1 Author´s response

Low Below-Ground Organic Storage in a Subarctic Alpine Permafrost Environment

This document is a combination of the **Author´s response** including 1) comments from Referees, 2) author´s response, 3) author´s changes in manuscript, and following to that part, the **revised manuscript** is added with all the changes and corrections made in the manuscript. All the changes made in the manuscript are visible.

In the first part, in the chapter "Author´s changes in the manuscript", there are always page and line numbers to find the corrections in the second part where the revised manuscript is added with all its corrections and improvements.

1.1 A Response to referee#1

A General comment of referee#1

This article discusses the soil organic carbon storage of an alpine site in northern Sweden. This research is important in that few alpine SOC assessments have been done and our understanding of circumpolar arctic SOC storage is lacking in alpine regions. It is a well-written paper with nicely composed graphics and tables. With a few modifications and clarifications, it will make an excellent contribution to the literature on arctic SOC storage.

A Author´s response

Thank you for your positive feedback and the comments on our discussion paper. We hope to address with this reply all your suggestions and questions. We follow the same order like you did in your comments.

A Author´s changes on the manuscript

No changes made on the manuscript following the general comment of referee#1

A 1.1 Referee comment 1:

Page 3497 lines 24-26: were these samples collected from the pit face (horizontal sampling) or vertically? Was soil of uniform nature (sans cryoturbation) such that one sample per 5-10cm was sufficient to capture any variation? What horizonation is present?

A 1.2 Author´s response

Page 3497 lines 24-26: The samples were collected vertically by hammering down a steel pipe. Only the organic rich top soil layer was sampled from the pit dug. (This organic rich top soil layer was in average only 2.4 cm thick). In general, the whole vertical profile was sampled from top to the depth of 1 meter, if possible. In general, we collected the whole profile in 10cm increments, meaning that we got, in the best case, 10 samples with a length of 10cm for each profile (plus the organic rich top soil layer). Therefore, we collected the whole profile and not only one sample per 5-10cm.

The soil was mostly of uniform nature without any cryoturbation with a shallow O/A-horizon and a weak b-horizon. In general, the soils were very shallow so that we reached the bedrock in average already at c. 30cm depth of the profile.

A 1.3 Author´s changes in manuscript

Included the word *"vertically"* on page 17, line 25

Included the sentence *"Coring was pursued so that the whole profile was collected to a depth of one meter, if possible. [...] The soil was mostly of uniform nature and during collection of soil samples no indication of soil organic matter buried through cryoturbation could visually be detected."* on page 17, lines 26-30.

A 2.1 Referee comment 2

Page 3498: Are your LCC based on a standard class scheme used by others? Define how you came up with the 9 classes.

A 2.2 Author´s response

Page 3498: The LCC was not based on another standard class scheme. These classes were established based on the field observations and was adapted to the land cover classes present in the study area. Of course, more detailed land cover classes could have been established but the generalization into nine main classes was suitable for establishing a LCC based on remotely sensed data.

A 2.3 Author´s changes in the manuscript

Changed / Added the sentence *"Nine dominant land cover classes were recognized in Tarfala Valley, which form the basis for establishing a land cover classification based on field- and remotely sensed data. The classes are presented in the supplementary material (Table S1)."* on page 18, line 15-18.

A 3.1 Referee comment 3

Page 3499 lines 20-22: Again it looks like you are assuming carbon uniformity for each depth sample. Is that the case? You should note to the reader the degree (qualitative) of cryoturbation (or lack of) so that you are not over/underestimating SOC storage at each site. If you have patterned ground at the surface, you likely have visible cryoturbation in the subsurface which complicates quantification. Was it simply visually assessed? You note something to this affect in the abstract (absence of cryoturbation), but it would be worth noting again in the main body (methods). I do see note of it again on 3503 lines 4-6, but would love clarification of this earlier in the main body.

A 3.2 Author´s response

Page 3499 lines 20-22: For the analysis we took a representative sub-sample of the whole sample (which was usually 10 cm long with a diameter of c. 4cm). This, which we applied for all the samples we collected, gave us a mean carbon value for every 10cm of the soil depth resulting in 5-10 carbon values for the profile, depending on the profile depth. We did not find any signs of cryoturbation in the samples. However, we did not dug whole pits, we had only the profile samples we collected by pipe. The presence of cryoturbation assessed visually and by examining the laboratory results. There was no positive outlier of OC with depth. We have neither visual nor laboratory results, which would indicate buried organic carbon through cryoturbation. We conclude that there is no indication of organically enriched (i.e. A or O horizons) soil horizons buried by cryoturbation in any core. We acknowledge that soil movements by cryoturbation likely occur in this area, but it seems that it mainly affects poorly developed soil horizons and rocks and thus does not cause significant burial of SOC down the soil profile.

We will mention *cryoturbation* earlier in the main body as you suggested at page 3498, line 2: "[…] full reference depth of 100cm. *When collecting the soil samples no indication for buried organic carbon trough cryoturbation could visually be detected.* Furthermore, permafrost was never encountered during […]"

A 3.3 Author´s changes in the manuscript

Added the sentence *“[…] during collection of soil samples no indication of soil organic matter buried through cryoturbation could visually be detected”* on page 17, line 29-30 as well as added a part in the results where we state that even the laboratory results showed no signs of cryoturbation. (*“During field sampling there were no observations of buried SOM through e.g. cryoturbation or solifluction. Similarly, the laboratory results showed no single value or outlier with high %C below the top organic layer. Therefore, there are neither visual nor laboratory results indicating burial of organic carbon to depth in the investigated soil profiles.”* on page 22, lines 15-19).

A 4.1 Referee comment 4

Page 3502 lines 6-8: “This low SOC storage is a result of the large percentage of bare rock and stones, which cover almost 60 % in the study area.” Are you stating that the low subsurface SOC storage is a result of high surface rock coverage? While this may be true (i.e. current lack of carbon-containing plants), it is jumping to a conclusion a bit too soon in the paper. Save that for the discussion after you have provided more detailed data. Older carbon from older plants could still be there even with current surface rock coverage (we don’t know the contrary yet at this point in the paper).

A 4.2 Author´s response

Page 3502, lines 6-8: Ok thank you for the advice, we will change this.

A 4.3 Author´s changes in the manuscript

The sentence *“This low SOC storage is a result of the large percentage of bare rock and stones, which cover almost 60% in the study area”* was removed from page 21, lines 12-13. We wrote about this fact on page 25, lines 3-4 already in the discussion in the first manuscript. Therefore we will not add additional sentences on this topic in the discussion.

A 5.1 Referee comment 5

Page 3502 lines 21-22. The within class SOC variability seems important here. Can you expand on it? What are some of the possible reasons for it if cryoturbation is not a factor?

A 5.2 Author´s response

Page 3502, lines 21-22: As written on the following lines in the text, the variability of soil depth even within the same land cover class was an important factor that affected the organic carbon storage. We found large differences in profile depths when sampling. This is also shown in the high standard deviation in the soil depth of each LCC (Table 1). The high standard deviations of means of the SOC storage would maybe require a higher separation into sub-classes. This is however difficult to achieve in both the field and the land cover classification based on remotely sensed data.

Another factor is the coarse fragment fraction which was also different from profile to profile site and not uniform for single LCCs.

A 5.3 Author´s changes in the manuscript

The sentence about the coarse fragment fraction as well as a clarification was included that the SOC variability of LCCs is dependent on the high variability of sample depth in LCCs on page 21, lines 25-30.

A 6.1 Referee comment 6

Page 3504 line 5-10. In future studies I would recommend doing radiocarbon dating also on deeper soils even if they don’t have thick organic-rich surface horizons.

A 6.2 Author´s response

Page 3504, lines 5-10: Thank you for this advice, the current limited selection of radiocarbon dates reflect the financial resources that were available for ^{14}C dating.

A 6.3 Author´s changes in the manuscript
No changes made in the manuscript

A 7.1 Referee comment 7
Page 3507 line 17: “More abundant stone cover” than what? Important to clarify this.

A 7.2 Author´s response
Page 3507, line 17: Did you mean Page 3506, line 17? If so: In every land cover class there was a certain amount of stones present. Therefore, when we classified an area as “Patchy boulder moss” this meant that this area consists mostly of mosses on the ground but also of stones, which was in average 42% in the case of the class “Patchy boulder moss” (see Table S1, supplementary material). So, the abundant stone cover meant that there is a stone coverage in each class, even if it appears as vegetated in the LCC. For not overestimating the SOC stock in the different classes, we weighted the SOC stock of each LCC by the mean percentage of stones within a LCC as we considered that stones contain no organic carbon. The mean stone coverage in each LCC is presented in the supplementary material Table S1.

A 7.3 Author´s changes in the manuscript
The sentence *“The particular fraction of stone coverage in the different land cover classes varied between 4% and 47% (the soil volume occupied by stones was considered devoid of SOC in stock calculations)”* was included on page 25, lines 7-9. Additionally, there was also a section on page 19 lines 19-23, which explained the methods how this abundant stone cover was included in the SOC storage calculations.

A 8.1 Referee comment 8
Page 3507 lines 19-21: While shallow soils might accumulate less SOC than a deeper profile, it is not necessarily the primary (or secondary) cause of low overall SOC storage (some shallow peat soils have very high SOC storage). I would move the cryoturbation statement (line 20-21) in front of the shallow soil statement to indicate the greater importance of cryoturbation in potentially burying carbon (rather than its third place position (currently) which feels a bit of an afterthought.)

A 8.2 Author´s response
Page 3507, lines 19-21: We agree, shallow soils could indeed be carbon rich. Our statement is overgeneralized, but applies to Tarfala Valley where we did not find any evidence for peaty layers and in our study shallow soils have accumulated less organic carbon (in total) than deeper profiles. We will switch the statements as the lack of cryoturbation is probably a more important factor for low SOC storage.

A 8.3 Author´s changes in the manuscript
The cryoturbation statement was moved to page 25, lines 9-12, in front of the shallow soil statement.

A 9.1 Referee comment 9
Figure 1. Hard to distinguish between the shades of gray in sand/gravel and stones category.

A 9.2 Author´s response
Figure 1: Thank you for the advice, we will change this.

A 9.3 Author´s changes in the manuscript

We changed the colour of the land cover class sand/gravel to light brown.

A 10.1 Referee comment 10

Figure 2. Use of X to indicate area coverage of each class is a bit awkward. I wonder if the percentage written as text above each column would be better.

A 10.2 Author´s response

Figure 2: Thank you for the advice, we will try out written text instead of the X for the percentage area coverage.

