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

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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 17.8 million km^2 (Hugelius et al., 2014). The soils in the northern permafrost region store large amounts of soil organic carbon (SOC), which are vulnerable to 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). 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 1035 ±150 Pg C (±95% confidence interval). 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 associated with wide uncertainty ranges (Hugelius et al., 2014).

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.

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 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; 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.

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. Near surface organic layers 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 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 no single case 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.

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.

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).

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 $\delta^{13}C$ and $\delta^{15}N$. 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 third order polynomial regression between the C percentage (C, %) and LOI for those samples where both parameters were measured (n = 96, $r^2 = 0.95$):

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

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:

$$\mathrm{SOC}\,(\mathrm{kg\,C\,m^{-2}}) = \mathrm{DBD}\,(\mathrm{g\,cm^{-3}}) * \mathrm{C} * (1 - \mathrm{CF}) * \mathrm{depth} * 10 \qquad (2)$$

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.

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). 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).

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 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.

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 $\delta^{13}C$ vs PDB and $\delta^{15}N$ 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 S2).

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. There is a high amount of bare ground and glaciated terrain in the study area (almost c. 80%) which leads to very limited in situ production of organic plant matter in the system. 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 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).

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 ($\delta^{13}C$ and $\delta^{15}N$), 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 climate 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, wind exposure, 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), which could prevent vegetation establishment and soil development.

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.

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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	-/3/6/-
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

