) were conducted on four moraines of different ages (30, 160, 3000, and 10000 3 000, and 10 000 yrs). At each moraine, three dye tracer experiments were conducted on plots of 1.5 x 1.0 m. The three plots at each moraine were characterized by different vegetation complexities (low, medium, high). Each plot was further divided into three equal subplots for the application of three different irrigation amounts (20, 40, 60 mm) with an average irrigation intensity of 20 mm/h. The day after the experiment five vertical soil sections were excavated and the stained flow paths were photographed. Digital image analysis was used to derive average infiltration depths and flow path characteristics such as the volume and surface density of the dye patterns. Based on the volume density, the observed dye patterns were assigned to specific flow type categories. The results show a significant change in type of preferential flow paths along the chronosequence. The flow types change from a rather homogeneous gravity driven matrix flow in coarse material with high conductivities and a sparse vegetation cover at the youngest moraine to a heterogeneous infiltration pattern at the medium-age moraines. Heterogeneous matrix and finger flow are dominant at these intermediate age classes. At the oldest moraine only macro pore flow via root channels was observed in deeper parts of the soil, in combination with a very high water storage capacity of the organic top layer and low hydraulic conductivity of the deeper soil. In general, we found an increase in water storage with increasing age of the moraines, based on our observations of the reduction in infiltration depth as well as laboratory measurements of porosity. Preferential flow is, however, not only caused by macropores, but especially for the medium age moraine seems to be mainly initiated by soil surface characteristics (vegetation patches and micro-topography).

1 Introduction

The ability of soil to store and to transport water is essential for its ecosystem services such as nutrient cycling or water and gas balances [Clothier et al. (2008), Amundson et al. (2015), L. Hatfield et al. (2017), Shang et al. (2018)]. Thus, the interaction of water and soil is an elementary foundation for the existence and functioning of terrestrial ecosystems. This interaction is part of a large network of interactions of various ecosystem components (flora, fauna, material and energy fluxes, geomorphological conditions, climate), which are also necessary for the existence and functioning of ecosystems. Soil filters the percolating water, redistributes it to groundwater or stream water or holds it against gravity and makes it available for plants.

The soil functions are influenced and controlled by soil properties, which can vary spatially on the small (Hu et al., 2008) and large scale (vertically along the profile and horizontally across landscapes (Bevington et al., 2016)), as well as temporally. These properties include soil texture and structure, i.e. the pore- and ~~particle~~ grain size distribution which in turn control the storage- and transport capacity of the soil. Additional factors influencing soil functions are climate, topography and vegetation. In undisturbed natural systems these factors are usually assumed to be constant at the observational time scale and the inherent system dynamics only become apparent on long time scales.

Preferential flow, which is defined according to Hendrickx and Flury (2001) as a phenomenon 'where water and solutes move along certain pathways, while bypassing a fraction of the porous matrix', has impacts on water storage (Rye and Smettem, 2017) and thus plant water availability. It furthermore affects the transport of nutrients and contaminants (Jarvis, 2007) throughout the vadose zone and consequently also soil chemistry [Jin and Brantley (2011), Bundt et al. (2000)] and groundwater quality. Allaire et al. (2009) attributes rapid flow and mass transport to flow through earthworm burrows, cracks in soil, and to flow paths resulting from soil layering and hydrophobicity. They defined four types of preferential flow: crack flow, burrow flow (created by soil fauna), finger flow, and lateral flow along layer interfaces, where flow in burrows and cracks is also often classified as macropore flow. We will in the following distinguish flow in macropores according to their origin as crack flow and biopore flow, where the latter includes channels by activities of roots and soil fauna. Preferential flow in form of macropore flow occurs mostly in fine-textured soils whereas finger and funnel flow rather occurs in soils with a coarse texture (Hendrickx and Flury, 2001). General factors ~~causing~~ which can cause preferential flow paths are surface structure and properties such as vegetation cover, micro topography or hydrophobicity, as well as subsurface soil properties such as soil structure and soil type, subsurface heterogeneities, flow instabilities and plant root activities [Weiler and Naef (2003), Clothier et al. (2008), Bachmair et al. (2009) Jarvis (2007), van Schaik (2009), Wang et al. (2018)]. Soil water conditions were also found to have an influence on the preferential flow path characteristics [Gimbel et al. (2016), Hardie et al. (2011), Bogner et al. (2008)].

Many preferential flow-influencing properties such as soil structure, soil texture or vegetation cover change during landscape evolution [e.g. Vilmundardóttir et al. (2014), Egli et al. (2010), Dümig et al. (2011)] and thus also lead to a change in the soil hydraulic behavior (Lohse and Dietrich, 2005) which in turn has a direct impact on the surface and subsurface water transport. We therefore assume that the age of the soil has an influence on the prevailing preferential flow paths, and thus the type and also the depth extent of the preferential flow paths can change over time. Especially root activities can lead to generation of preferential flow paths in deeper layers, which was found by Cheng et al. (2014) based on a comparison of young and older forest plantations. On a large time scale of several million years Lohse and Dietrich (2005) found a transition from mainly vertical water transport in younger volcanic soils in the Hawaiian Islands to lateral water transport along the boundary of a subsurface clay layer. The younger soil was coarse textured with high saturated hydraulic conductivities along the profile and a rather low field capacity, whereas the older soil revealed a higher field capacity and a distinct reduction in saturated hydraulic conductivity throughout the profile due to clay accumulation. Yoshida and Troch (2016) observed a major change in flow paths from deep groundwater flow to shallow subsurface flow in volcanic catchments of ages between 200,000 and 82 million years. While the change of major flow paths with time has already been studied at the time scale on the order of 100,000 to millions of years, little is known how flow paths change during these first 10,000 years of landscape development. Therefore, this study addresses the occurrence and the evolution of preferential flow during the first 10,000 years of landscape evolution. More specifically, we test the hypotheses: (1) Vertical subsurface flow paths change through the millenia. (2) Macropores become more important with increasing hillslope age. (3) The soil develops from an unconsolidated material into a layered soil system with a reduction in particle size and an increase in porosity leading to an increase in subsurface water storage. To test these hypotheses we targeted a chronosequence of glacial recession in the Swiss Alps.

Areas with receding glaciers have been shown to be suitable for soil development studies [Crocker and Dickson (1957), Douglass and Bockheim (2006), He and Tang (2008), Egli et al. (2010), Dümig et al. (2011), Vilmundardóttir et al. (2014), D'Amico et al. (2014)]. In the cool and humid climate regions of former glacial areas the soils develop from mineral soils to soils with a highly organic topsoil. These organic soil types are less intensively studied with regard to their soil hydraulic behavior compared to mineral soils (Carey et al., 2007). It is known that these soils differ in their soil hydraulic properties from mineral soils (high total porosity (up to 90%) and a low bulk density (Carey et al., 2007)) but little is known about how this development impacts water flow paths. Therefore, this study addresses the occurrence and the evolution of preferential flow during the first 10 000 years of landscape evolution in glacial moraines in the Swiss Alps. More specifically, we test the hypotheses that (1) Vertical subsurface flow path types and vertical extent of flow paths 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.

Dye tracer experiments, and an analysis of soil texture and soil physical properties were used to investigate how water flow paths evolve with hillslope age. The hydropedological approach (Lin, 2003) that links pedon (Quisenberry et al., 1993), landscape (Cammeraat and Kooijman, 2009) and hydrologic processes studies has already been applied to the preferential flow phenomenon (Jarvis et al., 2012). Dye tracer experiments combined with digital image processing have been applied successfully to study preferential infiltration in soils [Weiler (2001), Bogner et al. (2008), Blume et al. (2008), Laine-Kaulio et al. (2015), Hardie et al. (2011), Cheng et al. (2014)]. In our study we use this method to identify how flow paths change during the co-evolution of soil, vegetation and topography. Understanding the changes in preferential flow paths as a result of the natural co-evolution of landscape forming factors can provide valuable knowledge on how these systems can also change as a result of human intervention (Richter and Mobley (2009)).

2 Material and methods

2.1 Study site

The study area is located in the foreland of the Stein glacier above the tree line in the Central Swiss Alps, south of the Sustenpass in the Urner Alps (appr. 47° 43'N, 8° 25'E). Elevations range from 1900-2100 m a.s.l. The area lies in the polymetamorphic "Erstfelder" gneiss-zone, which is part of the Aar-massif (Blass et al., 2003). The geology is defined by metamorphosed pre-Mesozoic, metagranitoids, gneisses, and amphibolites [Heikkinen and Fogelberg (1980), Schimmelpfennig et al. (2014)], thus the material is mainly acidic and rich in silicate. The closest official weather station is located 18 km away at Grimsel Hospiz (46° 34'N, 8° 19'E) at an elevation of 1980 m a.s.l. For the norm period from 1981 to 2010 the station recorded an annual mean temperature of 1.9 °C and an annual precipitation of 1856 mm. The precipitation distribution throughout the year is fairly uniform with a slight increase in the winter months (Schweizerische Eidgenossenschaft, 2016). The glacier foreland consists of moraines with unconsolidated glacial till. The humid and cool climate together with the nutrient-poor substrate and a relative high water permeability of the glacial till favor the formation of podsolic soils and humus in this area (Heikkinen and Fogelberg, 1980).

The moraines of the Stein glacier were exposed due to its retreat to the south. Four moraines were selected for this study (see Fig. 1). Schimmelpfennig et al. (2014) conducted a detailed dating study of the Stein glacier moraines, based on high-sensitivity beryllium-10 moraine dating and found that the ages of three moraines range between 160 to 10~~,~~ 000 years. The age of a fourth moraine was dated to 30 years based on maps and aerial photos.