A 10.3 Author´s changes in the manuscript

We changed figure 2 according to the referee’s suggestions.

A 11.1 Referee comment 11

Supplement Fig 1. Colour classes difficult to distinguish between. Suggest user selected colour classes rather than software default colour palette.

A 11.2 Author´s response

Supplement Fig 1: Ok, thank you for the advice. We will change it.

A 11.3 Author´s changes in the manuscript

We changed the colours according to the referee´s suggestion.

A 12.1 Referee comment 12

Table S1: Nice to show what the surface cover looks like, but I would love to see a representative subsurface (pit profile) from each class too. Visual evidence to show that there is a lack of cryoturbation.

A 12.2 Author´s response

Table S1: We sampled with a steel pipe in 10cm increments but did not dig pit profiles. Therefore we unfortunately do not have subsurface pictures from the profile sites.

A 12.3 Author´s changes in the manuscript

Unfortunately we cannot add pictures from the profile sites, therefore no changes were made on the manuscript.

1.2 B Response to referee#2

B General comments of referee #2

General comments: According to the title of the paper, the authors planned to show the soil organic carbon storage in a subarctic alpine permafrost environment in the Tarfala Valley, which is situated in the Scandes mountains of northern Sweden. After the brief mention at the beginning of the paper, it was indicated that the soils in the study area are Leptosols, Regosols and Turbic Cryosols. However, no mention is made as to which of the 56 pedons sampled have these soil types. They also neglected to include the basic properties of these soils and which pedons have been included in which land cover types. Later, the permafrost was discussed in detail although none of the soils were associated with permafrost. It appears that the authors are trying to ‘stuff’ a number of non-soil related aspects into the paper. As a result, they lost the real objective of the paper, which is the soil carbon. In addition, they provided no clear pedological explanation as to why the organic carbon was low in these subarctic alpine soils.

B Author´s response

Thank you for your comments on our paper. We hope to address all your comments and suggestions in this response. You bring up a lot of points including several suggestions that are useful to improve the manuscript. We wish to initially give our views on the general comments provided by the referee. More specific responses to individual issues are given below.

General comments

The referee objects to the fact that the word soil appears in the title when the paper contains no map of soil or classified pedons. We understand that a reader may expect to find more detail on pedology in a paper with this title and we will strive to accommodate this. We propose that a revised version of the manuscript includes a supplement summary of the pedon classifications related to land cover classes and SOC storage.

The referee suggests that we have “stuffed” a number of non-soil related aspects into the paper which has led us to lose sight of the true objective. On the contrary, the initial objective was always to provide an integrated landscape study of this valley, which included both land cover, geomorphology and permafrost characteristics. We consider land cover and geomorphological characteristics to be relevant indicators of soil types and many studies have shown that land cover can successfully be used to estimate soil organic carbon storage (see e.g. Kuhry et al., 2002; Ping et al., 2008; Hugelius and Kuhry., 2009; Horwath Burnham and Sletten, 2010, Hugelius et al., 2010; 2011). If our aim had been to carry out a pedological study, we would have focused on detailed studies of fewer profiles and applied a pedological analysis. With our initial aim of a complete landscape study in mind we designed a field sampling campaign that aimed to cover as many land cover types at different elevations as possible.

The referee also complains that the paper discusses permafrost in detail despite that fact that we did not encounter permafrost during soil sampling. Our study area has permafrost and is located within the northern circumpolar permafrost region (Brown et al., 1997). In recent decades, several studies have emphasized that soils of the permafrost region are very rich in SOC and many studies also emphasise a potential increase in greenhouse gas fluxes from permafrost SOC under a warming climate. We include permafrost mapping to very clearly demonstrate that for this particular study area there is no potential for a strong positive permafrost-carbon feedback with climate warming. Our paper includes discussion and comparison to other studies of alpine SOC as well as a direct comparison showing the large differences between our estimates and what was estimated using the Northern Circumpolar Soil Carbon Database (Tarnocai et al., 2009) for this same study area. Within this context we maintain that a careful analysis of permafrost conditions is relevant and interesting.

B Author´s changes in the manuscript

A table containing the pedon classification was added in the supplementary material (Table S2).

B 1.1 Referee comment 1

Page 3493. I find that the title of this paper does not represent the content of the paper. First, the soil organic carbon is presented on a land cover basis (mainly vegetation), not on a soil map. Secondly, no permafrost was encountered in any of the soils that were sampled. Permafrost may occur at a deeper depth (>4-15 m) but, as far as the soils are concerned, the area is associated with a non-permafrost soil environment. Thirdly, there is no big surprise about the low soil organic carbon since none of the soils are affected by cryogenic processes. I would suggest that the title be changed to "Below-ground organic carbon storage in a subarctic alpine environment in northern Sweden."

B 1.2 Author´s response

Page 3493. The referee states that the title does not represent the content of the paper. This statement is based on the three points which we address separately:

"First, the soil organic carbon is presented on a land cover basis (mainly vegetation), not on a soil map." We have accepted this suggestion and changed the title to "Below-ground carbon…" to avoid confusion regarding the papers content. We have upscaled our SOC estimates based on a land cover classification. Vegetation or land cover has been successfully used in many previous studies of SOC in high-latitude and high-altitude ecosystems (see e.g. Kuhry et al., 2002; Ping et al., 2008; Hugelius and Kuhry., 2009; Horwath Burnham and Sletten, 2010, Hugelius et al., 2010; 2011). We maintain that land cover based upscaling is a suitable choice for the present study. We acknowledge that a soil map would have been a nice complement to this study; however that is outside the scope of this study. Hugelius (2012) provides a more detailed discussion on the relative merits of land cover or soil maps for this type of thematic upscaling.

"Secondly, no permafrost was encountered in any of the soils that were sampled." We agree that no permafrost soil was sampled for SOC. But we maintain that Tarfala Valley is nevertheless a permafrost environment. As stated in our study area description, the active layer is documented to ca. 1.5 m in the upper part of the valley while the bottom of the valley is likely permafrost free. It is also interesting to emphasize that we are studying a permafrost environment that actually has very limited extent of permafrost in soils. This dichotomy is especially interesting in the context of the permafrost-carbon climate feedback (see our response to the general comments above).

"*Thirdly, there is no big surprise about the low soil organic carbon since none of the soils are affected by cryogenic processes."* We agree that the soils are relatively unaffected by cryogenic processes, especially compared to e.g. High Arctic soils of Pleistocene-aged landscapes. Regardless, we argue that the referees lack of surprise at our results is not a valid argument for removing the discussion of permafrost from the manuscript.

B 1.3 Author´s changes in the manuscript

We changed the title to *"Low Below-Ground Organic Carbon Storage in a Subarctic Alpine Permafrost Environment"*

B 2.1 Referee comment 2 and 3

Page 3496, lines 23-26. The authors indicate that, in this section, the soils in the study area are classified as Leptosols and Regosols and that in areas affected by frost-thaw cycles, the soils are Turbic Cryosols. How can they be Turbic Cryosols if, in a number of places in the paper it is mentioned that none of the pedons sampled have permafrost or any cryoturbation (page 3503, lines 4-6).

Page 3497, line 10. Permafrost is currently not present in a 15 m depth borehole at an elevation of 1135 m. The active layer depth in the valley floor is 2.5-4 m. This is a clear indication that none of the soils in the study area are Cryosols. In addition, it is also stated on Page 3498, Line 2-3 that "permafrost was never encountered during coring, even at higher elevations."

B 2.2 Author´s response

Page 3496, lines 23-26 and Page 3497, line 10. For clarity we start by stating that the short description of soils given in the study area is based on a combination of the 56 sampled profiles as well as an independent field survey by the authors. This will be clarified in a revised version of the manuscript. In the case of the soils of the upper valley, the combination of strong patterned ground formation with permafrost in the top two meters leads us to classify the soils here as Turbic Cryosols. The observation of active layer depth is from the PACE borehole as cited in the Study Area description (p3497, lines 7-10). Note that we describe "*no signs of SOC burial by cryoturbation or solifluction*" in our study. That does not mean there is no cryoturbation in the soils. There is extensive cryoturbation and frost heave of stones and mineral gravel/loam in the upper reaches of the valley. But because there is no measureable SOC in this material it does not affect the SOC storage which is what we were studying.

B 2.3 Author´s changes in the manuscript

The soil section on page 16, lines 26-31 in chapter 2 "Study area" was changed into the following: *"The Tarfala Valley is characterized by little and very shallow soil development. The predominant soils in the study area are characterized by very limited soil formation with poorly developed soil genetic horizons, high stone content and shallow regolith. These soils are classified as Leptosols and Regosols. (IUSS Working Group WRB, 2006). On Tarfalaryggen, soil movement caused by frost-thaw cycles (cryoturbation) have led to patterned ground formation and there is permafrost in the upper 2 meters of soil; these soils are classified as Turbic Cryosols. In riverbed deposits of glacial streams (e.g. in the glacier forefield of Isfallsglaciären) soils are classified as Fluvisols."*

A table containing the pedon classification and the corresponding land cover class was added in the supplementary material (Table S2).

B 3.1 Referee comment 3

Referee comment 3 was covered already in B 2.2

B 4.1 Referee comment 4

Page 3498, lines 24-26 and Page 1-3. Why has the organic carbon been determined for 199 samples using the loss on ignition (LOI) method and 96 samples using the CarloErba NC 2500 elemental analyzer? The LOI is not a recommended method for determining the percent of organic carbon, as is stated by D.W. Pribyl (Geoderma, 2010, 156:75-83). The conversion factor is not a universal physical constant. It may vary due to the types of vegetation, the amount and composition of the organic matter, and the depth of the sample in the soil profile. Pribyl further states that the LOI method provides only an estimate of the soil carbon content. He also points out that, for soil organic carbon studies, the amount of carbon should be determined directly rather than by relying on an estimate. Therefore, I would suggest that the LOI data not be used as an equivalent to the data determined by the CarloErba NC 2500 elemental analyzer.

B 4.2 Author´s response

Page 3498, lines 24-26. We fully acknowledge that it would be preferable to base all analyses on direct measurements with an elemental analyser. Because of financial and logistical constraints we were able to carry out elemental analyses on 96 samples, while the remaining samples 199 samples were analysed using LOI. Such constraints are unfortunate, but a part of reality for most researchers. The paper by Pribyl (2010) which the referee mentions is entitled "*A critical review of the conventional SOC to SOM conversion factor*". As the name states it is a critical review of the commonly used conversion factor to estimate SOC from loss on ignition (1.724). We agree with this conclusion by Pribyl (2010) and we did not use the LOI values with a fixed conversion factor but instead developed a local transfer model. We had the capacity for 96 samples with the CarloErba NC2500 elemental analyser and got the %C values for these samples. With these 96 values we applied a statistical regression analysis with the LOI values of these 96 samples and applied the resulting third order polynomial function on the LOI results of the remaining 199 samples.

