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Black carbon contributes to organic matter in young soils in the Morteratsch proglacial area (Switzerland)

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Abstract

Most glacier forefields of the European Alps are progressively exposed since the glaciers reached their maximum expansion in the 1850s. Global warming and climate changes additionally promote the exposure of sediments in previously glaciated areas. In these proglacial areas, initial soils have started to develop so that they may offer a continuous chronosequence from 0 to 150 yr-old soils.

The build-up of organic matter is an important factor of soil formation, and not only autochthonous but also distant sources might contribute to its accumulation in young soils and surfaces of glacier forefields. Only little is known about black carbon in soils that develop in glacier forefields, although charred organic matter could be an important component of organic carbon in Alpine soils.

The aim of our study was to examine whether black carbon is present in the initial soils of a proglacial area, and to estimate its relative contribution to soil organic matter. We investigated soil samples from 35 sites distributed over the whole proglacial area of Morteratsch, covering a chronosequence from 0 to 150 yr. BC concentrations were determined in fine-earth using the benzene polycarboxylic acid (BPCA) marker method. We found that the proportion of BC to total C_{org} was related to the time since the surface was exposed. Soils on surfaces exposed less than 40 yr ago contained the highest proportion of BC. The absolute concentrations of BC in fine-earth were generally low but increased in soils that had been exposed for more than 40 yr.

Charred organic matter occurred in the whole area, and it was a main component of soil organic matter in young soils, where total C_{org} concentrations were very low. Specific initial microbial communities consequently may profit from this additional C source during the first years of soil evolution and potentially promote soil development in its early stage.

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1 Introduction

Alpine glacier forefields, or proglacial areas, are defined as the area between the present-day glacier front and the terminal moraines deposited in the 1850s, when the glaciers reached their maximum expansion. The most evident developments in Alpine soil formation occur in proglacial areas where new soils form after glaciers retreat and recently formed soils are continuously developing (Egli et al., 2006). Increasing temperatures will lead to a further retreat of glaciers and additional areas will become subject to weathering and formation of soil organic matter. Proglacial environments are also important for the understanding of global CO_2 cycling on glacial/interglacial timescales as they made up a significant amount of the global land surface during the Quaternary due to the advance and retreat of glaciers and ice sheets (Gibbs and Kump, 1994).

Retreating glaciers often expose barren substrates that become colonised by organisms, beginning the process of primary plant succession which affects the evolution of organic matter in the developing topsoils (Burga et al., 2010). Not only autochthonous but also distant (allochthonous) sources may contribute to the accumulation of soil organic carbon (C_{org}) in young soils and surfaces of glacier forefields. Among these sources are dry and wet atmospheric deposition, faecal deposit, ground-nesting of birds, soot deposit, input due to photo-autotroph organisms, or organic matter of fossil (and preserved) soils (e.g. Bauer et al., 2002; Kim et al., 2005, 2011; Arimitsu et al., 2007; Mindl et al., 2007; Xu et al., 2009; Bogdal et al., 2011; Wientjes et al., 2011). Bernasconi et al. (2011) demonstrated that soil organic matter in initial soils of the Damma glacier forefield contains a relatively high proportion of labile organic compounds which are easily oxidisable and have a short turnover time (annual to decadal). Autochthonous recalcitrant organic matter is not formed in significant amounts in this environment at decadal time scales.

Bardgett et al. (2007) measured changes in the composition of microbial communities and their use of carbon compounds along a 150-yr chronosequence in the Austrian Alps. They found that the initial soil microbial communities of the youngest sites

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were heterotroph organisms that used previously buried recalcitrant carbon, e.g. black carbon, as an energy source. On older sites, after 50 yr of exposure, the soil microorganisms respired modern carbon that derived from modern plant growth.

Charred organic matter and soot, or compounds of black carbon (BC), that are released during vegetation fires or fossil fuel burning are ubiquitous components of soils. Several studies demonstrated that BC can be an important compound even in Alpine soils (Bucheli et al., 2004; Eckmeier et al., 2010) or Alpine lake sediments (Bogdal et al., 2011), and in glacial ice cores (Lavanchy et al., 1999; Thevenon et al., 2009), either due to in-situ burning of biomass or via atmospheric deposition. Glaciers can be sources of BC, when they release BC with glacial runoff water that has been incorporated into the ice after melting (Stubbins et al., 2012).

Although the build-up of organic C is an important factor governing the formation of soils and weathering, only very little is known about the presence of BC in very young soils that are developing in glacier forefields. To analyse time trends in such areas, the study of soil chronosequences is an important tool to derive short- to long-term formation rates. The aim of our research was to examine whether BC is an allochthonous source of soil organic matter in the young soils that develop in the proglacial area of the Morteratsch glacier (Upper Engadine, Switzerland) and to estimate its relative contribution (as a function of time) to total organic matter in soils.