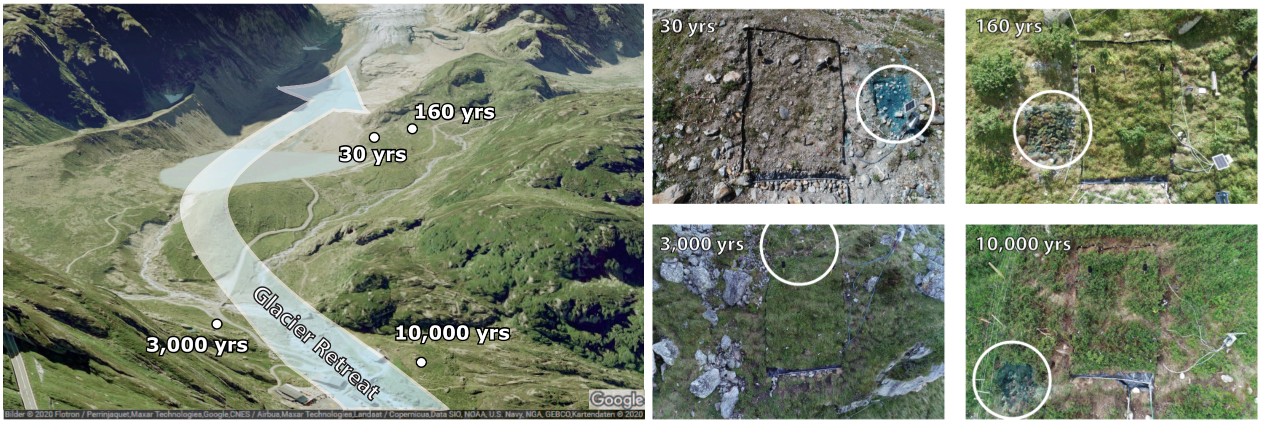


Figure 1. Location (left) and surface cover (right) of the four selected proglacial moraines of the ~~Stone Glacier~~Stein glacier. White circles show locations of one of the three brilliant blue experiment plots per age class. Photo of location is provided by Google (n.d.). Photos of the 30, 160, and 10~~,~~ 000-year-old moraine were taken after the brilliant blue experiment (photos ~~were~~ taken by ~~Florian~~ F. Lustenberger~~, Uni Zurich~~).

The oldest moraine with an age of 10, 000 years is facing north-east. The second oldest moraine with an age between 2, 000 and 3, 000 years is the only one facing south. The two youngest moraines were exposed in the years 1860 and 1980-1990, and thus have an age of 160 and 30 years, respectively. Both moraines are facing north-east and are located closer to the glacier tongue at a distance of approximately 1 km from the oldest moraines. Both moraines are south of the glacial lake "Steinsee" (1930 m a.s.l.), which is a proglacial lake that was formed by the glacier retreat in 1924 (Blass et al., 2003).

The vegetation of the moraines was mapped in summer 2017 by the project partners of the Geobotany Group of the University of Freiburg, Germany (Maier et al., 2019). Pronounced differences in vegetation coverage and species distributions were found among the four age classes. The vegetation of the oldest moraine was dominated by a variety of prostrate shrubs together with small trees and several grasses. On the 3, 000-year-old moraine a grassland cover with fern, mosses, sedges and forbs was found. The two youngest moraines, however showed a lower degree of vegetation complexity. On the 160-year-old moraine a combination of grasses, lichen, forbs, and shrubs was present. The youngest moraine still shows only a sparse vegetation cover with mainly grass, moss, forbs, and a few shrubs. Three study plots were selected at each moraine, based on degree of vegetation complexity (low, medium and high complexity). Vegetation complexity is characterized by the plant structural complexity, which is determined by plant species diversity. A more detailed description of the application of this method can be found in Musso et al. (2019).

2.2 Field experiments

The dye tracer experiments were conducted between mid July and mid August 2018. We used Brilliant Blue FCF as dye tracer due to its good visibility, high mobility and non-toxicity. We used a concentration of 4 g/l at which the tracer shows good sorption and visibility (Weiler and Flühler, 2004). Three study plots were selected at each moraine, based on degree of vegetation complexity (low, medium and high complexity). Vegetation complexity is characterized by vegetation coverage, number of species and the plant functional diversity. The functional diversity is calculated based on specific leaf area, nitrogen content, leaf dry matter content, Raunkiaérs life form, seed mass, clonal growth organ, root type and growth form. The collection of the required data and calculation of the vegetation complexity was done by the Geobotany Group of the University of Freiburg and is described in more detail in Maier et al. (2019).

The size of each study plot was 1.5 x 1.0 m. The distances between the three study plots at each moraine ranged from 10 to 100 m. Each plot was further divided into three equal subplots of 0.5 x 1.0 m. Figure 2 shows the experimental design at each moraine and illustrates the irrigation procedure.

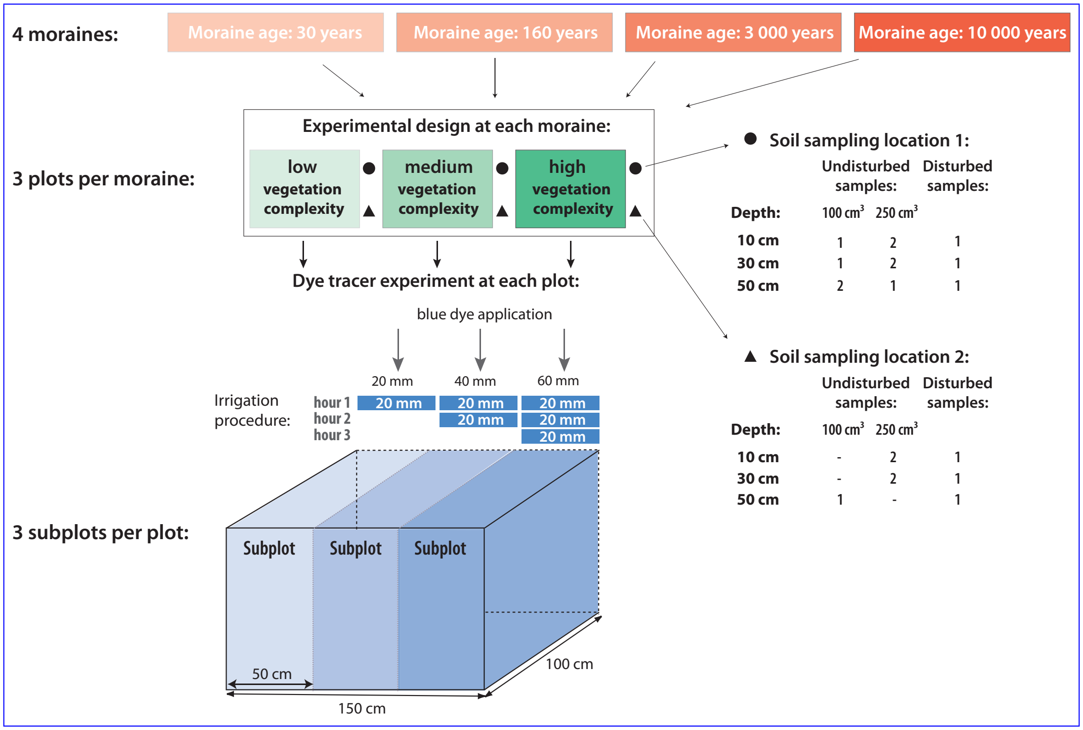


Figure 2. Illustration of the experimental design and soil sampling scheme at each moraine.

The subplots were irrigated with three different amounts of dyed water (20 mm, 40 mm, 60 mm) and an irrigation intensity of 20 mm/h~~(Fig. 3).~~

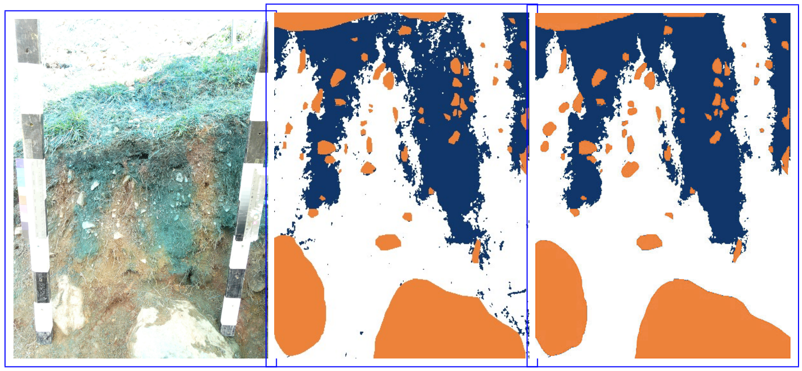
~~Blue dye experimental set-up (a), photograph of vertical soil profile of the 3,000-year-old moraine and an irrigation with 40 mm (b), tricolor image of the photograph (c). Blue indicates stained soil, white unstained soil, and orange indicates rocks.~~ . The irrigation intensity is relatively high with a return period of 2.8 years (Fukutome et al., 2017). In preparation of the tracer application large vegetation in form of shrubs and bushes were cut off to a height of a few centimeters to reduce interception. The tracer was applied with a hand-operated sprayer connected to a battery powered pump which guaranteed a constant pressure for a uniform flow rate of 60 l/h. ~~The tracer was applied in three steps. In each step, the alternating intervals of irrigation and breaks varied~~For a time-efficient irrigation of the three subplots with three irrigation amounts, the irrigation procedure was divided into three steps. In the first step all three subplots were irrigated simultaneously for 60 ~~minutes~~ min in a sequence of 5 ~~minutes~~ min irrigation and 5 ~~minutes break.~~ min break. This provides an application of 20 mm to all three subplots. After finishing the first step the first subplot was covered ~~for protection. In the~~ to avoid any additional water input. In a second step, the other two subplots were simultaneously irrigated for additional 60 min in ~~the same~~ a sequence of 5 min irrigation and ~~a~~ 10 min ~~break.~~ breaks. This provides an application of additional 20 mm to each of the two remaining subplots. In the last step only the third subplot was irrigated for 60 min in a sequence of 2 min irrigation and 10 min breaks while the other two plots remained covered providing an additional 20 mm to this subplot. After the ~~tracer application the whole~~ end of tracer application, the entire plot was covered ~~.~~ to avoid any disturbance by natural rainfall.