B 4.3 Author´s changes in the manuscript

We included the sentence *"Rather than using a constant conversion factor, this is based on a third order polynomial regression between the C percentage (C,%) and LOI for those samples where both parameters were measured (n=96, r2=0.95)"* on page 19 lines 4-6 for making clear that we did not just apply a conversion factor for the calculation of %C from loss-on-ignition results.

B 5.1 Referee comment 5

Page 3503, lines 12-13. The organic carbon content of the organic-rich surface soil horizon(s) are almost always higher than the underlying mineral horizons in non-permafrost soils. You do not need a statistical analysis to find this out.

B 5.2 Author´s response

Page 3503, lines 12-13. We are aware that these results are likely not surprising to most readers. In the absence of pedogenic processes that accumulate sub-surface SOC it is indeed common to have the highest SOC content (density) in the upper soil horizons. There are however many cases where the SOC density is actually higher in the mineral sub-soil (see e.g. Harden et al. 2012) than in surface O-horizons. In this context this statistical analysis of our data seems justified.

B 5.3 Author´s changes in the manuscript

No changes made in the manuscript.

B 6.1 Referee comment 6

Page 3504, lines 5-13. This is the first time in the paper that soil development in relation to carbon was mentioned. Therefore, the 56 pedons sampled represent a variety of soils based on their development.

B 6.2 Author´s response

Page 3504, lines 5-13. We agree with the referees comment that the 56 different profiles span across a range of different soil development.

B 6.3 Author´s changes in the manuscript

No changes made in the manuscript.

B 7.1 Referee comment 7

Page 3506, lines 15-22. It is unfortunate that the authors have not clearly pointed out the main pedological reasons for the low SOCC. The High Arctic soils are associated with a higher percentage of bare, stony ground and sparse vegetation cover than those used/studied in this paper in spite of the fact that these High Arctic soils contain many-fold higher SOCC than the Swedish soils. These High Arctic soils have the pedological processes (not only/just cryoturbation), so they can store organic matter for thousands of years. The soils studied in this paper behave just like their southern neighbours. They do not have the pedological processes that are able to concentrate and hold organic matter in the subsoil.

B 7.2 Author´s response

Page 3506, lines 15-22. We fully agree that a revised version of this paper would benefit from a deeper discussion of the pedogenic processes that lead to the formation of SOC stocks in cold-region soils. We will strive to accommodate this suggestion in a revised version of the manuscript.

B 7.3 Author´s changes in the manuscript

We included the sentence *"The active layer in Tarfala Valley is significantly deeper than the depth of active soil formation, which means that organic carbon decomposition is not impeded by sub-zero temperatures during the warm season. The steep topography and coarse sediments favor rapid drainage and aerated soils. No peat formation or peaty soils was observed in the Tarfala Valley. Finally, the soils are rather shallow; in most cases they do not reach a depth of 1 m and sometimes not even 30 cm. As a consequence of all these factors, the soils in Tarfala Valley are not characterized by any of the pedogenic processes that often lead to the accumulation of high stocks of SOC in permafrost region soils (Tarnocai et al., 2009)."* in the discussion on page 25, lines 15-22.

B 8.1 Referee comment 8

Table 1. The SOCC is presented in this table according to the cover classes. There is no information in the paper as to which pedons are included in these various cover classes. I assume that the column called "profile site" is the sampling depth of the pedon. According to this data, most of the pedons were only sampled to the16-40 cm depth and only one pedon was sampled to the 53 cm depth. Since most of the pedons have been sampled only to a very shallow depth, the SOCC calculated for 100 cm is completely unreliable. Lastly, I am not sure how to interpret the data in the last column of this table relating to "sites in permafrost."

B 8.2 Author´s response

Table 1. We believe that the referee has misinterpreted this table. It does not show individual pedons but aggregated mean values for different classes. The sub-headline "Profile Site" is under the headline "Mean Profile Depth", therefore the values in this column represent the mean profile depth for the sites for the different LCC. So it is not the case that the profiles were only sampled to 40 or 56 cm. These columns below "Mean Profile Depth" indicate only the mean values and not the maximum values of sampled depth. There were profiles to a depth of 80 cm, but it is true, most profiles were

rather shallow, but this was due to shallow soils. In most cases, the underlying bedrock was the reason for shallow profiles.

In our calculations, we considered bedrock as zero carbon. So we calculated to a depth of 1 meter even though the profiles were shallower. So the values for 1 meter do not indicate that the soil was 1 meter deep. On the other hand, which reference depth, beside 30 cm, should have been chosen instead? There was no uniform soil and/or sampling depth. There would have always been some bedrock included in the calculations. Therefore we thought it is reasonable to take the common reference depths of 30 and 100 cm.

The SOCC for 0-100 cm indicates how much carbon in present in the first meter, but it does not say that this carbon is distributed uniformly in this first meter. For a comparison, the mean SOCC values of 0-30 cm and 0-100 cm are given in Table 1.

The last column “Sites in Permafrost” indicate how many of the profile sites in a particular land cover class are situated in the different mapped zones of continuous, discontinuous, sporadic, or isolated patches / no permafrost.

B 8.3 Author´s changes in the manuscript

A table containing the pedon classification and the corresponding land cover class was added in the supplementary material (Table S2).
No changes were made on table 1.

B 9.1 Referee comment 9

Figure 1. Maps A and B are so small that it is difficult to read them, even with a magnifying glass. I think that maps like these are especially important and should be able to be read easily with a “naked” eye. I would suggest including only maps A and B but make them at least twice the size presented here.

B 9.2 Author´s response

Figure 1: The purpose of Figure 1 is not only to show the areas where we collected the soil samples but also to show and introduce the entire study area. Therefore, we think it is important not only to show maps A and B. The size of the map already covers an entire page but we will try to make it a little bit wider. If the map was presented in the A4 format rather than the screen format of TCD it would likely be larger and easier to read.

B 9.3 Author´s changes in the manuscript

We made figure 1 a little bit wider, increased the font size and increased the scale of maps A and B. It is hoped that Figure 1 will be printed on a whole page so that it is easily readable. We tried to make it as visible and informative as possible.

B 10.1 Referee comment 10

Figure 3. Why is there such a great variation (0.3-3.0 g cm3) in bulk density for the mineral samples, especially since the organic matter content is low? In these graphs it appears that data is available for some pedons to a depth of 80 cm. It would be very useful to see the properties of the individual pedons.

B 10.2 Author´s response

Figure 3: The variation in bulk density is difficult to explain. But one reason might be the sampling technique. We sampled by hammering down a steel pipe into the soil. Normally the sample with known volume stayed in the pipe. In most cases, this worked fine, however in a few wet, sandy spots, it might have happened that the sample volume got disturbed which would explain the high bulk densities >2 g cm^{-3}. On the other side, the carbon values were very low for these sandy samples. The elemental analyses showed carbon values below 1%. Nevertheless, we wanted to show the complete data set analysed with the CarloErba NC2500 elemental analyser, even though some bulk density values are questionable.

In the supplementary we show the properties of two individual pedons where we have the radiocarbon dates as well.

B 10.3 Author´s changes in the manuscript

In the figure caption of Figure 3 the following sentence was added to explain the high bulk density values: *"Some high bulk density values (up to 3.0 g cm-^{3}) in sandy profile sites are probably the result of errors in field volume estimates due to difficulties in collecting these loose materials."* on Page 41, lines 6-8.

B 11.1 Referee comment 11

Figure 4. Showing the permafrost probability in relation to altitude has some usefulness but not for the soils sampled here since none of the 56 pedons sampled contain permafrost.

B 11.2 Author´s response

Figure 4: Thank you for this comment. Indeed, the figure is maybe not so relevant for the individual sampled pedons, but we maintain that it is highly relevant to demonstrate how unlikely it is to find permafrost SOC in this permafrost environment. The figure is also useful in the context of the future trajectory of the C cycling in the Tarfala Valley as discussed in chapter 5.2.

B 11.3 Author´s changes in the manuscript

No changes are made in the manuscript.

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Low ~~Soil~~ Below-Ground Organic Carbon Storage in a Subarctic Alpine Permafrost Environment

Kommentar [MF1]: Title changed according to referee #2 B1.1

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Abstract

This study investigates the soil organic carbon (SOC) storage in Tarfala Valley, Northern Sweden. Field inventories upscaled based on land cover show that this alpine permafrost environment does not store large amounts of SOC, with an estimate mean of 0.9 ± 0.2 kg C m^{-2} for the upper meter of soil. This is one to two orders of magnitude lower than what has been reported for lowland permafrost terrain. The SOC storage varies for different land cover classes and ranges from 0.05 kg C m^{-2} for stone-dominated to 8.4 kg C m^{-2} for grass-dominated areas. No signs of organic matter burial through cryoturbation or slope processes were found and radiocarbon dated SOC is generally of recent origin (<2000 cal yr BP). An inventory of permafrost distribution in Tarfala Valley, based on bottom temperature of snow measurements and a logistic regression model, showed that at an altitude where permafrost is probable, the SOC storage is very low. In the high altitude permafrost zones (above 1500 m), soils store only ca 0.1 kg C m^{-2}. Under future climate warming an upward shift of vegetation zones may lead to a net ecosystem C uptake from increased biomass and soil development. As a consequence, alpine permafrost environments could act as a net carbon sink in the future, as there is no loss of older or deeper SOC from thawing permafrost.

1 Introduction

The permafrost-affected soil area in the northern circumpolar region is widespread, occupying about 1~~8.~~7.8 million km^2 (~~Tarnocai et al., 2009~~Hugelius et al., 2014). The soils in the northern permafrost region store large amounts of soil organic carbon (SOC), which are vulnerable to

Kommentar [MF2]: updated

climate change. With a warming climate, which is expected to be most pronounced in northern high latitudes, thawing permafrost soils may cause remobilization of soil organic matter (SOM) previously protected in permafrost (Gruber et al., 2004; Schuur et al., 2008). This can lead to an increased microbial decomposition of SOM and a release of carbon dioxide (CO_2) and methane (CH_4) to the atmosphere. As a consequence, permafrost soils may act as a future carbon (C) source and lead to a positive climate feedback. However, the total storage of SOC within the northern permafrost region and the amount of greenhouse gases that can be released to the atmosphere and trigger accelerated climate warming are still uncertain (Schuur et al., 2009; Kuhry et al., 2010; McGuire et al., 2010; Schuur et al., 2013).