2 Materials and methods

2.1 Investigation area

We investigated soils and sediments of the glacier forefield Morteratsch in the Upper Engadine (Switzerland), which is limited by the terminal moraines that have been deposited during the "Little Ice Age" in the 1850s (Fig. 1). The recent length of this proglacial area is approx. 3 km and it has an area of 1.8 km^2. The proglacial area is situated in a valley that runs N to S, in an altitude of 1900 m a.s.l. to about 2050 m a.s.l.

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Present climatic conditions are approx. 0.5 °C mean annual temperature and approx. 1000–1300 mm mean annual precipitation (calculated from data from the meteorological stations Samedan and Bernina). The history of the Morteratsch glacial environment has been studied extensively in geomorphologic and climatic studies (cf. Burga and Perret, 1998; Magny, 1992; Maisch, 1992; Renner, 1982; Gamper, 1985; Fitze, 1982; Patzelt, 1977). The glacial till in the glacier forefield represents the parent material of soil formation. It consists of granitoid and gneissic rock material which underwent a "green schist" metamorphic event during the high Alpine orogenesis (Büchi, 1994; Spillmann, 1993; Trommsdorff and Dietrich, 1999). Glacial transportation lead to a relatively homogeneous distribution of parent material in the proglacial area.

Primary plant succession of the proglacial area starts about 7 yr after deglaciation with the pioneer plant communities *Oxyrietum digynae* and *Epilobietum fleischeri* and ends with the larch/Swiss stone pine forest (*Larici-Pinetum cembrae*) after more than 150 yr. The first small larch trees, the first shrubs of willows and green alder and the first dwarf-shrubs (e.g. the rust-leaved alpenrose) are found on areas that have been ice-free for about 12 to 15 yr. The *Larici-Pinetum cembrae* forest had been established after about 77 yr (Burga et al., 2010).

The dominant soil units (some sites do not have a soil) in the proglacial area are Haplic Fluvisols (Endoskeletic), Skeletic or Lithic Leptosols and Humi-skeletic Leptosols, and Dystric and Endogleyic Cambisols (endoskeletic) (IUSS working group, 2006). The youngest soils showed almost no morphological signs of chemical weathering and alteration products. The development of soils in the Morteratsch area during 150 yr of surface exposure, including soil organic matter formation and mineral weathering processes, have been studied in detail (e.g. Egli et al., 2010; Mavris et al., 2010).

2.2 Methods

Two sets of samples were investigated that had been taken from the whole proglacial area and that cover a chronosequence ranging from 0 to 150 yr (Table 1). Samples S1–10 are ten topsoils samples (soil depth between 1 to max. 12 cm) from ten sites, which

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are shown in Fig. 1. Close to these sites, material from soil pits has been analysed in detail (Mavris et al., 2010). Samples AS1–29 were sampled from additional sites of the proglacial area at a depth of 0–5 cm.

All samples have been dried at 105 °C, sieved (< 2 mm) and ball-milled for further analysis.

Total C, nitrogen (N) and hydrogen (H) contents were measured using a C/H/N analyzer (Elementar Vario EL). Ash content was determined gravimetrically after dry combustion in a muffle furnace at 550 °C for 6 h (Nocentini et al., 2010). The oxygen (O) content was calculated from the measured data.

The concentration of black carbon (BC) in fine-earth samples was determined as benzene polycarboxylic acids (BPCA) according to the method described by Brodowski et al. (2005). The samples (two replicates) were first treated with trifluoroacetic acid (TFA) to remove polyvalent cations and then digested with HNO_3 at 170 °C for eight hours. The sum of BPCAs in each sample was determined after derivatisation on a gas chromatograph equipped with a flame ionisation detector (GC-FID). The patterns of benzene rings is dependent on the degree of condensation of the polyaromatic carbon compounds. We used a conversion factor of 2.27 to estimate BC contents from total BPCA-C concentrations. The factor provides a conservative minimum estimate of the true BC contents in soil (Glaser et al., 1998; Brodowski et al., 2005).

Environmental scanning electron microscopy (ESEM) and energy-dispersive spectroscopy (EDS) were performed on three loose granular samples (uncoated) (AS 21, 24, 28) at the Institute for Building Materials (ETH Zurich, Switzerland). The fine-earth fraction of the samples was washed with deionized water and the floating material (density $< 1\,g\,cm^{-3}$) was collected and air-dried. This enabled the selective extraction of the organic fraction of the sediment, including charcoal material. The analysis was performed using a Dual Beam Quanta 200 3D FEI coupled with EDX, with Dual BSD detector and W emitter operating at an accelerating voltage of 20 kV. The EDS detector is equipped with an ultra-thin window allowing detection of mineral elements and carbon, which provided the elemental composition of the solid phases.