The next day ~~the plot~~ each subplot was excavated in up to five profiles of 7 to 10 centimeters. After the profile cuts were made with pickaxes, spades and hand shovels, the profile walls were cleaned. Hanging roots were cut off and rocks were not removed but made visible. The ~~photographs of the profile walls were taken~~ profiles of each subplot were photographed with a Panasonic Lumix DMC-FZ18 camera and a resolution of 2248 x 3264 pixels. A big umbrella was used to provide a uniform light distribution in the photographs and to avoid direct sunlight. A wooden frame for a geometric correction and a gray-scale (Kodak) attached to the frame (Fig. 3) for a later color adjustment were included in the photographs.

Since dye tracer experiments only provide snapshots of flow patterns at 24 h after the irrigation, we cannot exclude the possibility that initial preferential flow paths were obliterated by a later downward movement of the infiltration front. However, as the probability for this special case is relatively low, we assume that these snapshots are a viable basis for the comparison of characteristic flow patterns along the moraine ages.

2.3 Image analysis

The image analysis procedure by Weiler (2001) was used to generate ~~binary~~ tri-color images of the photographs showing stained and unstained areas (Fig. 3). A detailed description of the method can be found in Weiler and Flühler (2004). Instead of the original IDL software package a similar Python version was used. Basically, a geometric correction, a background subtraction and color adjustment was carried out to correct differences in image illumination and changes in the spectral composition of daylight. The delineation of rocks and plants was done manually. In the resulting ~~binary~~ tri-color image the horizontal and vertical length of a pixel correspond to 1 mm. Due to poor lighting conditions or a heterogeneous background color distribution in the soil caused by material transitions, small stones or organic matter, the image analysis software was not able to recognize all large dye stains as coherent objects. Thus, a manual correction of the images using the photographs was necessary (see Fig 3).



(a) (b) (c)

Figure 3. Exemplary image analysis procedure for the subplot irrigated with 40 mm at the 3 000-year-old moraine: (a) Photograph of the vertical soil profile with wooden frame and attached gray-scale. (b) Software generated tri-color image of the photograph. (c) Manually corrected tri-color image. Blue indicates stained soil, white unstained soil, and orange indicates rocks.

For a quantitative comparison of the dye patterns the maximum infiltration depth, the volume density and surface area density, as well as the stained path width were calculated. These ~~parameter~~ parameters are frequently used for an objective comparison and description of the dye patterns [Weiler and Flühler (2004), Bachmair et al. (2009), Laine-Kaulio et al. (2015), Cheng et al. (2014), Gimbel et al. (2016), Laine-Kaulio et al. (2015), Mooney and Morris (2008) Öhrström et al. (2002)]. Volume and surface area density are originally steorological parameters which are used to relate three-dimensional structures to measured two-dimensional parameters (Weibel, 1979). The volume density corresponds to the dye coverage and can be derived from one-dimensional information by calculating the fraction of stained pixels for each depth. The volume density profile is defined by the fraction of stained pixels per depth and is calculated as the average of all excavated profiles per plot. The surface area density in one-dimension is calculated by using the intercept density, which describes the ~~amount~~ number of intercepts between stained and unstained pixels divided by the horizontal width of the soil profile. The profile of the surface area density describes the amount of intercepts per depth and is then also averaged over all photographed profiles per plot. Volume density provides no information whether the stained area is the sum of many small fragments or a few large ones, thus the volume density alone should not be used to characterize flow patterns and the surface area density should be used as a supplementary parameter. A high surface area density indicates a large number of small features.

Following the method described by Weiler (2001) the resulting dye patterns were next classified into flow type categories based on the proportions of three selected stained path width classes (stained path width <20 mm, 20 mm-200 mm, >200 mm) relative to the volume density. The stained path width is equal to the horizontal extent of a stained flow path (Weiler, 2001). This classification method distinguishes between five flow types: (1) macro pore flow with low interaction, (2) mixed macro pore flow (low and high interaction), (3) macro pore flow with high interaction, (4) heterogeneous matrix flow/finger flow, and

(5) homogeneous matrix flow. Dye patterns, which cannot be classified as one of these flow types are categorized as undefined. The classification method based on proportions of the stained path width classes is illustrated in Figure 4.

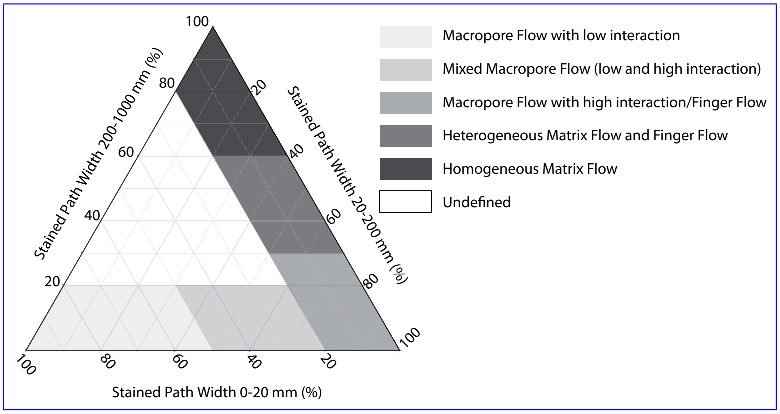


Figure 4. Flow type classification based on the proportion of the three stained path width classes: ternary diagram after Weiler (2001).

This method is based on the assumption that the dye patterns are mainly controlled by certain preferential flow processes and each flow process creates a characteristic dye pattern that can be described by the extent and distribution of stained features. This method was proven to be suitable for the investigation of Weiler (2001) and Weiler and Flühler (2004) and was also used in a variety of additional studies [Bachmair et al. (2009), Gimbel et al. (2016), Mooney and Morris (2008)]. However, an extension of the flow type categorization was needed for our study site with soils of different ages, texture and additionally a high stone content. In the extended classification, we avoid a clear differentiation between macro pore flow and finger flow. The original classification assigns finger flow only when both ,the medium sized stained path width class (20-200 mm) and the class with the biggest stained path widths (> 200 mm) account for approximately half of the dye coverage. This implies that finger flow is only prevalent when the dye pattern is characterized by a majority of broader stained path widths, ignoring that the size of the finger-like flow paths can vary over a broad range (Wang et al., 2018). Thus, we argue that while finger flow and macro pore flow are caused by different properties and flow mechanisms, they can lead to similar dye patterns and distributions of stained path width classes. This is especially the case for macro pore flow with high interaction, which creates broader stained paths that could also be assigned to finger flow. Therefore, both flow types were considered in the extended classification for this class. Furthermore, it was observed that the presence of rocks within the image analysis interrupts homogeneous blue stained areas and thus leads to smaller stained path widths. Using the original classification scheme on a soil profile with high stone content suggests a heterogeneous flow pattern, which can be classified as heterogeneous matrix flow, finger flow, or macro pore flow depending on the abundance of rocks. Therefore, an additional class has been introduced, which is used when homogeneous matrix flow between rocks takes place. The classification rule for the additional flow type class is based on the proportion of blue dye coverage of the available permeable matrix space (profile width minus sum of stone widths per row). If at least 95 % of the permeable space is stained by blue dye the flow type is classified as matrix flow between rocks.

2.4 Soil sampling and laboratory analysis

Soil samples were taken during August and September of 2018 close to each dye tracer plot. For ~~particle~~ grain size analysis, two disturbed bulk soil samples per depth were taken at 10, 30, and 50 cm depth at each plot. The total of 72 samples was analyzed in the laboratory between November 2018 and January 2019 by using a combination of dry sieving (~~particles~~ grain sizes > 0.063 mm) and sedimentation analysis (~~particles~~ grain sizes < 0.063 mm) with the hydrometer method (Casagrande, 1934). Organic matter removal was only possible by floating off the lighter fractions prior to ~~particle~~ grain size analysis. Since three plots were selected per moraine for the brilliant blue experiments, six samples per depth and age class (a total of 18 samples for each moraine) were available for the ~~particle~~ grain size analysis. ~~Particles~~ Grain sizes between 2 mm and 0.063 mm were classified as sand, between 0.063 mm and 0.002 mm as silt and ~~particles~~ grain sizes smaller than 0.002 mm as clay. Grain size fractions of particles < 2 mm were calculated as weight percentages of total weight of particles < 2 mm, thus excluding gravel and stones to avoid that single larger stones shift or dominate the distribution. The gravel and stone fraction was calculated separately as a weight percentage of the entire soil sample.

~~Furthermore, at~~ For the analysis of the structural parameters soil samples were taken with sample rings to provide undisturbed cores which preserve the natural soil structure. At each plot two 250 cm^3 and one 100 cm^3 undisturbed soil samples were taken at a depth of 10 and 30 cm. Three samples of 100 cm^3 were taken at 50 cm depth. Thus, per age class nine samples per depth were available for the determination of the structural parameters porosity and bulk density. A detailed overview of the sampling scheme at each plot is given in Figure 2.