Several local to regional scale studies have been carried out to investigate stocks of SOC in northern permafrost environments, e.g. Michaelson et al. (1996), Kuhry et al. (2002), Zimov et al. (2006a), Ping et al. (2008), Horwath Burnham and Sletten (2010) and Hugelius et al. (2010, 2011). ~~Tarnocai et al. (2009)~~ Based on the Northern Circumpolar Soil Carbon Database (NCSCD), Hugelius et al. (2014) estimated the 0-300 cm SOC stock in the northern permafrost region to be 10~~24~~35 ±150 Pg C (±95% confidence interval),~~ based on the Northern Circumpolar Soil Carbon Database (NCSCD)~~. However, many regions in the NCSCD are under-represented and contain few sampled pedons, leading to a much generalized estimation of the C stocks for some remote areas (Mishra et al., 2013). Especially in regions of thin sedimentary overburden, including highlands and alpine terrain, estimates are based on limited data and assosciated with wide uncertainty ranges (Hugelius et al., 2014).~~Especially in the Eurasian and the High Arctic sectors, confidence for C estimates is low (Tarnocai et al., 2009).~~

~~Limited data are available for the more mountainous areas in the northern permafrost region.~~ This study presents a detailed SOC inventory for a subarctic alpine permafrost environment by investigating the C stocks in soils of the Tarfala Valley, Northern Sweden. It is essential to establish to what extent these type of environments contribute to the large SOC storage in the northern permafrost region. Mountain areas and alpine permafrost are sensitive to climate change due to steep ecoclimatic gradients. The aim of this study is to assess the permafrost extent and SOC pools in a subarctic alpine environment, and evaluate their potential fate under conditions of future global warming.

Kommentar [MF3]: updated

2 Study area

Tarfala Valley is located in the Scandes mountains of northern Sweden, at c. 67°55 North and 18°37 East. The study area (31.2 km^2) is delineated based on the catchment of Tarfala River (Tarfalajåkk), which drains into the broader Ladtjovagge. It includes the alluvial fan of the Tarfala River to encompass the entire altitudinal gradient from the source to the outlet of Tarfala River. The area ranges between 550 and 2100 m above present sea level (a.p.s.l.) and is characterized in the upper part by six glaciers that drain into Tarfala River (Figure 1).

The mean annual air temperature (MAAT) at Tarfala Research Station is -3.4°C (1965-2009) and the mean annual precipitation for the Tarfala River catchment is 1997 mm (Dahlke et al., 2012). The MAAT in Tarfala has increased by 0.54°C per decade for the period 1969 – 2009, whereas the mean annual precipitation did not change significantly (Dahlke et al., 2012). The mean altitudinal lapse rate between Tarfala Research Station (1135 m a.p.s.l.) and the mountain saddle (Tarfalaryggen) along the eastern border of the study area (1540 m a.p.s.l.) is c. 4.5 °C km^{-1}, however, the lapse rate in the summer months (JJA) of around 5.8°C km^{-1} is significantly higher than the winter lapse rate (DJF) of around 2.7°C km^{-1} (Jonsell et al., 2013).

The vegetation cover in the study area is generally sparse. In high elevation areas there is mostly barren ground. The middle part of the valley, around the Tarfala Research Station (1135 m a.p.s.l.), is characterized by patchy boulder fields and shallow soils with a mix of bare rocks, grasses, mosses and lichen. Further down the valley, dwarf shrubs (mainly *Salix* species and *Empetrum hermaphroditum*) appear up to 1000 m a.p.s.l. and the mountain birch forest (*Betula pubescens* ssp. *czerepanovii*) reaches up to c. 750 m a.p.s.l. On the alluvial fan, in the lowest part of the study area, the vegetation consists of a mix of deciduous and evergreen shrubs, graminoids and herbs.

The Tarfala Valley is characterized by little and very shallow soil development. The predominant soils ~~types~~ in the study area are characterized by very limited soil formation with poorly developed soil genetic horizons, high stone content and shallow regolith. These soils are classified as Leptosols and Regosols. ~~–~~(IUSS Working Group WRB, 2006). On Tarfalaryggen, soil movement caused by frost-thaw cycles (cryoturbation) has led to patterned ground formation and there is permafrost in the upper 2 meters of soil;~~and in~~ these ~~areas~~ soils are classified as Turbic Cryosols. In ~~riverbeds~~ riverbed deposits of glacial streams (e.g. in the glacier forefield of Isfallsglaciären) soils are classified as Fluvisols.

Kommentar [MF4]: Changed / Added due to comment referee#2 B 2.1

Extensive research has been carried out in Tarfala Valley, focusing mainly on glaciology and permafrost. Glaciers are the main subject of studies, with Storglaciären having the longest ongoing glacier mass balance measurements in the world (Holmlund et al., 2005). According to Brown et al. (1997) Tarfala Valley is located in the discontinuous permafrost zone. A permafrost borehole installed by the PACE (Permafrost and Climate in Europe) project is situated at 1540 m a.p.s.l. on Tarfalaryggen (Harris et al., 2001). The borehole measures the soil temperature down to 100 m every six hours (Sollid et al., 2000). Mean annual ground temperature at the depth of zero annual amplitude is -2.8 °C, with a mean active layer depth of 1.5–1.6 m. Permafrost is currently not present in a 15 m deep borehole located at an elevation of 1135 m a.p.s.l. near Tarfala Research Station (Bolin Centre for Climate Research, 2013). King (1984) reports an active layer depth of 2.5–4 m in the valley floor around 1200 m a.p.s.l. Even though many scientific studies have been carried out in Tarfala Valley (e.g., Stork, 1963 on vegetation cover; King, 1984 and Isaksen et al., 2007 on permafrost; Holmlund et al., 2005 and Jansson and Pettersson, 2007 on glaciology; Dahlke et al. 2012 on hydrology), there are no previous studies on SOC storage from this area.

3 Methods

3.1 Soil sampling

In August 2012, a stratified-random sampling program was executed in the Tarfala Valley during which soil profiles were collected along five transects. Transects were chosen to represent the altitudinal zones and vegetation types in the valley. Individual profiles were placed at strict equidistant distances along the transects to introduce a degree of randomness in the sampling. ~~Whenever possible,~~ ~~n~~Near surface organic layers ~~and fine textured soils~~ were collected from pits dug into the soils by cutting out samples of known volume. Deeper soil layers were sampled by hammering a steel pipe of c. 4 cm diameter into the soil vertically ~~at~~in 5 – 10 cm depth increments. Coring was pursued so that the whole profile was collected to a depth of one meter, if possible. Most of the collected soil profiles were shallow as the stony soils did in most cases not enable a sampling to the full reference depth of 100 cm. The soil was mostly of uniform nature and –during collection of soil samples no indication of soil organic matter buried through cryoturbation could visually be detected. Furthermore, permafrost was never encountered during coring, even at high elevations, indicating generally deep active layers in Tarfala Valley. In total, 56 profile sites were sampled and described and 295 individual soil samples collected.

Kommentar [MF5]: Added due to referee#1 comment A 1.1

Kommentar [MF6]: Added due to referee#1 comment A 3.1

3.2 Land cover classification

A description of the vegetation cover in a ground truth plot (diameter 10 meters) was made around each profile site, with special attention paid to the occurrence of stones and boulders (see description of SOC mass calculation below). For upscaling purposes, a land cover classification (LCC) was compiled from remotely sensed data. For this LCC, an orthophoto (compiled with ERDAS Imagine LPS from CIR aerial photographs with 0.5m spatial resolution) (Lantmäteriet, 2008), a WorldView2 satellite image (European Space Imaging GMBH, 2012), and a Landsat 5TM (USGS, 2011) satellite image were used. The remote mountainous area as well as cloud- and snow cover in the images made a usage of different datasets unavoidable to cover the whole valley. The LCC includes nine different classes which have been separated by a combination of a 3D stereo analysis and supervised classification (maximum likelihood). The requirements for a supervised classification in general and the training areas in particular followed Campbell (2011). To verify the classification, the kappa index of agreement was calculated based on the 56 ground truth plots. ~~The~~ N~~n~~ine dominant land cover classes were recognized in~~for~~ Tarfala Valley, which form the basis for ~~are presented in the supplementary material (Table S1) .~~establishing a land cover classification based on field- and remotely sensed data. The classes are presented in the supplementary material (Table S1).

Kommentar [MF7]: Added due to comment referee#1 A 2.1

Formatiert: Englisch (Großbritannien)

3.3 Geochemical analyses

Soil samples of known volume were weighed in the laboratory after oven drying at 60°C (for 48h) to calculate dry bulk density (DBD, g/cm^3). For loss on ignition (LOI), samples were burned at 550°C for six hours to determine the organic carbon content and at 950°C for two hours to determine the carbonate content (Dean, 1974; Heiri et al., 2001). In addition, a subset of 96 samples was further homogenized, freeze-dried and analyzed, first with a CarloErba NC 2500 elemental analyzer to determine C/N (weight) ratios, and second with a coupled mass spectrometer (Finnigan DeltaV advantage) to determine the stable isotope composition of δ^{13}C and δ^{15}N. Four bulk soil samples were submitted to the Radiocarbon Laboratory in Poznan, Poland, for dating with the accelerator mass spectrometry (AMS) approach (Walker et al., 2005). After the analysis, radiocarbon dates were calibrated into calendar years, cal yr BP (1950), and expressed as mean age of the highest 68% probability interval using the software OxCal 4.1.7 (Bronk Ramsey, 2010).