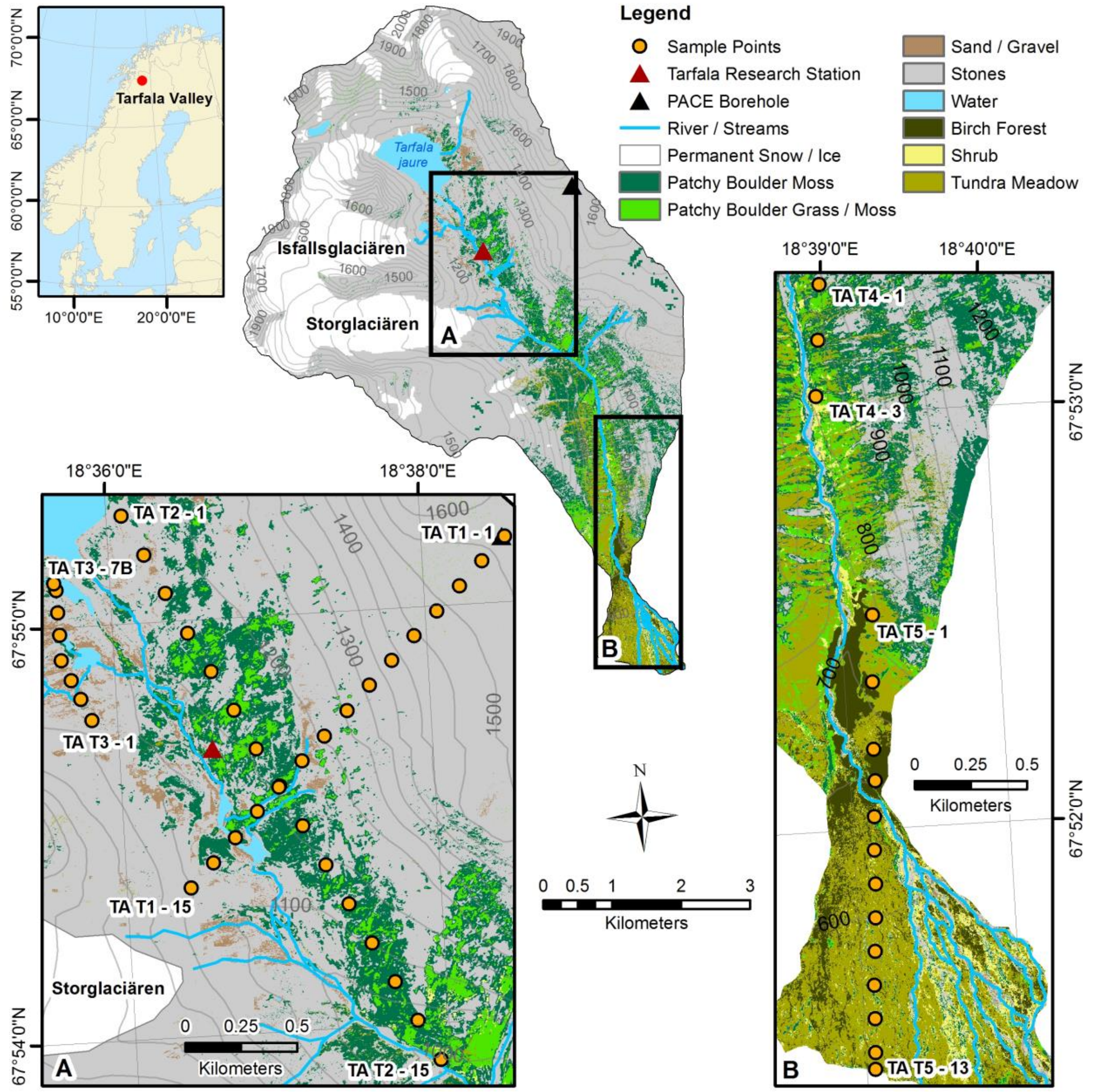

Figure 1. The Tarfala Valley study area, including an overview location map, a map of the whole study area with land cover classification and detailed maps showing transect and sample point locations in the central (A) and lower (B) parts of the valley.

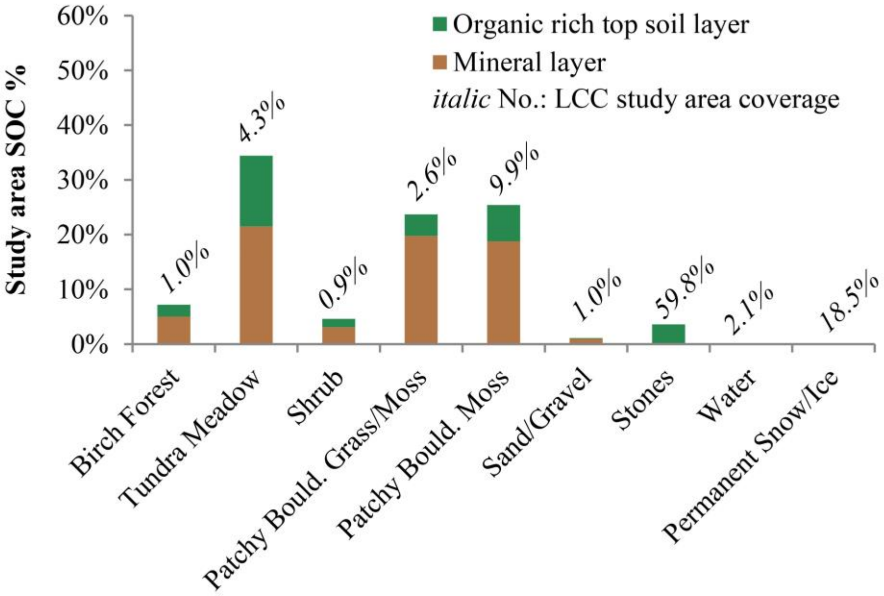

Figure 2. Partitioning of total SOC storage and proportional area coverage of land cover classes in Tarfala Valley (31.2 km^2).