The porosity was determined in the lab using the water saturation method. For this method sample weights were recorded at saturation and after drying at 105 °C. For saturation, the samples were placed in a small basin. The water level in the basin was increased step wise by 1 cm per day. When the water level reached the top of the soil sample and the sample was fully saturated, the bottom of the sample was sealed and the weight at saturation was measured. Bulk density was determined by relating the dry mass after drying at 105 °C to the sample volume. The loss on ignition is a measure of the organic substance in the soil and describes the proportion of the organic substance that was oxidized during annealing for 24 hours at 550 °C. The loss on ignition was determined by drying sub-samples (4-6 g) for at least 24 hours at 105 °C and then at 550 °C. The ignition loss is then calculated by relating the weight loss after drying at 550 °C to the sample weight after drying at 105 °C.

2.5 Statistical analysis

The non-parametric Kruskal-Wallis test was used to test the significance of the differences in the soil texture among the four moraines of differing age classes. It can be applied when the assumption of a normal distribution can not be made and is also valid for small sample sizes. We applied the test to each ~~particle~~ grain size fraction across the four age classes. Average values were based on 18 samples per age class. The grain size distribution at 10 cm depth of the oldest moraine was excluded from consideration, as due to the high organic content not ~~the entire~~ all organic matter could be removed and the results may therefore be erroneous.

3 Results

3.1 Soil texture and structural parameters

Comparing the depth averaged soil texture over the millennia we find that while the soil texture at the youngest moraine mainly consists of sand, the ~~particle~~ grain sizes decrease over the millennia with silt being the largest fraction after 10~~,~~ 000 years (~~Figure 3~~Fig. 5). Clay content increased with age for the three older moraines, with the youngest moraine being the exception (having the second highest clay content). The Kruskal-Wallis test with a 0.05 confidence level showed that differences in ~~particle~~ grain size fractions among the four age classes were statistically significant (p-values < 0.05; sand: p=0.0013, silt: p=0.0006, clay: p=0.0018).

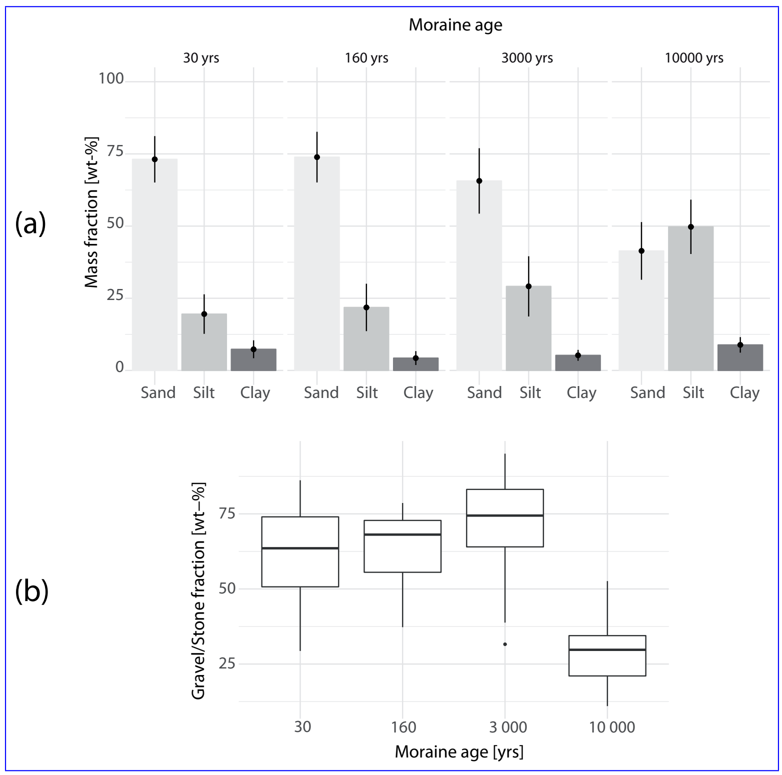
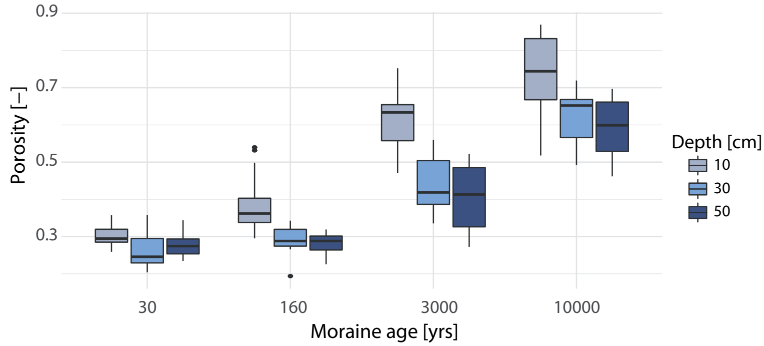


Figure 5. (a) Profile ~~average particle~~ averaged grain size fractions for the four moraines. Fractions are percentages of the fine earth fraction (< 2 mm). (b) Profile averaged gravel content (> 2mm) calculated as the percentage of the entire sample weight. Each average is based on 18 samples.

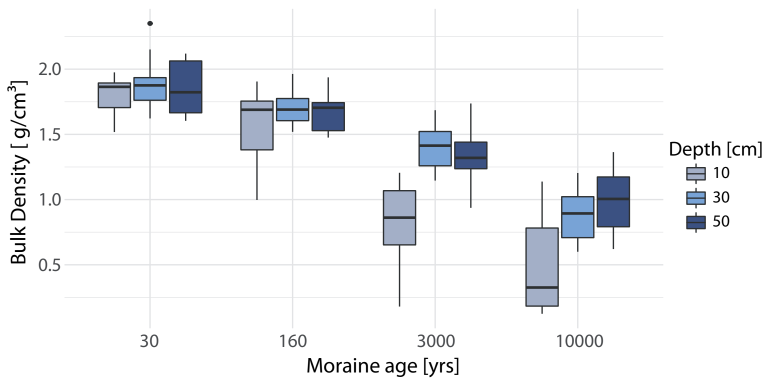
A significant reduction in ~~particle~~ grain size over time was observed, which is most pronounced between 3~~,~~ 000 and 10~~,~~ 000 years of soil development. ~~At the same time the~~ The gravel and stone fraction is roughly the same at the three younger moraines and significantly lower at the oldest moraine (Fig. 5(b)). The structural parameters porosity and bulk density also show a clear trend with age, with porosity increasing and bulk density decreasing (~~Figure~~ Fig. 6).

Table 1. Linear rates of change in porosity, bulk density and grain size between adjacent age classes calculated based on median values.

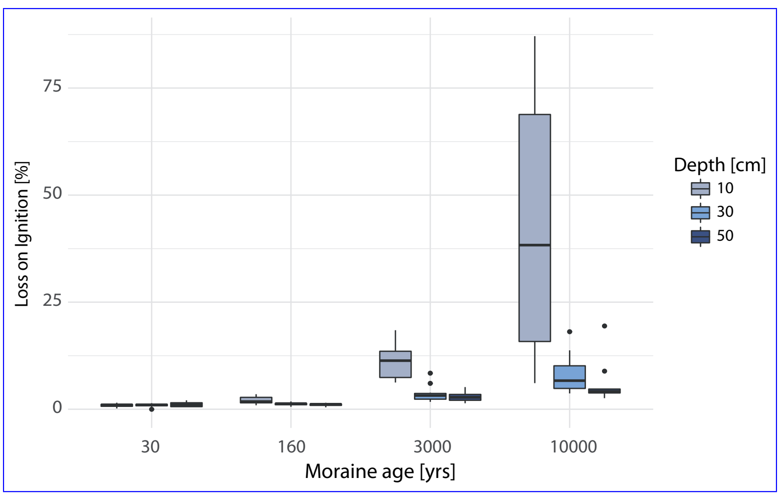
	Porosity $[yr^{-1}]$			*Bulk Density* $[g\ cm^{-3} yr^{-1}]$			*Grain Size* $[mf - \%\ yr^{-1}]$		
	10 cm	30 cm	50 cm	10 cm	30 cm	50 cm	*sand*	*silt*	*clay*
Period $[yrs]$									
30 – 160	5.1x10^{-4}	3.2x10^{-4}	1.1x10^{-4}	-1.3x10^{-3}	-1.4x10^{-3}	-9.1x10^{-4}	2.5x10^{-2}	1.5x10^{-2}	-2.0x10^{-2}
160 – 3 000	9.5x10^{-5}	4.6x10^{-5}	4.4x10^{-5}	-2.9x10^{-4}	-9.7x10^{-5}	-1.4x10^{-4}	-3.2x10^{-3}	3.2x10^{-3}	3.1x10^{-4}
3 000 – 10 000	1.6x10^{-5}	3.3x10^{-5}	2.6x10^{-5}	-7.6x10^{-5}	-7.4x10^{-5}	-4.5x10^{-5}	-3.3x10^{-3}	2.4x10^{-3}	3.2x10^{-4}



(a)



(b)



(c) ~~Evolution of soil porosity (a) and bulk density (b) in 10, 30, and 50 cm depth.~~

Figure 6. Evolution of soil porosity (a) bulk density (b) and loss on ignition (c) in 10, 30, and 50 cm depth.