3.4 SOC storage calculations

The organic C values obtained from the elemental analysis for 96 samples were used to estimate the C percentage of the remaining 199 samples for which only LOI results were available. Rather than using a constant conversion factor, this is based on a ~~The following~~ third order polynomial regression between the C percentage (C, %) and LOI ~~was applied~~ for those samples where both parameters were measured (n = 96, r^2 = 0.95):

Kommentar [MF8]: Added due to comment referee#2 B 4.1

$$\mathrm{C}\,(\%) = 0.000004 * (\mathrm{LOI}_{550})^3 - 0.000352 * (\mathrm{LOI}_{550})^2 + 0.481602 * (\mathrm{LOI}_{550}) \qquad (1)$$

SOC mass (kg C m^{-2}) was calculated for each sample with the dry bulk density (DBD, g cm^{-3}), the percentage organic carbon (C, %), the coarse fragment fraction (> 2 mm) (CF, %) and the sample depth interval with the following equation:

$$\mathrm{SOC}\,(\mathrm{kg\,C\,m^{-2}}) = \mathrm{DBD} * \mathrm{C} * (1 - \mathrm{CF}) * \mathrm{depth} * 10 \qquad (2)$$

The SOC storage (kg C m^{-2}) in each soil profile was calculated by adding up the SOC mass of all samples (5-10 cm depth increments) for the reference depths of 0 – 30 cm and 0 – 100 cm. It should be noted, however, that in all cases it was not possible to reach a full depth of 100 cm due to the occurrence of large stones, boulders or bedrock (these are assumed to contain no SOC). Storage was calculated separately for the organic rich top soil layer and the underlying mineral soil layer. The division between these layers was made based on field observations. The mean SOC storage for each of the recognized land cover types is calculated as the arithmetic mean of all soil profiles representing those land cover types. To avoid overestimation of the C content, each LCC mean SOC kg C m^{-2} value was weighted by the mean percentage of large stones (>4 cm diameter) visible at the surface. These areas were considered to have no soil development and to contain no SOC. The coverage of large stones was derived by field observations at every sample spot within a radius of five meters. Thereafter, the mean SOC storage in Tarfala Valley was calculated, based on the proportions of the land cover classes in the LCC. These calculations were performed for all land cover classes together (including glaciers, barren grounds and lakes) and for the vegetated classes only.

Kommentar [MF9]: Added due to comment referee#1 A 3.1

3.5 Statistical methods

The results from the geochemical analyses and the upscaling were further analyzed with statistical methods. All statistical analyses were carried out with the open source statistical analysis package PAST 2.17 (Hammer et al., 2001). Three main statistical analyses were carried out: 1) confidence intervals (CI) for the mean C estimates of the total study area were calculated according to Hugelius (2012); 2) linear correlations (Pearson´s correlation) between soil depth and the different geochemical parameters (DBD, %C, LOI, C/N-ratio, $\delta^{13}C$, $\delta^{15}N$) were calculated to examine whether the different parameters decrease or increase significantly with increasing depth; 3) the student´s t-test was applied to examine if there is a statistically significant difference between the organic rich top soil and the underlying mineral samples for all the different geochemical parameters. In all cases, the probability limit of $p \leq 0.01$ was chosen for statistical significance.

3.6 Permafrost mapping

In addition to the SOC inventory, the permafrost distribution in Tarfala Valley was mapped. Bottom temperature of snow (BTS) measurements were carried out in March 2013, with a precision temperature measuring instrument Series P400 (Dostmann Electronic, 2013). This handheld thermometer has an accuracy of ±0.3°C and a resolution of 0.1°C. The temperature probe was calibrated in ice water to 0°C before every field day. The BTS-method is a simple and cost effective approach to get a first impression on the distribution of permafrost by measuring the temperature at the snow-ground surface interface. For this method a snow cover of a minimum of 80 cm is required to provide sufficient insulation from variable air temperatures above the snow pack (Haeberli, 1973; King, 1983). With the BTS-values, a logistic regression with altitude as single independent variable was used to map the probability of permafrost occurrence. For the logistic regression, BTS-values were classified into permafrost likely and non-permafrost likely. The threshold values for permafrost likely BTS values vary dependent on snow depth and range from -2.5°C to -4.5°C (King, 1984). Altitude was chosen as single independent variable because other possibly important parameters for permafrost occurrence (slope, aspect, solar radiation, etc) showed no significant correlation with measured BTS-values. Using the permafrost probability map, the amount of SOC stored in probable permafrost areas could be estimated.

4 Results

4.1 Land cover classification

The LCC presented in Figure 1 has an overall accuracy of 72.2% and a kappa index of agreement of 0.68. The reasons for the rather low kappa index can be explained by snow cover at higher elevations in the orthophoto, which needed to be corrected by a Landsat 5 TM image with a coarser spatial resolution. The LCC shows that Tarfala Valley is dominated by rocks and stones, which cover almost 60% of the area, followed by permanent snow and ice which covers more than 18% of the landscape. The largest vegetated land cover class is “Patchy Boulder Moss” which covers almost 10% of the landscape, but this class is defined as a mix of moss and stones that on average has more than 40% stones. All land cover classes include a certain amount of stones, which ranges from 4% in the class ‘Birch Forest’ to 47% in the class ‘Sand/Gravel’ (for more details, see supplementary material Table S1).

4.2 SOC quantity

The mean study area SOC storage including all land cover classes is 0.7 ± 0.2 and 0.9 ± 0.2 kg C m^{-2} for 0 – 30 cm and 0 – 100 cm soil depths, respectively (mean ±95% CI) (Table 1). ~~This low SOC storage is a result of the large percentage of bare rock and stones, which cover almost 60% in the study area (Table 1).~~ Calculations have also been made for the vegetated area only. This area excludes the low SOC land cover classes ‘Stone’, ‘Sand/Gravel’, ‘Water’, and ‘Permanent Snow/Ice’ and, therefore, the mean C storage is considerable higher than for the entire study area. The mean SOC for the vegetated area only is 3.7 ± 0.8 and 4.6 ± 1.2 kg C m^{-2} for 0 – 30 cm and 0 – 100 cm soil depths, respectively (mean ±95% CI).

Kommentar [MF10]: Sentence was removed due to comment referee#1 A 4.1

A detailed analysis of the different land cover classes shows the partitioning of the C stored in Tarfala (Figure 2). Most of the SOC in Tarfala Valley is stored in the class ‘Tundra Meadow’ (35% of SOC) even though it only covers 4.3% of the total study area. However, the highest mean value occurs in the class ‘Patchy Boulder Grass/Moss’, which stores on average 8.4 ± 5.4 kg C m^{-2} (Table 1) and accounts for 24% of the total SOC storage in Tarfala Valley.

The coefficient of variation of the mean SOC values of the land cover classes is high (near 1 in many cases), which is an effect of the high within-class variability in depth of the fine grained deposits overlying coarse regolith or bedrock (also reflected in the standard deviation of the mean profile depth, see Table 1). Therefore the variability of profile depth within the different land cover classes is reflected in the variability of organic carbon for single classes. Additionally, the coarse fragment fraction (> 2 mm) varied within classes (data not shown). Besides the variability in fine-soil depth, the results show that most of the organic C is stored in near surface layers. In average, more than 80% of the SOC is stored within the upper 30 cm of soil and a third of the SOC is stored in the organic rich top soil layer. This

Kommentar [MF11]: Sentence added due to comment referee#1 A 5.1

also allows an estimation of the SOC stored within the permafrost layer. As the active layer in Tarfala Valley seems to be in the order of 1.5 – 4 m thick (King, 1984; Isaksen et al., 2007), it can be considered that only a very minor to negligible amount of organic C is stored within the permafrost layer. It should be noted that permafrost was never reached during field coring due to the occurrence of bare rock and stones.

The soils of Tarfala Valley display no signs of cryoturbation of the organic rich top soil layer into the deeper mineral soil horizons. Likewise, no burial of the organic rich layer due to solifluction processes on slopes was observed.

4.3 SOM quality and age

The soils in Tarfala Valley are characterized by a steady, statistically significant ($p < 0.01$) increase in bulk density with depth (Figure 3a; Table 2). However, LOI (550°C) and percentage C show strong, statistically significant ($p < 0.01$) negative correlations with depth (Figure 3b; Table 2). As a result, there is less SOM with greater depth in the soil. There is also a statistically significant (t-test, $p < 0.01$) difference in the C content of the organic-rich top soil layer and the underlying mineral layer (Table 2). During field sampling there were no observations of buried SOM through e.g. cryoturbation or solifluction. Similarly, the laboratory results showed no single value or outlier with high %C below the top organic layer. Therefore, there are neither visual nor laboratory results indicating burial of organic carbon to depth in the investigated soil profiles.

Kommentar [MF12]: Sentence added due to comment referee#1 A 3.1

Besides C content, other geochemical analyses of the soil samples also show a coherent picture. The C/N ratio and stable isotopic composition of SOM reflect its relative state of decomposition (e.g. Mariotti and Balesdent, 1990; Kuhry and Vitt, 1996; Ping et al., 1998; Hugelius et al., 2012). There is a statistically significant (t-test, $p < 0.01$) difference between the mean C/N ratio of the organic rich top soil layer (23.3 ± 11.4) and that of the mineral layer (14.6 ± 4.05). The C/N ratio decreases with increasing depth ($p < 0.01$), indicating progressively more decomposed SOM (Figure 3c). Ping et al. (1998) pointed out that the C/N ratio is dependent on vegetation cover and that trends need to be interpreted carefully. In the Tarfala Valley, the decrease of C/N ratio with depth is consistent across all land cover classes. However these trends are not statistically significant for the separate land cover classes, probably due to the limited number of replicates within each class (data not shown). The stable isotope composition of δ^{13}C vs PDB and δ^{15}N vs air show statistical significant ($p < 0.01$) enrichment of stable isotopes with increasing soil depth (Figure 3d; Table 2). The enrichment of $\delta^{13}C$ and $\delta^{15}N$ with depth can be considered an indication for SOM degradation through microbial respiration (Mariotti and Balesdent, 1990; Ping et al. 1998).

Four bulk soil samples (living roots removed) from two profiles belonging to the class 'Patchy Boulder Grass/Moss', located close to the floor of the central Tarfala Valley, have been radiocarbon-dated (Table 3). These profiles were selected because they had the thickest organic-rich top soil layer among the collected profiles in the study area and displayed a slight, but highly unusual for this area, C-enrichment in the underlying mineral soil (weak B-horizon development). Results indicate that the SOM close to the surface is recent in age (< 100 years old), whereas the mineral soil at greater depths contain slightly older SOM, with ages of 1269 and 1919 cal yr BP (Table 3). Considering the fact that the two dated profiles are among the most well-developed soils in the study area, it is most likely that most of the SOM in Tarfala Valley is of very young age. The geochemistry of these two dated profiles, which reflect the general trends described for the whole dataset, is presented in the supplementary material (Figure S1).