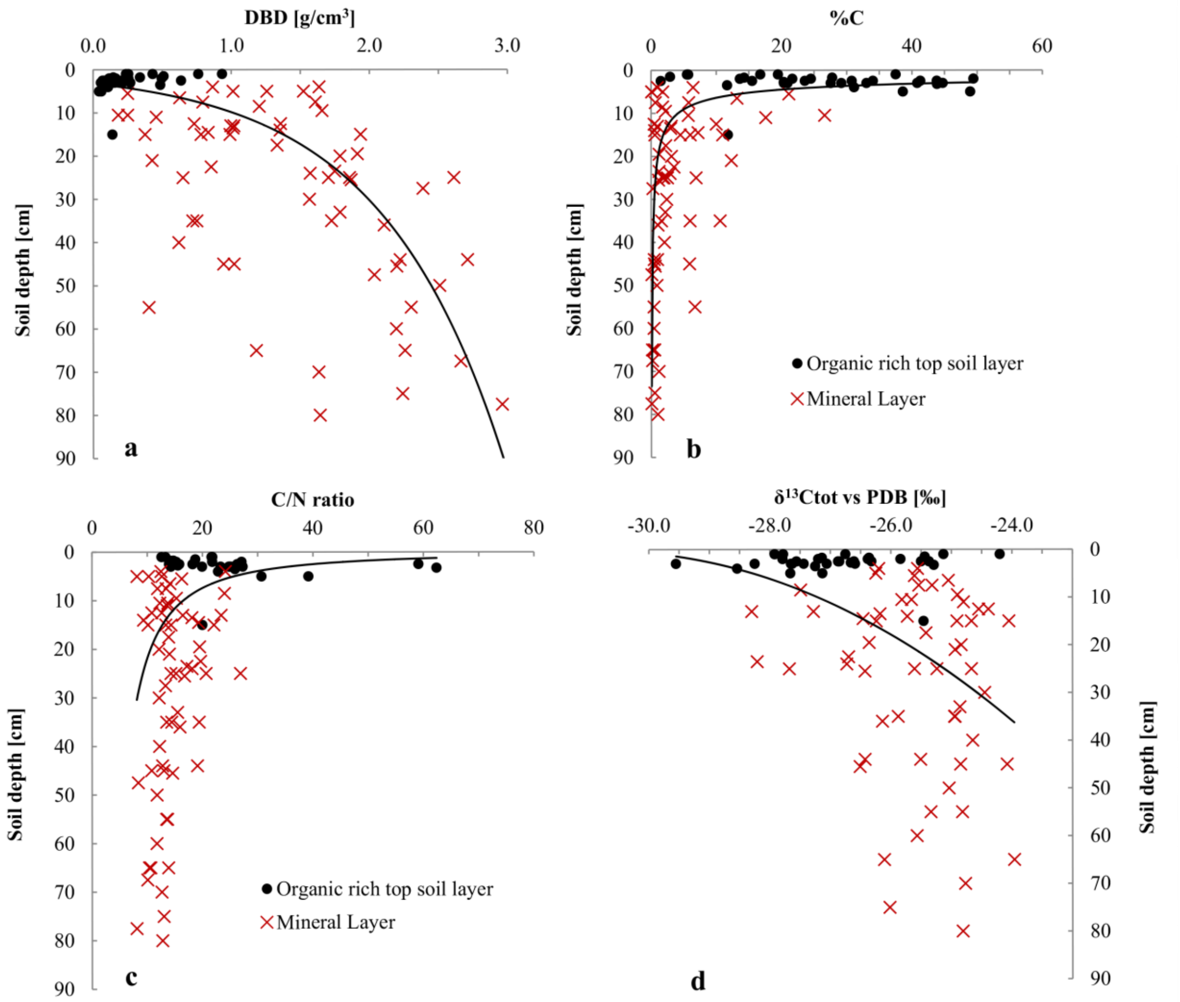

Figure 3. Results of the geochemical analyses of the soils samples of Tarfala Valley. DBD: Dry bulk density (a); %C: percentage C (b); C/N weight ratio (c); $\delta^{13}C_{tot}$ vs PDB: stable isotope δ ^{13}C analyzed to the international standard PeeDeeBelemnite (d). Lines are best-fit power-, polynomial- 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.