The porosity observed at the youngest moraine ranges between 0.22 and 0.37, with no pronounced differences among the three soil depths. The 160-year-old moraine has a higher porosity in the upper 10 cm than the 30-year-old moraine. After 3~~,~~ 000 years the increase in porosity continues but is now also visible in 30 and 50 cm, but with much higher values at 10 cm (~~Figure 6a~~Fig. 6(a)). After 10~~,~~ 000 years the porosity at 10 cm ranges from 0.6 to up to more than 0.8. The other two depths also experienced a further increase in porosity. The decrease in bulk density is also most pronounced in the top layer of the soil (~~Figure 6b~~Fig. 6(b)). While after 30 years the bulk density in the upper 10 cm ranges around 1.7 g/cm^3 the bulk density after 10~~,~~ 000 years is much smaller and ranges between 0.2 and 0.7 g/cm^3. After 3.000 years the trend is also visible in 30 and 50 cm.

The loss on ignition, as a measure for the organic matter content, shows an increase throughout the first 10 millennia of soil development, which is most pronounced in the upper soil layer (see Fig. 6(c)). At the two youngest moraines the organic matter content is still very low (< 2 weight-%). At these two age classes the organic matter content is homogeneously distributed over the profile, with a slight tendency to higher values in the topsoil at the 160-year-old moraine. The 3 000-year-old moraine shows a strong increase in organic matter content in the surface layer. At the oldest moraine the trend of increasing organic matter continues in all three depths. Here, the organic matter content in the topsoil makes up to two-thirds of the soil material. However, the organic matter content varies distinctly with a minimum of 6 weight-% and a maximum of 87 weight-%. In deeper depths, the organic content also increases compared to the 3 000 year old soil, but remains below 20 weight-%.

Even though the differences in soil physical characteristics between 30 and 160 years are comparatively small, the rates of change during this initial phase are highest (~~Table~~ Tab. 1). Between 160 and 3~~,~~ 000 years, the rates of change are significantly reduced and remain in a similar range between 3~~,~~ 000 and 10~~,~~ 000 years.

3.2 Vertical dye pattern analysis

Flow patterns traced with brilliant blue dye changed considerably with ~~hillslope age (Figure~~ moraine age (Fig. 7). The volume density profile is a measure for the amount of blue dye per depth. The profile patterns of volume and surface area density show distinct differences among age groups, while differences between the vegetation complexity levels are not as clear (~~Figure 7 and Figure~~ Fig. 7 and Fig. 8).

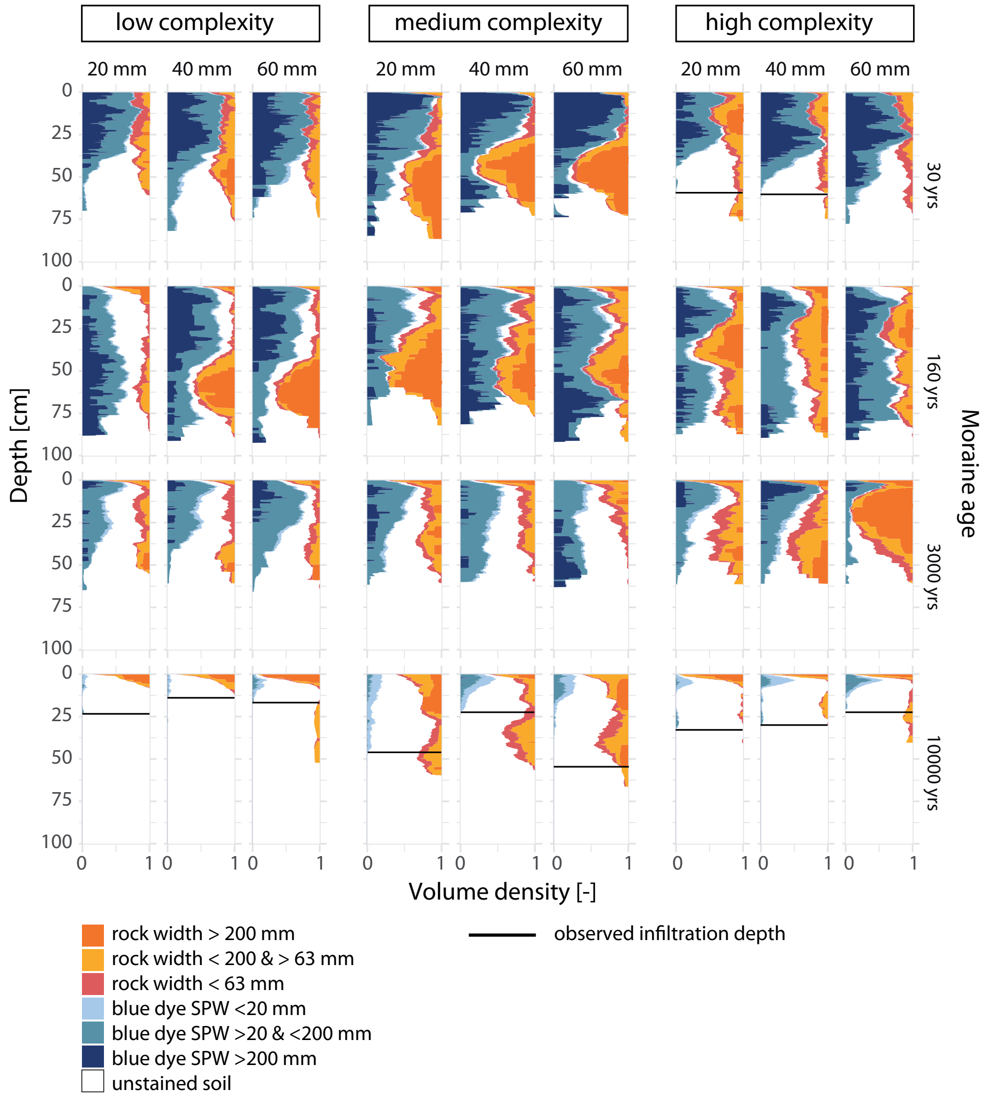


Figure 7. Volume density profiles per age class, vegetation complexity and irrigation amount. The volume density is the fraction of stained pixels, here colored by flow path width (stained path width, SPW) and rock sizes.

280 The volume density of the blue dye was classified in three selected stained path width groups (Weiler, 2001). Additionally, the volume density of rocks was also classified in three groups (~~Figure~~ Fig. 7).

An analysis of the average or maximum infiltration depth based on the dye profiles was not possible because not all profiles could be excavated up to the maximum infiltration depth. In most cases large boulders prevented further excavation or the infiltration depth was more than one meter. The latter was mostly the case at the youngest moraines. Only at the oldest moraine a maximum infiltration depth could be determined based on the dye profiles.

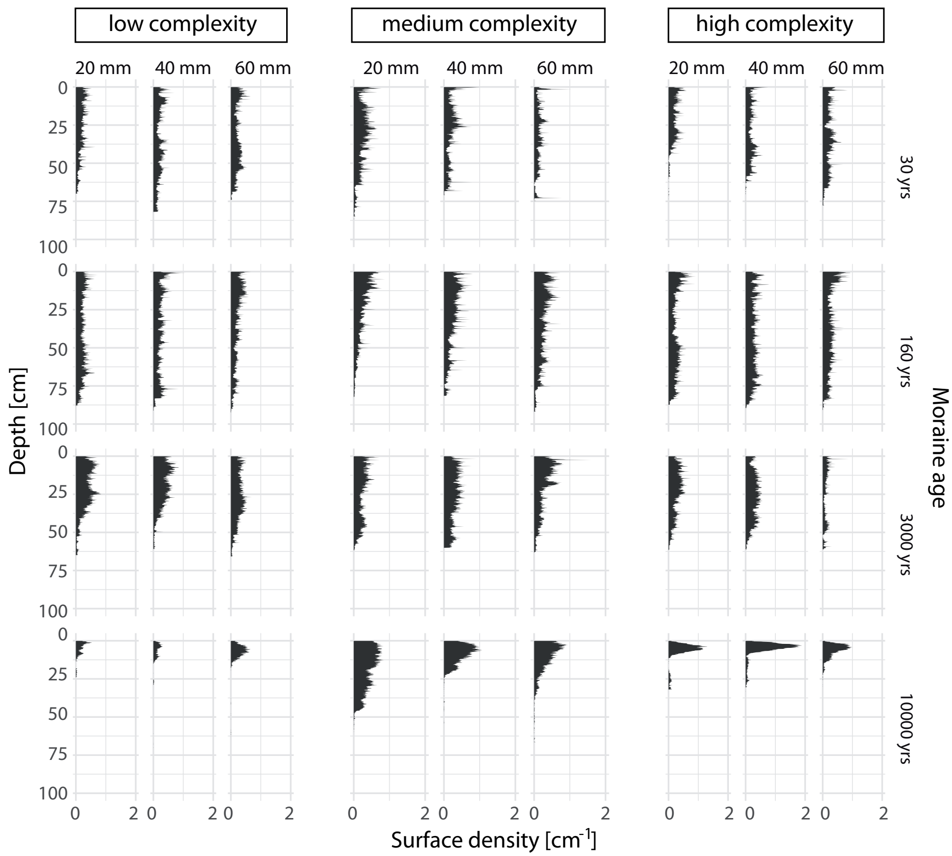


Figure 8. Surface area density profiles per age class, vegetation complexity and irrigation amount (20, 40 and 60 mm). A high surface area density indicates a large number of small features.