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Soil colour was measured for dried and homogenised soil samples in triplicates using a spectrophotometer (Konica Minolta CM-5) by detecting the diffused reflected light under standardised observation conditions (2° Standard Observer, Illuminant C). The colour spectra were obtained in the 360 to 740 nm range, in 10 nm increments. The spectral information was converted into Luminance (L^*) values (CIE 1976 Standard Observer), which indicate the extinction of light on a scale from L^* 0 (absolute black) to L^* 100 (absolute white), and into Munsell colour values.

3 Results

3.1 C_{org}

The C_{org} concentrations ranged from 1.9–131.0 g kg^{-1}, with an average of 23.6 and a median of 11.5 g kg^{-1}. The C/N ratios scattered between 2 and 58 (mean 19, median 15), and for samples S1–10 which were taken from the topsoil material, they fell between 12 and 36 (Table 2).

Figure 2 shows that the C_{org} concentrations in younger soils did not exceed 5 g kg^{-1} while after about 40 yr of surface exposure, the C_{org} concentrations increased and reached values close to 80–100 g kg^{-1} after about 60 yr, and a maximum of 131 g kg^{-1} at 75 yr. There is, however, a strong scatter of C_{org} concentrations that is not only related to the factor time but also to others such as vegetation. The average C_{org} concentrations were higher under the pioneer grass communities (46 g kg^{-1}, 10 sites; vegetation type 2 in Table 1) than under the *Epilobietum fleischeri* sites (17 g kg^{-1}, 15 sites). Only three sites were under green alder scrub (*Alnetum viridis*), they reached an average of 15 g kg^{-1}.

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3.2 Black Carbon

The BC concentrations (calculated with a conversion factor from BPCA-C) varied between 0.2 and 5.6 $g\,kg^{-1}$, with an average mean of 1.0 and a median of 0.5 $g\,kg^{-1}$ (Table 2). Since the BPCA-C yield exceeded 1.2 $g\,kg^{-1}$ C_{org} (without conversion factor), we can exclude competing biogenic sources that could significantly add to the BC concentrations (Brodowski et al., 2005).

The concentration of BC is higher in soils that have been developing since more than 40 yr, as is the C_{org} concentration. The BC and C_{org} concentrations were highly correlated ($R^2 = 0.89$, $p < 0.001$). The proportion of BC to total C_{org} was between 23 and 137 $g\,BC\,kg^{-1}$ C_{org} (mean 50, median 46 $g\,BC\,kg^{-1}$ C_{org}. Excluding sample AS6, which was considered an outlier, the relationship with time of surface exposure reaches $R^2 = 0.4$ on a logarithmic scale ($y = -16.4\ln(x) + 114.35$), as shown in Fig. 3. The youngest soils (< 40 yr) contained the highest proportion of BC (68–118 $g\,BC\,kg^{-1}$ C_{org}, while C_{org} concentrations were low (2–4 $g\,kg^{-1}$).

The relative distribution of B6CA (6 carboxyls) to total BPCAs was 25 % in average (Fig. 4). The patterns of benzene rings were similar for all samples, with the exception of AS6 where the proportion of B6CA reached 50 %.

3.3 Atomic ratios O/C and H/C

The O/C ratios varied from 0.0 to 1.3, the H/C ratios from 0.1 to 2.8. There was no significant relation between O/C ratios and BC concentrations or the proportion of BC at C_{org}. The position of the samples in the van Krevelen plot in Fig. 5 (after Kim et al., 2003) showed that the average atomic ratios for most age groups are typical for plant lignin or cellulose material, with the exception of the youngest age group (0–20 yr) that was characterized by lower H/C ratios.

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3.4 ESEM-EDS

ESEM-EDS allowed the identification of charcoal particles based on their morphology and elemental composition in all analysed samples (AS 21, 24, 28), as shown in Fig. 6. The visual identification was supplemented with the measurement of the atomic ratios of the particles. Following Brodowski et al. (2005), we considered BC as particles that had an O/C ratio of ≤ 0.33 (Stoffyn-Egli et al., 1997) on at least one point of an observed particle.

3.5 Soil colour

Soil colour, in particular the Luminance, or brightness, of the soil colour (L^*), varied between 38 and 70 (mean 54, median 55). It was correlated both to C_{org} ($R^2 = 0.545$, $p < 0.001$) and BC concentrations ($R^2 = 0.462$, $p < 0.001$), but not to time.