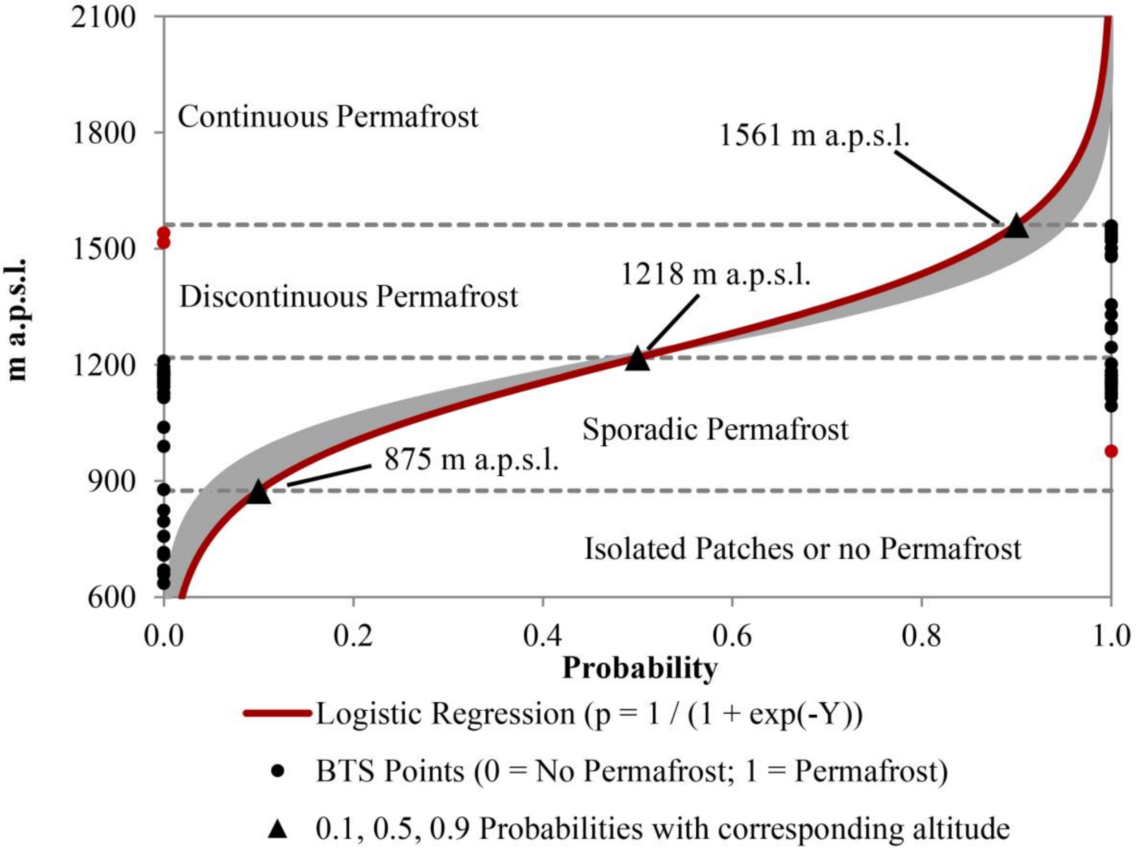

Figure 4. Permafrost probability in relation to altitude – the probability is based on a logistic regression model with the altitude as single independent variable. The grey corridor shows the range of the permafrost probability if outliers (red dots) are removed from the model.

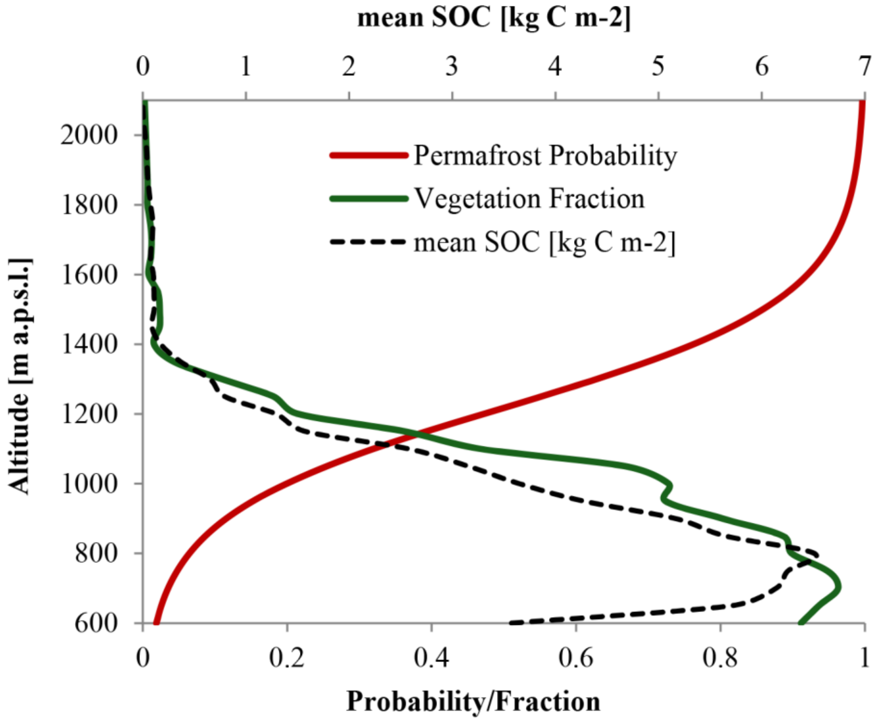

Figure 5. Fraction of vegetation cover and probability for permafrost presence in relation to altitude in Tarfala Valley, including the mean SOC storage per altitude (calculated in 50 m altitudinal intervals). The permafrost probability is based on the BTS-measurements and a logistic regression with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