Combining the volume density profiles with the surface area density profiles, it is possible to derive whether the stained area described by the volume density is made up of many small flow paths or few large ones. The shapes of the volume density profiles and the surface area density of the youngest moraine are all very similar across the vegetation complexity levels and irrigation amounts. The ~~volume density~~ youngest moraine has a higher volume density of flow paths in the top half of the soil profile ~~is the highest of all ages (Figure~~ than all other moraines (Fig. 7). There are almost no unstained areas. Beginning from approximately 30 cm depth the volume density declines. The surface area density profiles show an opposite pattern (Figure Fig. 8). The surface area density is smaller in the upper half and increases in the lower half of the profile. The combination of both parameters indicate a homogeneous staining in the top half, where interruptions of stained areas are only caused by rocks. In the lower part of the soil profiles the flow paths are subdivided, which is indicated by the increase in surface area density (apparent at 30 cm depth for the low, 25 cm depth for medium and 50 cm depth for the high vegetation complexity plot). This combined with a decline in volume density indicates a narrowing of the flow paths. For the low and high vegetation complexity plots the change in flow paths coincides with a layer of higher clay and silt content. This layer does not exist at the medium vegetation complexity plot. In this case, the narrowing and splitting up of flow paths is caused by large rocks. No clear differences are visible between the different irrigation amounts. The proportion of the stained path width classes are controlled by the existence of rocks. The maximum infiltration depth is either controlled by the position of the clay layer or is deeper than the profile depth and therefore cannot be determined.

Comparing the 160-year-old moraine to the youngest moraine we find that the volume density is lower and the surface density is higher in the upper part of the profile. Also unstained areas (colored white in Figure 7) are visible, which indicates that the higher surface density is not caused by the existence of rocks that split up a homogeneously stained area as it was the case for the youngest moraine. In this case there is no total dye coverage of the permeable soil and the preferential flow paths are initialized already near/at the soil surface. The surface density profiles show a decrease in the lower half of the soil profile, which either goes along with a decrease in blue dye coverage and an increase in stone coverage or an increase in blue dye coverage without a significant change in stone coverage. Both indicates a reduction in the amount of separate flow paths and an increase in flow path widths, even if the permeable space is reduced due to an increase in rock content. Also the fraction of stained path widths (SPW) bigger than 200 mm increases, which indicates that the dye plumes widens in deeper soil depths.

Compared to the two youngest moraines the moraine of 3, 000 years shows in general a higher surface area density and a lower dye coverage combined with a higher fraction of unstained permeable soil matrix. This indicates that similar to the 160 years old moraine water is transported in individual flow paths, but here there are more flow paths and they have a smaller width. This can also be seen in the less frequent appearance of stained path width higher than 200 mm (Figure Fig. 7). Similarly to the 160-year-old moraine, preferential flow paths are already initialized at the top of the soil during infiltration (apparent from the white colored areas across the profile in Figure 7).

The oldest moraine with an age of 10, 000 years shows the highest surface area density and the lowest volume density combined with the lowest infiltration depths. The surface and volume density profiles show the same pattern: After a peak close to the soil surface, both density profiles show a decrease with soil depth. This means that the dyed water is only transported deeper into the soil via a few individual flow paths.

3.3 Flow type classification

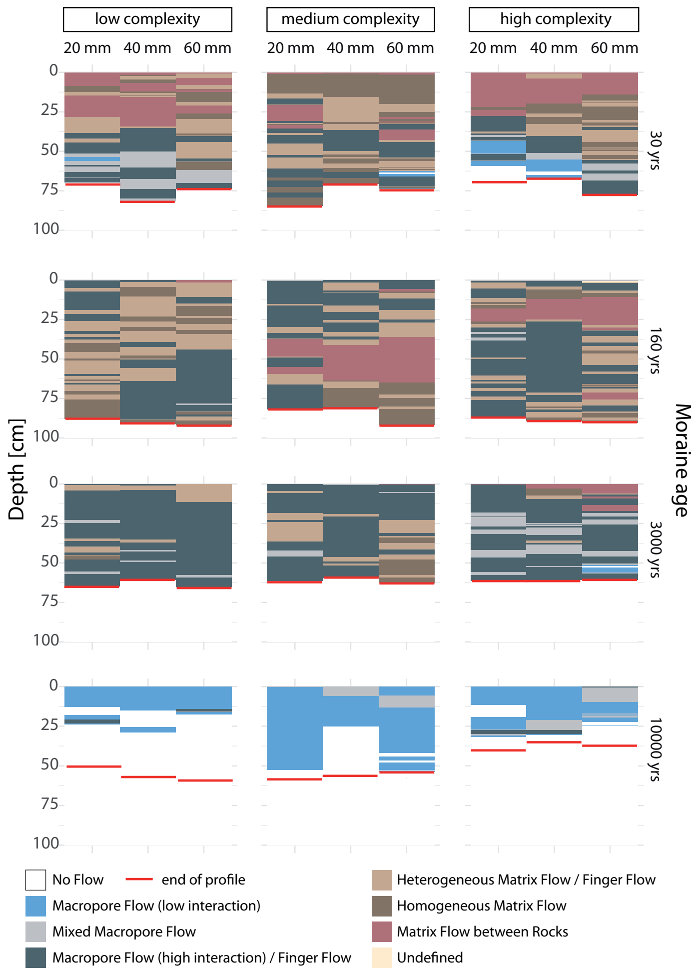


Figure 9. Profiles of flow types per age class, vegetation complexity and irrigation amount.

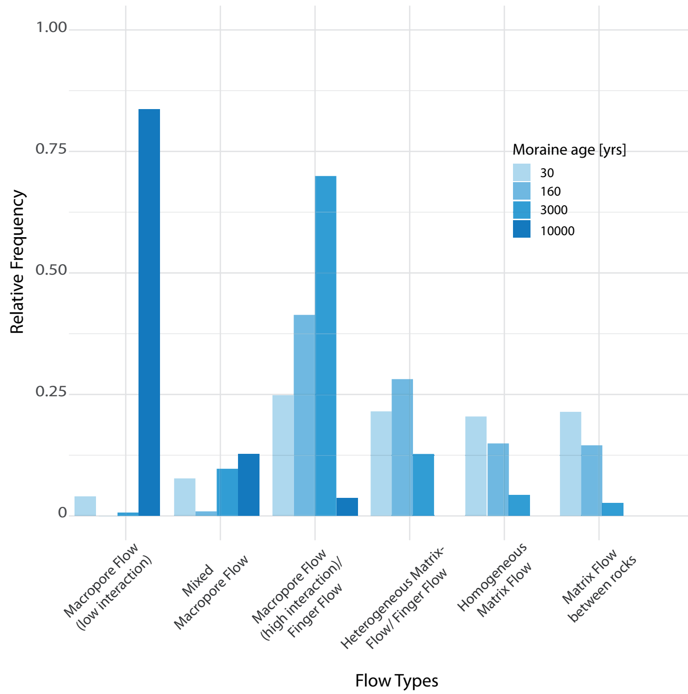


Figure 10. Relative frequency distribution of flow types of the four moraine age classes. Basically all observations fit into the six flow type categories. The fraction of observations categorized as "undefined flow type" is negligible.

Using the information in the volume density profiles and the stained path widths to characterize flow types (Weiler, 2001) we found a trend from a rather homogeneous flow pattern with ~~gravity driven matrix flow , especially in the top soil ,~~ matrix flow in a fast draining coarse textured soil at the youngest moraine to a more heterogeneous flow pattern with a mix of heterogeneous matrix flow and finger flow at both medium age moraines (~~Figure~~ Fig. 9). While the flow characteristics of both the 160 and 3~~,~~ 000-year-old moraine are dominated by finger flow with smaller stained path widths, this is much more pronounced in the ~~3000-year-old~~ 3 000-year-old moraine. By contrast, the oldest moraine stands out clearly from the other age groups. Here, only macro pore flow is predominant. For the deeper soil layers, this was confirmed during the field experiments, since the few macro pore flow paths were clearly visible. For the topsoil, the result is less certain, as the blue areas were very difficult to identify during the image analysis due to the very dark color of the organic layer.

The relative frequency distribution of the flow types per moraine age class derived from the results in Figure 9 show a clear shift in the flow type distribution along the age classes (~~Figure~~ Fig. 10). At the youngest moraine all types of finger flow and matrix flow are present and the frequency distribution does not show a distinct peak at any flow type. With increasing age macropore flow becomes more and more important and the peaks in the frequency distribution become more and more pronounced (~~Figure~~ Fig. 10).

4 Discussion

~~**Evolution of soil texture and structure**~~

4.1 Evolution of soil texture and structure

The early years: 30-160

The observation of bulk density, porosity and soil texture show significant differences between the age groups as well as some clear trends with age. The 30-year-old soil is characterized by coarse material, with a soil texture composed of almost three quarters of sand. The soil texture observed at the 160-year-old moraine does not differ strongly from the 30-year old moraine, whereas slight changes are already evident in porosity and bulk density. These findings are similar to findings by Dümig et al. (2011), who found no specific trend in ~~particle~~ grain size distribution for soils in the range of 15 to 140 years at a soil chronosequence in the foreland of the retreating Damma glacier (Switzerland). They furthermore found a high variability in ~~particle~~ grain size distribution within the single age classes. However, in the same study a slight decrease in variability with increasing age and a noticeable higher clay content was found at the reference site with an age of more than 700 years. He and Tang (2008) also revealed a non-linear increase in maximum clay content for soils up to 180 years at a glacier foreland in a monsoon-temperate region in southwest China.