4.4 Permafrost mapping

Permafrost zones are commonly separated into the classes continuous, discontinuous, sporadic and isolated patches (e.g. Brown et al., 1997). However with the logistic regression approach, not the areal extent of permafrost but the probability for the occurrence of permafrost was used to map the permafrost distribution into the conventional classes (Figure 4). This was already applied by Lewkowicz and Ednie (2004) in their study in the Yukon Territory, Canada. However, with this approach, the permafrost distribution has to be interpreted carefully, especially in a highly heterogeneous alpine environment like Tarfala Valley. Areas with a >90% probability for the occurrence of permafrost are considered as continuous, which in Tarfala Valley includes all areas above 1561 m a.p.s.l. The discontinuous permafrost zone (probability between 50-90%) occurs at an altitude between 1218 and 1561 m a.p.s.l., while the sporadic permafrost zone commences at an altitude above 875 m a.p.s.l. (probability >10%). The altitudinal zonation of permafrost as depicted in Figure 4 is very similar to those proposed by King (1983) and Marklund (2011), particularly if some outliers are removed from our analysis. The lowermost site where BTS-values suggest permafrost is located at 976 m a.p.s.l.; measurements at two high-elevation sites (c. 1500 m a.p.s.l) suggest absence of permafrost. While there are no technical reasons to reject these results, these outliers should be considered with caution due to the inherent large uncertainty range in the BTS method.

5 Discussion

5.1 Current SOC quantity and SOM composition

The results presented for Tarfala Valley show very low SOC storage compared to inventories from lowland areas in the northern permafrost region (e.g., Michaelson et al., 1996; Kuhry et al., 2002; Hugelius et al., 2010). However, the mean value of 0.9 kg C m^{-2} (0 – 100 cm) is quite close to values reported for other mountainous environments. Kuhry et al. (2002) estimated a mean value of 0.3 kg C m^{-2} for the land cover class ‘natural barelands’ and 1.3 kg C m^{-2} for the land cover class ‘alpine sparse tundra’, which together represent c. 8% of the total catchment area of the Usa Basin (Northeast European Russia); Ping et al. (2008) estimated a value of 3.8 kg C m^{-2} for ‘mountain soils’ in the North American Arctic region. The number of pedons in both these studies is very low (n = 1 to 4).

Considering values from only the vegetated area in Tarfala Valley, the mean SOC values are 3.7 kg C m^{-2} for 0 – 30 cm and 4.6 kg C m^{-2} for 0 – 100 cm soil depth intervals. Similar SOC inventories on vegetated patches have been carried out in the Tibetan Plateau. Doerfer et al. (2013) measured the SOC content in the Huashixia and Wudaoliang region, which resulted in mean values of 10.4 and 3.4 kg C m^{-2} for 0 – 30 cm, respectively. The land cover was in both cases classified as ‘alpine meadow’. Our mean SOC value for the class ‘tundra meadow’ and the corresponding depth interval is 6.0 kg C m^{-2}. Other SOC inventories on the Tibetan Plateau showed similar results. Ohtsuka et al. (2008) measured a mean SOC content of 1.0 – 13.7 kg C m^{-2} for 0 – 30 cm in ‘alpine meadow’; Yang et al. (2008) measured 9.6 kg C m^{-2} in ‘alpine meadow’ and 3.1 kg C m^{-2} for ‘alpine steppe’; and Wang et al. (2008) measured 9.3 – 10.7 kg C m^{-2} for ‘alpine grasslands’ (our corresponding value for the ´patchy boulder grass/moss’ class is 6.2 kg C m^{-2}). A SOC inventory from the Swiss Alps showed higher values than Tarfala Valley. Zollinger et al. (2013) investigated ‘alpine grassland’ (at 2700 m a.p.s.l.) and ‘subalpine forest’ (at 1800 m a.p.s.l.) soils and estimated the C stocks down to the C-horizon at c. 10 kg C m^{-2} for permafrost and c. 15 kg C m^{-2} for non-permafrost sites. It has to be emphasized that these values represent only the mean of the vegetated sites and are not based on a landscape upscaling to include all mountainous terrain. Nonetheless, in all these studies, the high SOC content often reported from lowland permafrost areas, ranging between c. 25-50 kg C m^{-2} (e.g., Michaelson et al., 1996; Kuhry et al., 2002; Hugelius et al., 2010), is never achieved.

Several reasons for the low SOC values in Tarfala Valley seem obvious. ~~First, t~~There is a ~~the~~ high amount of bare ground and glaciated terrain in the study area (almost c. ~~6~~80%) which leads to very limited in situ production of organic plant matter~~store negligible amounts of SOC~~ in the system. ~~Second, e~~Even the vegetated classes have abundant stone cover which diminishes the landscape fraction with fine soil development. The fraction of stone coverage in the different land cover classes varied between 4% and 47% (the soil volume occupied by stones was considered devoid of SOC in stock calculations.) Furthermore, no signs of SOM burial by cryoturbation or solifluction processes were observed in any investigated soil profile. Burial of SOM through cryoturbation or slope processes are important mechanisms explaining high SOC stocks in other permafrost environments (Palmtag et al., 2014). ~~the soils are rather shallow; in most cases they do not reach a depth of 1 m and sometimes not even 30 cm. Finally, no signs of SOC burial by cryoturbation or solifluction processes were found in the field.~~ The active layer in Tarfala Valley is significantly deeper than the depth of active soil formation, which means that organic carbon decomposition is not impeded by sub-zero temperatures during the warm season. The steep topography and coarse sediments favor rapid drainage and aerated soils. No peat formation or peaty soils was observed in the Tarfala Valley. Finally, the soils are rather shallow; in most cases they do not reach a depth of 1 m and sometimes not even 30 cm. As a consequence of all these factors, the soils in Tarfala Valley are not characterized by any of the pedogenic processes that often lead to the accumulation of high stocks of SOC in permafrost region soils (Tarnocai et al., 2009).

Kommentar [MF13]: updated

Kommentar [MF14]: Added due to comment referee#1 A 7.1

Kommentar [MF15]: Sentence was moved to this position due to comment referee#1 A 8.1

Kommentar [MF16]: Sentence included as a consequence on referee #2 B 7.1

The mean value for Tarfala soils down to 1 m depth (0.9 kg C m^{-2}) is considerably lower than the one reported for the Swedish mountains (26.1 kg C m^{-2}) in the Northern Circumpolar Soil Carbon Database (Hugelius et al., 2013). The high value in the NCSCD can be explained by the highly generalized soil map on which these estimates are based. The NCSCD soil polygon that overlaps with the Tarfala Valley study area has an area of c. 2900 km^2 and includes adjacent lowland terrain with peatland (Histosols) and forested (Podsols) areas.

Geochemical indicators, such as C/N ratios and stable isotopes (δ^{13}C and δ^{15}N), indicate that the SOM in Tarfala soils becomes gradually more decomposed with depth and age. Cryoturbation of C-enriched material is one of the mechanisms that significantly increase SOC storage in permafrost soils (e.g., Ping et al., 2008). In Tarfala, we did not find evidence for burial of relatively undecomposed SOM from the organic rich top soil layer deeper into the profiles. The two dated soil profiles are exceptional for Tarfala Valley as they have the thickest organic-rich top soil layer and relatively high carbon values in greater depths. But basal dates for even these thickest organic rich top soil layers are recent and the SOC at greater depth is also quite young (< 2000 cal yr BP). Therefore, much of the SOM in Tarfala Valley seems to be cycled within 100 years or less and does not accumulate at greater depths. This is in stark contrast with permafrost soils from lowland regions, which are reported to have extensive cryoturbation of relatively undecomposed SOM that has been preserved at greater soil depths for thousands of years (e.g., Bockheim, 2007; Hugelius et al., 2010).

5.2 Future developments

Our results indicate that there are no large amounts of SOC stored in the soils of Tarfala Valley. The relatively highest mean SOC storage is found in vegetated ground at lower elevations. A further analysis that takes into account the permafrost zonation shows that the potential for SOC storage in permafrost affected soils is very small (Figure 5). The mean SOC value at an elevation of 1250 m a.p.s.l., where the probability for permafrost is just above 50%, is 0.7 kg C m^{-2} (for 0 – 100 cm) and at an altitude of 1500 m a.p.s.l. (permafrost probability 85%) it is only 0.1 kg C m^{-2}. Therefore, most of the SOC in Tarfala Valley is stored at lower elevations where the probability for permafrost affected soils is low. Taking into account that the active layer is 2.5 – 4 m thick in the valley floor around 1200 m a.p.s.l. (King, 1984) and the fine soil is only rarely deeper than 1 m, the amount of SOC stored in the permafrost layer is assumed to be negligible.

The vegetation and SOC distribution in Tarfala Valley allow some considerations about future total ecosystem C storage in the area under conditions of global change. Climate warming will result in an upwards shift of vegetation zones with the corresponding initiation of soil development in currently high-alpine barren areas. Upwards altitudinal shifts of plants due to increased temperatures have been observed in alpine regions (e.g., Walther et al., 2005), including the Scandinavian mountain range (e.g., Klanderud and Birks, 2003; Kullman, 2002; 2010). Kullman and Öberg (2009) report an altitudinal upward shift of trees of about 200 m in the past 100 years in the Swedish Scandes, in accordance with observed temperature increases. For a first rough estimation of potential upwards shifts of vegetation zones, the mean summer temperature change was taken as a first indicator, even though many other factors will affect the vegetation (e.g. winter temperatures, precipitation, windexposition, etc. (Kullman, 2010)). The projected mean summer (JJA) temperature increase for the Tarfala mountain region until 2100 is 2.8°C (SRES A1B scenario, SMHI, 2013). Considering a summer lapse rate of 5.8°C km^{-1} (Jonsell et al. 2013), the potential altitudinal upward shift for the vegetation cover is c. 500 m. Grace et al. (2002) and Kullman (2010) calculated a similar potential treeline shift in the region by the end of this century. However, not the entire Tarfala Valley will be suitable for plant colonization, because of steep slopes, a lack of fine soil matrix and wind-exposed ridges.