~~At 3,000 years of soil development we observe a distinct increase in silt and a reduction in sand content and this development continues, as observed in the 10,000 year moraine, where the silt content now makes up the largest share. These findings correspond with findings by Douglass and Bockheim (2006) who studied several moraines in Buenos Aires with ages ranging from 16,000 year to even 1,000,000 years and found an accumulation of clay-sized particles with increasing age, but with a decrease in accumulation rate over the years.The soil material at the 30-years-old moraine showed a relatively uniform porosity and bulk density throughout the profile.~~ After 160 years of soil development the porosity in the top layer increased ~~. As these changes cannot be traced back~~ and bulk density decreased. In general, these changes could be linked to changes in ~~the grain size composition, the increase in porosity is probably due to the development of a more dense vegetation .~~ grain sizes, as the breakdown of particles leads to an increase in total pore space (porosity) and thus to a reduction in bulk density (Arvidsson, 1998). However, since changes in grain sizes were only marginal, the vegetation development, which includes an increase in root activities, litter accumulation, and biological activities in the root zone, is likely the main cause for changes in bulk density and porosity [Neris et al. (2012), Carey et al. (2007)]. The vegetation coverage of both moraines differs significantly (Maier et al., 2019). The youngest moraine still shows only low vegetation cover with only single plants (mainly grasses and forbs) and little root mass with an observed maximum rooting depth of 15 cm (occasionally up to 30 cm), whereas the 160-year-old moraine already has a relatively closed vegetation cover with a combination of shrubs and smaller plants like forbs and grasses forming a loose root network with roots up to a maximum diameter of 5-6 mm and a maximum depth of 35 cm (as observed during the excavation of the soil profiles).

~~The bulk density shows a reduction in the top layer of the 160-year-old moraine. The decrease in bulk density is also linked to~~

the change of particle sizes and the development of vegetation with time, which includes accumulation of organic matter and the development of a root system. Similar findings in bulk density evolution were also observed by Crocker and Major (1955) who found a decrease in bulk density over the first 200 years of soil development from more than 1.4 g/cm^3 to less than 0.8 g/cm^3 for glacial till in southeastern Alaska. A less pronounced reduction was also found by Crocker and Dickson (1957). He and Tang (2008) found a reduction for the time span of 180 years from appr. 1.42 to 0.95 g/cm^3 that was also more distinct in the upper horizon. Vilmundardóttir et al. (2014) revealed at a glacier foreland in southeast Iceland under maritime climate conditions a reduction from 1.36 to 1.07 g/cm^3 for a time span of 120 years . All studies mentioned above linked this decrease in bulk density to the vegetation development with time.

Intermediate stage: 3 000 years

At 3 000 years of soil development we observe a distinct increase in silt and a reduction in sand content and this development continues, as observed in the 10 000 year moraine, where the silt content now makes up the largest share. These findings agree with findings by Douglass and Bockheim (2006) who studied several moraines in Buenos Aires with ages ranging from 16 000 year to even 1 000 000 years and found an accumulation of clay-sized particles with increasing age, but with a decrease in accumulation rate over the years. 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 soil material at the 30-years-old moraine showed a relatively uniform porosity and bulk density throughout the profile. After 3, 000 years, porosity increases and bulk density decreased even further, and this development is now also visible in deeper soil depths. The continuous increase in porosity and reduction in bulk density can still be attributed to the continuing change in soil texture on the one hand and on the other hand to the pronounced vegetation developmentand the . Especially the latter with the resulting accumulation of soil organic matter with an even more dense (see Fig. 6(c)) and the growth of an even denser root network that is now over 35 cm deep.

, is the main cause for the pronounced changes in the top soil.

The late stage: 10 000 years

The oldest moraine shows a significantly higher silt content and porosity compared to the 3, 000-year-old moraine and a significantly lower bulk density. The change is visible at all soil depths, with the porosity in the uppermost depth being distinctly higher than the other depths. These differences in soil properties between the soil layers also indicate a progressive formation of distinct horizons in the soil.

The significantly higher porosity in the upper layer of the oldest moraine is caused by its thick organic layer (thickness up to 20 cm), which is characterized by porosity of up to 90 percent [this was also found by Nyberg (1995) in sandy-silty till on the west coast of Sweden and Carey et al. (2007) in organic soils in a permafrost region in northwest Canada].

Musso et al. (2019) investigated the evolution of pore sizes in the top 5 cm at the same soil chronosequence and found an increase in number of small soil pores and a decrease in relative proportion of macropores (pore diameter > 0.05 mm) between

160 and 10~~,~~000 years. Thus the high porosity in the organic top layer at the oldest moraine is mainly composed of small pores. The top layer therefore has an increased water storage and water holding capacity. Due to the finer soil texture and higher porosity the total storage water capacity of the oldest moraine is larger than that of the ~~the~~ younger moraines.

An investigation of the saturated hydraulic conductivity evolution of the near-surface (in 0-5, 5-20, and 20-40 cm) at the same chronosequence by Maier et al. (2019) found a decrease with increasing moraine age and soil depth. ~~The reduction in saturated~~ Saturated conductivity was found to be ~~positively correlated with soil texture, indicating that the increasing~~ negatively correlated with the fraction of fine particles~~with increasing age have even a bigger~~ . The decrease in gravel content and the increase in silt seem to have an even a stronger effect on the saturated conductivity ~~evolution~~ than the root network development (Maier et al., 2019).

Soil heterogeneity and vegetation complexity

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 ranges for all properties in the top layer in Fig. 6), but occasionally also individual depths show a higher heterogeneity, irrespective of age.

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 taken into account by averaging the volume density and surface area density across the five vertical profiles per subplot instead of relying on individual profiles. We therefore assume that the results of the flow path analysis are sufficiently representative to investigate their evolution across the chronosequence.

~~Evolution of flow paths~~

4.2 Evolution of flow paths

The flow type classification by Weiler (2001) was used to classify the volume density patterns into flow type categories. A comparison between the observations made during the excavation and the derived flow types showed that in this case an adaptation of the flow type classification was necessary. On the one hand, this adaptation involved the treatment of rocks to prevent mis-classification and, on the other hand, we introduced the possibility of finger-like flow paths with smaller widths. After these adaptions the derived flow types correspond well with the observations made in the field.

The observed staining patterns and derived flow types show a significant difference between the age groups, whereas no significant difference was observed with respect to vegetation complexity and irrigation amount.

The early years: 30-160

At the 30-year-old moraine the water infiltrates homogeneously into the soil, probably due to the very low vegetation coverage and the coarse material texture. The dye pattern showed a mainly homogeneous staining of the soil material, thus derived flow types are mainly matrix flow in form of homogeneous and heterogeneous matrix flow as well as matrix flow between rocks. Also finger flow occurs at the boundary to the clay layer or is caused by large blocks of rock, which are surrounded by clay. The determined macro pore flow takes place only within the clay layer at a depth below 50 cm. In the clay layer, no significant ~~macropores~~ biopores were identifiable, which is why it is assumed that the water is transported in cracks or along material interfaces. The upper coarse soil material with large pores and a low water holding capacity causes the water to be transported quickly deeper into the soil. ~~The water flow is mainly driven by gravity.~~

After 160 years the derived predominant flow types shift to heterogeneous matrix flow and finger flow. The observed widening of the dye plumes in deeper soil depths might be caused by a change in material or a reduction of hydrophobicity with soil depth where the influence of plants and organic material decreases (Blume et al., 2009). The dye coverage images show unstained soil areas starting also at the top of the soil profile, which indicates that preferential flow paths are initialized already at the soil surface or in the near-surface layer. This was also observed during the irrigation where we saw that the irrigated water often mainly infiltrated in depressions. Grass patches also tend to inhibit infiltration. It was observed that in the presence of dense grass patches, the water infiltrated only next to the patches, leaving the area below the patches unstained.

Intermediate stage: 3 000 years

Similar observations were made at the 3~~,~~ 000-year-old moraine. The image analysis revealed that preferential flow paths start at the soil surface and thus are initiated by vegetation and micro topography causing a heterogeneous infiltration pattern. Field observations also revealed that heterogeneous infiltration was not only created due to dense grass patches, but also occured under relatively homogeneous grass cover. A laboratory test of the water drop penetration time [DeBano (1981), Doerr et al. (2000)] on a soil sample of the upper soil material showed that the organic layer is highly water repellent in dry conditions (air dried for 2 weeks, water drop penetration time > 10 minutes). An increase in the Hydrophobicity Index (Tillman et al., 1989) with increasing moraine age was also found by Maier et al. (2019). Thus, we conclude that hydrophobicity of the organic top layer has a big impact on infiltration and the initiation of unstable flow. Unstable flow occurs when horizontal wetting fronts break into fingers or preferential flow paths during the downward movement (Hendrickx and Flury, 2001). Compared to the 160-year-old moraine the 3~~,~~ 000-year-old moraine is characterized by a higher number of narrower preferential flow paths. The derived dominant flow type class at the 3~~,~~ 000-year-old moraine is macro pore flow with high interaction/finger flow. Of both possible flow types, finger flow is the prevalent flow process causing the dye pattern. Several studies linked the formation of finger-like flow paths to hydrophobic properties of the soil [Wallach and Jortzick (2008), Dekker and Ritsema (2000), Ritsema and Dekker (1994), Blume et al. (2008), Wang et al. (2018), Hardie et al. (2011)]. It is assumed that hydrophobic compounds that are released during the decay of litter (Reeder and Jurgensen, 1979) or by root activity (Doerr et al., 1998) coat soil particles or are deposited in the pore space and thus create a hydrophobic soil matrix (Doerr et al., 2000). The humid and cool climate of former glacial areas leads to a slow decomposition of vegetation and thus to an accumulation of hydrophobic compounds (Doerr et al., 2000).

The late stage: 10 000 years

At the oldest moraine, we ~~see a significantly lower~~ saw a distinctly shallower infiltration depth (~~Figure~~ Fig. 7). During the experiment no surface runoff was observed. Most of the water was stored in the organic top layer. The soil beneath the top layer was almost completely unstained and water was transported only via a few macropores into deeper layers. A dense network of roots was only observed in the organic top layer, which included the thicker roots of the alpenrose (Rhododendron ferrugineum). The root network in the soil underneath was less dense with roots of smaller diameters but extended to a depth of more than 50 cm. Although the vegetation cover has been reduced to ~~lower~~ decrease interception, the interception storage capacity at the oldest moraine is still comparatively high. Thus, a reduction in the water available for infiltration cannot be ruled out.

Impact of rocks

The rock content at the 30, 160, and 3~~,~~ 000-year-old moraines is relatively high, with especially large rocks (widths > 20 mm) in deeper parts of the soil (~~Figure~~ Fig. 5(b) and Fig. 7). The large rocks lead to a reduction of the permeable area and thus can cause funnel flow (Hendrickx and Flury, 2001). This type of preferential flow was especially observed at the youngest moraine, where large boulders (> 25 cm) located at deeper soil depths were surrounded by unstained fine textured material. Smaller sized rocks in the upper part seemed not to have an influence on water transport (apart from reducing the flow-through volume), since these rocks and the surrounding soil were completely stained.

A splitting of flow paths caused by rocks was also observed a few times at the 160- and 3~~,~~ 000-year old moraines. In this case, water flowing past the sides of medium to large sized rocks create a type of finger flow that is not caused by water repellency or air entrapment. The tendency of higher rock contents to increase the number of flow paths was also found by Bogner et al. (2014).

Flow path controls along the age gradient

Integrating all of our findings on soil structural parameters, texture, vegetation cover and flow path patterns provides an overview over their co-evolution and highlights the derived major flow path controls (~~Figure~~ Fig. 11).

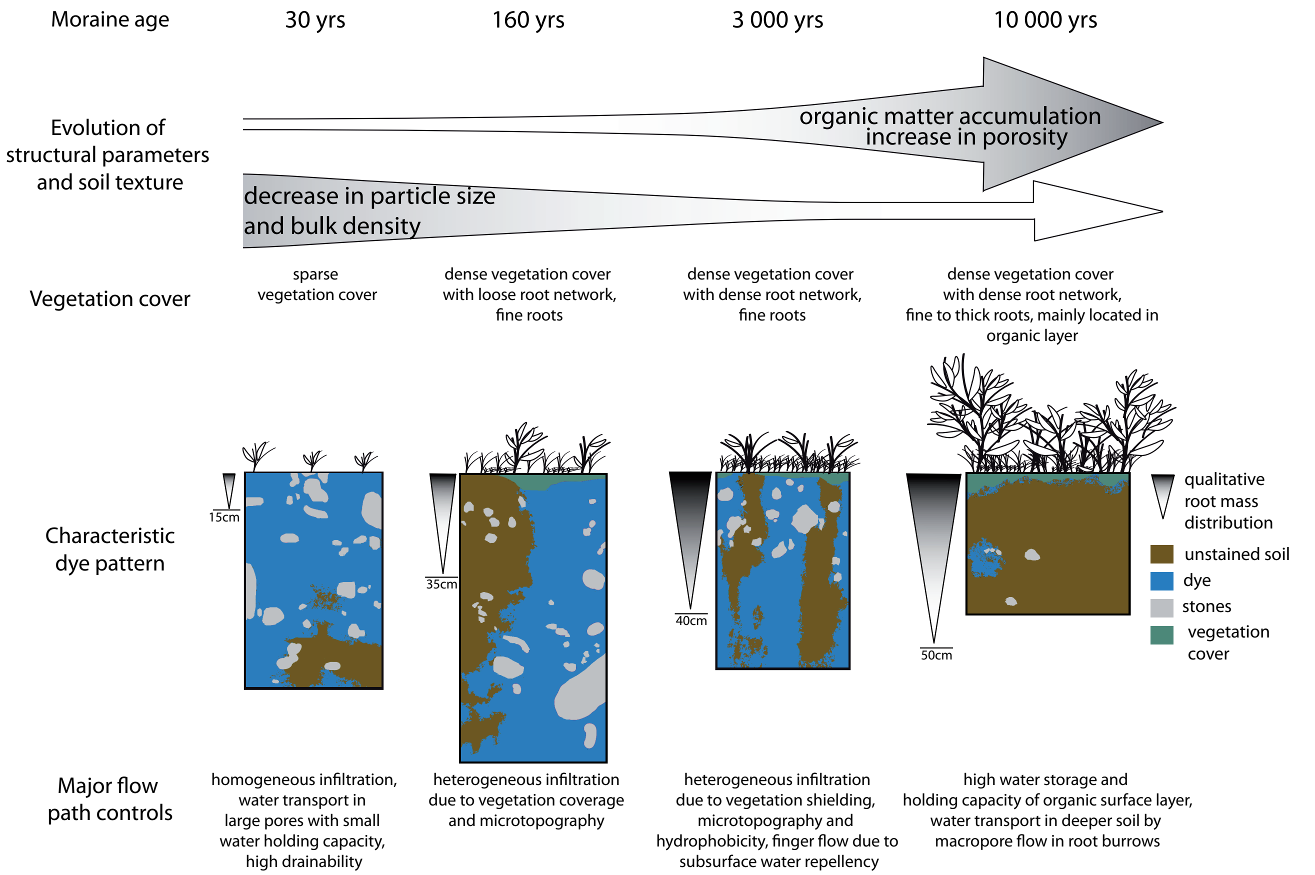


Figure 11. Sequence of observed characteristic dye patterns and derived flow path controls compared to the qualitative evolution of soil texture, structural parameters and vegetation. The shade of the root mass-distribution-triangles is a measure for the vertical root mass distribution with darker color indicating a higher root mass. The width of the triangles is a measure for the root mass comparison between the moraine ages, with broader triangles indicating a higher root mass.

Along the co-evolution of soil and vegetation over 10~~,~~ 000 years the major controls of subsurface flow paths change. At the youngest moraine flow paths are only controlled by soil texture. The coarse material leads to ~~mainly gravitation driven flow~~downward movement of the infiltration front. Preferential flow paths only occur at the interfaces between coarse and finer material.

At the medium aged moraines flow paths are mainly controlled by vegetation shielding, microtopography and hydrophobicity. The latter is assumed to have an increased impact at the 3~~,~~ 000-year-old moraine. After 10~~,~~ 000 years of hillslope evolution subsurface water transport is highly preferential and controlled by flow paths caused by root channels or boundaries of textural classes. Water storage in the organic layer which is also the main rooting horizon increases strongly.

5 Conclusions

Using brilliant blue dye experiments and soil sampling we investigated the evolution of water transport paths along soil forming processes. To our knowledge this is the first study examining flow path evolution across the ~~millenia~~ millennia in such detail. The evolution of the grain size distribution shows that ~~particle~~ grain size decreases with increasing age. The biggest changes are in the sand and silt fraction. Furthermore, ~~also~~ water flow defining structural parameters such as porosity and bulk density change during soil development, resulting in an increasing water storage capacity with age. The depth dependent evolution of these parameters ~~confirms~~ supports our hypothesis that the soil material develops with increasing age from a ~~homogeneous structure to a layered soil~~ homogeneously mixed material to a depth differentiated soil system with vertical gradients in flow and storage defining soil properties. Changes in these flow defining parameters are caused by the evolution of grain size distribution and vegetation.

~~We also confirmed the hypothesis that subsurface flow paths change significantly through the millenia, which is indicated by the derived flow types~~The derived flow types also support our hypothesis that vertical subsurface flow path types and their vertical extent change through the millennia. Flow types change from homogeneous ~~gravity driven matrix flow~~ matrix flow in a fast draining coarse textured soil to a heterogeneous matrix and finger flow over the first ~~100-1,~~100-3 000 years. At very young moraines the water is homogeneously distributed within the soil matrix. However, the water storage capacity is relatively low due to the coarse material and water is transported quickly deeper into the soil due to ~~gravity driven flow~~the high drainability. At the medium age moraines, water is transported preferentially via finger-like flow paths deeper into the soil by leaving parts of the soil dry.

With increasing hillslope age, we expected macropores induced by root activities to become more important. After 10~~,~~ 000 years, were the amount of soil matrix macropores decreased significantly, macro pore flow along roots plays an important role, but is not very pronounced. Only a few roots reach beyond the organic top layer. However, this allows a fast transport of water from the upper layer into deeper soil. The organic top layer has a pronounced influence on the soil water budget, by storing a significant amount of water. The increase in water storage with increasing age of the moraines also caused a reduction in infiltration depth.

The ~~influence~~ proportion of preferential flow paths increases with soil age. Preferential flow is, however, not only caused by macropores, but especially for the medium-age moraines seems more controlled by soil surface characteristics such as vegetation patches, micro-topography and hydrophobicity. Thus, the evolution of flow paths is tightly linked to the complex interplay of soil forming processes and vegetation development over the millennia. A lot of changes in vegetation cover, soil (hydraulic) properties and flow paths ~~already~~ occur within the first 160 years.

It was shown that the complex interaction of vegetation and soil development and its proven effect on flow path development also impacts the water balance, as the storage and conductivity properties of the soil change. However, the interplay between preferential flow paths and the soil hydraulic behavior not only influences the soil water budget, but also runoff formation. These findings provide important insights on hydrological flow path evolution in transient systems.

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