Schuur et al. (2009) showed that in the Alaskan tundra, increased plant productivity is eventually outweighed by increased decomposition of deeper and older SOM following permafrost thaw. For projections of permafrost degradation in Tarfala Valley, the mean annual air temperature has to be considered. A climate scenario for the Tarfala mountain region estimates a mean annual temperature increase of c. 4.6°C until 2100 (SRES A1B scenario, SMHI, 2013). Taking into account a mean annual lapse rate of 4.5°C km^{-1} (Jonsell et al., 2013) the 0°C air temperature isotherm could rise with c. 1000 meters, which would greatly affect permafrost occurrence in the area. Data from the PACE borehole at Tarfalaryggen shows that the permafrost temperature at the zero annual amplitude depth of 20 m has already experienced a warming of 0.047°C yr^{-1} (Jonsell et al., 2013). Even though future permafrost degradation is highly plausible for most of the upper Tarfala Valley, only a negligible amount of SOC is currently stored in the area and could be affected by thaw. Under future climate warming and permafrost thawing little or no SOC will be remobilized from permafrost soils in Tarfala Valley. On the contrary, increased temperatures will lead to an upward vegetation shift, phytomass production and soil development, with the result of an increased C uptake in Tarfala Valley in the future. The only way that projected permafrost thaw might negatively affect C uptake is through an initial increased slope instability in steep terrain (Gregory and Goudie, 2011; French, 2007).

Compared to lowland permafrost regions in the northern circumpolar region (see e.g. Gruber et al., 2004; Zimov et al., 2006b; Schuur et al., 2009), a subarctic high-alpine permafrost environment like the upper Tarfala Valley cannot be considered a future source of C to the atmosphere. In general, alpine permafrost environments above the contiguous vegetation limit have the potential of becoming a C sink in the future and therefore stand out as an exception in the general assessment of thawing permafrost soils representing an important positive feedback to future climate warming (e.g., Schuur et al., 2013).

6 Conclusion

The SOC inventory in Tarfala Valley, with a mean storage of 0.9 kg C m^{-2} for the upper meter of soil, shows that this area cannot be considered a C-rich permafrost environment. This low value is a result of the high amount of barren ground and stony surfaces in the study area, low plant productivity, shallow soils, and lack of SOM burial through cryoturbation or slope processes. The low SOC storage leads to the conclusion that environments like Tarfala Valley cannot become significant sources of C with future permafrost thawing. Instead, they could act as net C sinks following an upward shift of vegetation zones causing increased phytomass production, soil development and SOM accumulation. The potential magnitude of an increased C uptake in this type of mountainous permafrost region remains to be addressed by further studies. Nevertheless, this study shows that there is a need to include alpine environments to estimate the total SOC stock in permafrost soils of the northern circumpolar region and to fully assess the permafrost thaw-C feedback.

Acknowledgments

We wish to thank Eva-Lisa and Juri Palmtag, Niels Weiss and Malin Brandel for help with the fieldwork, ~~and~~ Andreas Bergström and his team for the support at Tarfala Research Station, and two anonymous reviewers for their constructive comments. The study was supported by the Nordic Center of Excellence DEFROST project.

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Table 1: Mean soil organic carbon (SOC) storage and sample site characteristics for the different land cover classes in Tarfala Valley

	Mean SOC Storage				Mean Profile Depth					Profile Distribution		
Land Cover Classes	0-30 cm (kg C m^{-2} ± std)	0-100 cm (kg C m^{-2} ± std)	Organic Rich Top Soil Layer (kg C m^{-2} ± std)	Mineral Layer (kg C m^{-2} ± std)	Profile Site (cm ± std)	Organic Rich Top Soil Layer (cm ± std)	Mineral Layer (cm ± std)	Area (km^2)	Area (%)	Mean Altitude of Profiles incl. Range (m a.p.s.l.)	Number of Sites	Sites in Permafrost[c] (cont./discont./sporad. /isol. or none)
Birch Forest	5.7 ± 3.5	6.6 ± 5.0	2.0 ± 0.6	4.6 ± 4.6	25 ± 22	3.4 ± 0.9	22 ± 22	0.3	1.0	656 (636-675)	3	-/-/-/3
Tundra Meadow	6.0 ± 3.0	7.2 ± 5.5	2.7 ± 1.4	4.5 ± 4.7	24 ± 24	4.3 ± 2.1	20 ± 23	1.3	4.3	652 (562-864)	8	-/-/-/8
Shrub	4.6 ± 4.3	4.6 ± 4.3	1.5 ± 0.8	3.1 ± 3.6	16 ± 11	4.0 ± 1.8	12 ± 10	0.3	0.9	688 (581-824)	5	-/-/-/5
Pat. Bould. Grass/Moss	6.2 ± 4.0	8.4 ± 5.4	1.4 ± 0.8	7.0 ± 5.2	38 ± 25	4.8 ± 1.8	33 ± 25	0.8	2.6	1129 (993-1202)	11	-/-/11/-
Patchy Boulder Moss	1.8 ± 1.7	2.3 ± 1.9	0.6 ± 0.6	1.8 ± 1.5	40 ± 23	2.9 ± 1.5	37 ± 24	3.1	9.9	1181 (1076-1485)	12	-/1/11/-
Sand/Gravel	0.7 ± 0.8	1.0 ± 0.9	0.1 ± 0.1	0.9 ± 0.9	53 ± 27	1.3 ± 1.0	52 ± 27	0.3	1.0	1293 (1122-1559)	9	-/6/3/-
Stones	0.05 ± 0.1	0.05 ± 0.1	0.05 ± 0.1	0.0	3 ± 2	3.0 ± 1.6	0	18.6	59.8	1304 (1154-1542)	8	-/5/3/-
Water	——	——	——	——	——	——	——	0.7	2.1	1194[d] (——)	0	——
Permanent Snow/Ice	——	——	——	——	——	——	——	5.8	18.5	1530[d] (——)	0	——
Study Area[a]	**0.7 ± 0.2**	**0.9 ± 0.2**	**0.3 ± 0.1**	**0.6 ± 0.2**	**8.6**	**2.4**	**6.2**	**31.2**	**100**	**1059 (562-1559)**	**56**	**-/9/31/16**
Vegetated Area[a,b]	3.7 ± 0.8	4.6 ± 1.2	1.3 ± 0.3	3.3 ± 1.0	33.7	3.5	30.2	5.8	18.7	954 (562-1485)	39	-/1/22/16

[a] Mean SOC storage is based on the land cover classification upscaling. The second number in each column is not the standard deviation like in the land cover classes, but the 95%-confidence interval (calculated according to *Hugelius*, 2012) which is based on the SOC variance and areal extent of each LCC.

[b] Only the vegetated area is considered. The following classes have been excluded from the calculations: ‘Sand/Gravel’, ‘Stones’, ‘Water’, ‘Permanent Snow/Ice’.

[c] The permafrost table was not reached during sampling at any of the sample sites.

[d] The mean altitude of the classes ‘Water’ and ‘Permanent Snow/Ice’ is based on the land cover classification and not on profile sites.

Table 2. Statistics of the geochemical analyses of soil samples

Geochemical analysis	All samples, *mean ± std*	Organic rich top soil layer samples, *mean ± std*	Mineral layer samples, *mean ± std*	Significant difference between organic and mineral samples, student's t-test	Correlation with increasing depth, Pearson´s correlation
DBD (g/cm^3)[a]	0.9 ± 0.8	0.4 ± 0.3	1.6 ± 0.7	yes ($p < 0.01$)	0.71 ($p < 0.01$)
LOI$_{550}$ (%)[a]	21.6 ± 27.0	40.3 ± 28.5	4.8 ± 8.1	yes ($p < 0.01$)	-0.47 ($p < 0.01$)
LOI$_{950}$ (%)[a]	0.4 ± 0.4	0.4 ± 0.4	0.3 ± 0.4	no ($p = 0.06$)	-0.11 ($p = 0.05$)
% C	11.4 ± 13.8	25.8 ± 13.7	3.8 ± 5.2	yes ($p < 0.01$)	-0.54 ($p < 0.01$)
C/N ratio (-)	17.6 ± 8.5	23.3 ± 11.4	14.6 ± 4.1	yes ($p < 0.01$)	-0.38 ($p < 0.01$)
$\delta\,^{13}C_{tot}$ vs PDB (‰)	-26.1 ± 1.2	-26.8 ± 1.0	-25.6 ± 1.0	yes ($p < 0.01$)	0.42 ($p < 0.01$)
$\delta\,^{15}N$ vs air (‰)	1.8 ± 2.6	-0.54 ± 2.0	3.2 ± 1.8	yes ($p < 0.01$)	0.53 ($p < 0.01$)

[a] calculations carried out with all 295 samples; other calculations based on 96 samples from elemental analysis

Table 3. Results from the radiocarbon analysis

Site	Depth (cm)	Lab. No.	Site and sample description	Age ^{14}C	Age cal yr BP
TA T1-9B	19-20	Poz-51853	Grass/moss patch, base of top organics	123.48 ± 0.4 pMC	modern
TA T1-9B	50-60	Poz-51854	Grass/moss patch, silty sand and stones	2035 ± 35 BP	1919
TA T2-11	10-15	Poz-51856	Grass/moss patch, base of top organics	95 ± 30 BP	20
TA T2-11	33-37	Poz-51857	Grass/moss patch, silty sand and small stones	1380 ± 30 BP	1269

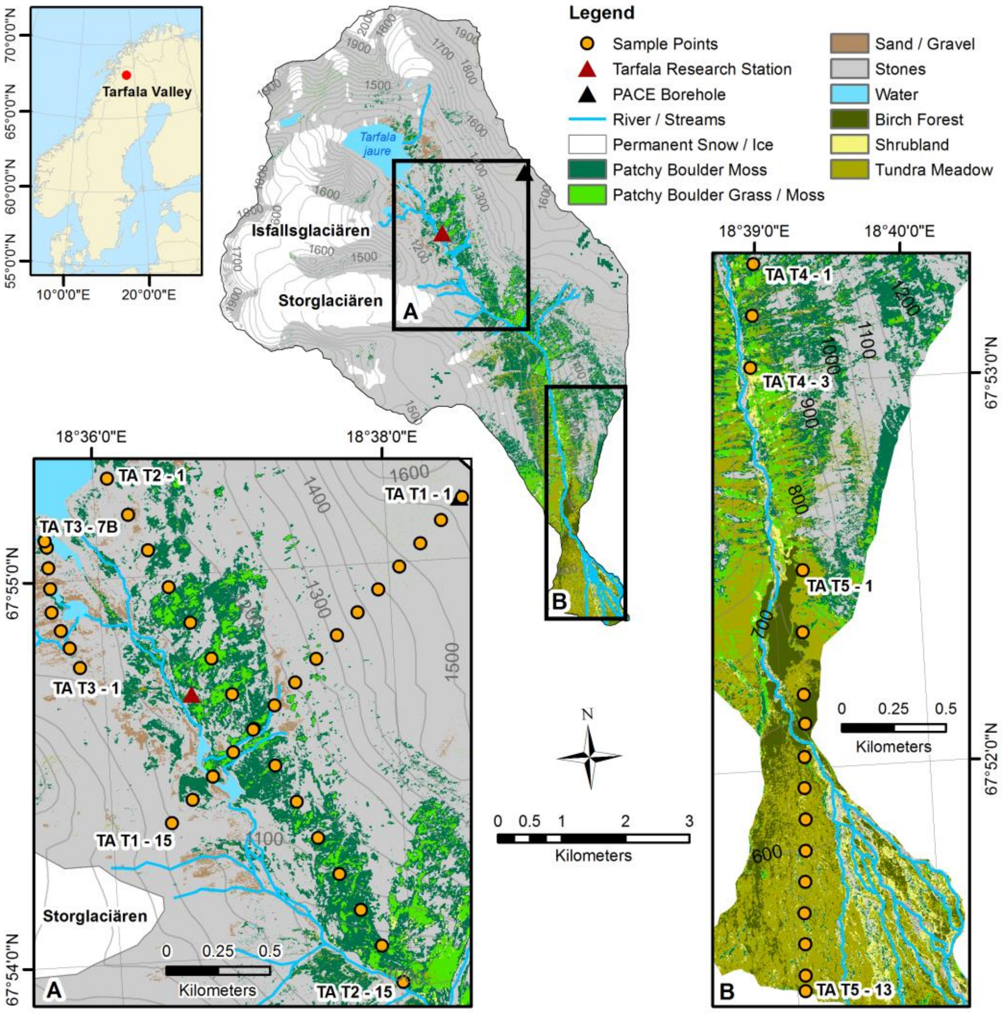

Figure 1. The Tarfala Valley study area, including an overview location map, a map of the whole study area with land cover classification and detailed maps showing transect and sample point locations in the central (A) and lower (B) parts of the valley.

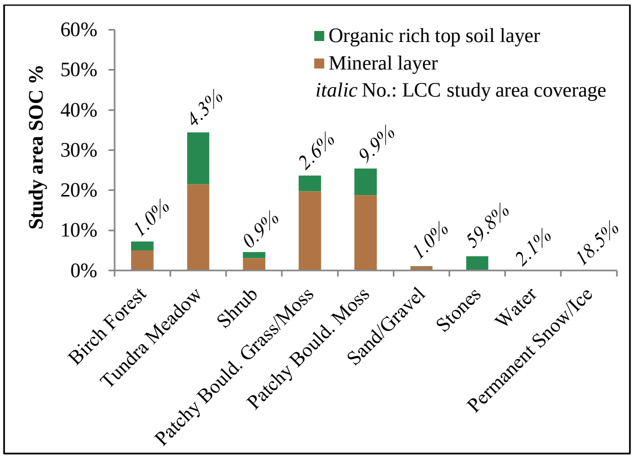

Figure 2. Partitioning of total SOC storage and proportional area coverage of land cover classes in Tarfala Valley (31.2 km^2).

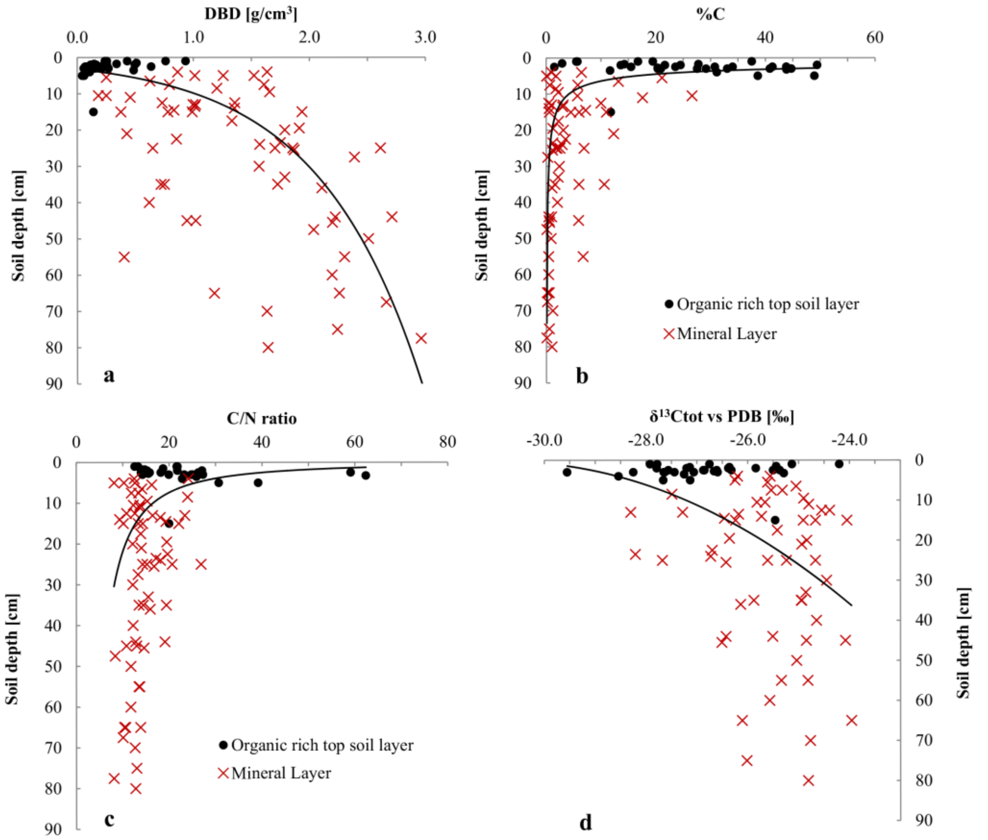

Figure 3. Results of the geochemical analyses of the soils samples of Tarfala Valley. DBD: Dry bulk density (a); %C: percentage C (b); C/N weight ratio (c); δ ^{13}C$_{tot}$ vs PDB: stable isotope δ ^{13}C analyzed to the international standard PeeDeeBelemnite (d). Lines are best-fit power-, polynomial- or exponential regressions, shown for graphic representation of mean trends only. Some high bulk density values (up to 3.0 g cm-^{3}) in sandy profile sites are probably the result of errors in field volume estimates due to difficulties in collecting these loose materials.

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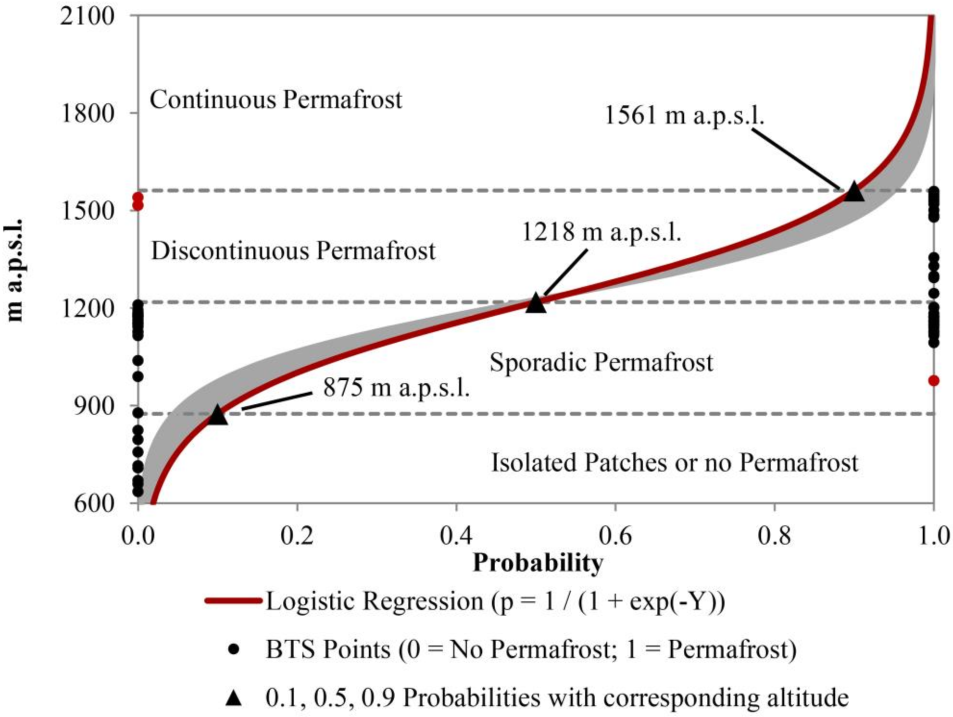

Figure 4. Permafrost probability in relation to altitude – the probability is based on a logistic regression model with the altitude as single independent variable. The grey corridor shows the range of the permafrost probability if outliers (red dots) are removed from the model.

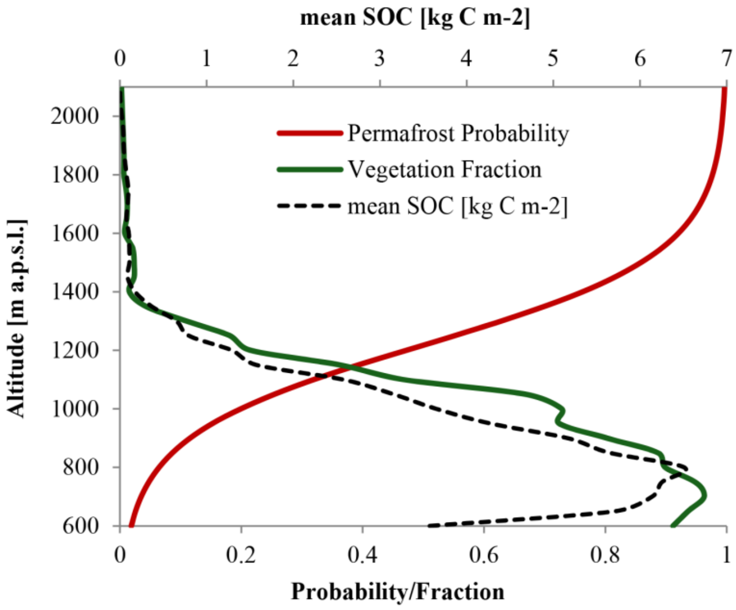

Figure 5. Fraction of vegetation cover and probability for permafrost presence in relation to altitude in Tarfala Valley, including the mean SOC storage per altitude (calculated in 50 m altitudinal intervals). The permafrost probability is based on the BTS-measurements and a logistic regression with the altitude as single independent variable. The vegetation fraction is based on the altitudinal distribution of vegetated classes in the land cover classification. ~~Relatively~~ Slightly lower SOC values at elevations below 700 m are related to exposed streambeds in the Tarfala River alluvial fan.