4 Discussion

Although the environmental conditions in the Morteratsch proglacial area are relatively homogeneous, small scale variability affects soil properties. This is reflected, among others, in the C_{org} concentrations which considerably varied after 30 to 40 yr of soil evolution. Small changes such as water content of the substrate, the micro-relief and micro-climate seem to be crucial for both the development of the vegetation and, consequently, also the early evolution of the soils. Two vegetation types persisted over large parts of the chronosequence: pioneer grass communities (*Geo montani-Nardetum* and *Poion alpinae*) and *Epilobietum fleischeri* with single willow shrubs and Alpenrose. The C_{org} concentrations were affected by these differences in vegetation, the average concentrations were highest under the pioneer grass communities. Due to the temporal trend, the variability of soil organic matter under all vegetation types was high. The soil colours reflected the heterogenity of soil formation. Due to their low evolution stage, the

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soils had a relatively light colour but darkened progressively with increasing C_{org} and BC contents (cf. Eckmeier et al., 2010). The yellow hues showed that the soils were not affected by soil forming processes as brunification yet.

BC was present in the whole investigated area, independent from the time since the surface has been exposed, although the concentrations were very low in the youngest soils. The occurrence of BC in remote mountainous environments is not unusual. BC, or, more generally, combustion residues that have been transported as aerosols were deposited on the surfaces of Tibetan glaciers (Xu et al., 2009). Stubbins et al. (2012) found that fossil dissolved organic matter in runoff water of glaciers in Alaska was dominated by aerosols produced during combustion, and that these are a major element in the carbon cycle of glacial environments. BC is also commonly found in the Alpine environments of Switzerland. In the sediments of Lakes Thun, Engstlen and Oberaar, up to one-third of C_{org} was BC (determined by CTO-375; Bogdal et al., 2011). The analysis of ice cores from Colle Gnifetti showed that the deposition of BC increased strongly since the end of the 19th century (Thevenon et al., 2009). The same trend was measured for polycyclic aromatic hydrocarbons (PAHs), which are also produced during burning and which are likely to be absorbed at BC particles. PAH concentrations reached a maximum 1945–1955, and then decreased again. A source assignment using specific PAHs indicated that the ratio of wood and coal burning in contrast to fossil fuel combustion decreased until the 1980s, then the trend reversed (Gabrieli et al., 2010).

The source of BC measured in the Morteratsch forefield is charcoal or diagenetic coal. Charcoal particles were found by microscopic inspection, and the BPCA pattern correspond to BPCA pattern of charcoal and coal as described by Roth et al. (2012). The BPCA method, however, would also underestimate the amounts of soot-derived BC (Hammes et al., 2007). Potential sources for the BC in the Morteratsch proglacial area would be wood combustion for heating, charcoal kilns which have been common in the area until the 20th century, or the railway (Rhaetische Bahn) which is passing in

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a distance of about 2.5 km from the glacier front that had been equipped with a steam engine until the 1920s.

In two rural areas of Switzerland and in the city of Zurich, burning of wood produced up to one-third of BC emissions (measured during 2.5 yr on aerosols using a spectroscopic method) during the winter and 2–10 % during summer (Herich et al., 2011). Szidat et al. (2007) even reported contributions of up to 88 % of residential wood burning on particulate matter in Alpine valleys during winter. The analysis of 104 soil samples from the Swiss soil monitoring network showed that the BC concentrations had a very uniform distribution because of the uniform deposition of the atmospherically transported BC aerosols (Agarwal and Bucheli, 2010).

Up to now, BC concentrations have not been measured in initial soils of glacier forefields. A small decrease in the proportion of aromatic C with soil age has been found in the Damma glacier forefield using ^{13}C-NMR (Dümig et al., 2011), while the proportion of aromatic C in soil organic matter of the Morteratsch glacier forefield, measured using DRIFT, was increasing with time of exposure (Egli et al., 2010). This increase in aromatic compounds was, however, not related to fire-derived organic matter, but rather indicated the presence of condensed and lignin-derived compounds (Poirer et al., 2003).

Charred organic matter was deposited over the whole proglacial area. Local fires could have influenced specific sites, especially S9 where the absolute BC concentration was considerable, or AS6 where the proportion of BC at C_{org} and the proportion of B6CA were highest. The youngest soils are characterised by very low C_{org} concentrations, which resulted in a higher proportion of BC in these soils. This is reflected by the H/C ratios which are rather low in the youngest soil samples. Here, specific initial microbial communities consequently may profit from this additional C source during the first years of soil evolution, as was shown for the Austrian Alps by Bardgett et al. (2007), and potentially promote soil development in its early stage.

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5 Conclusion

The developing soils in the Morteratsch proglacial area contained charred organic matter, most likely derived from charcoal or coal, which was distributed over the entire investigated area. It is, however, not known if all BC was deposited by atmospheric deposition, or if the source of BC was material that has accumulated on the glacier and was deposited on the parent material or soil after the ice finally melted. BC concentrations were lowest on surfaces that were exposed during the last 40 yr, either due to their lower exposure time or to a reduced input of BC during the last 40 yr. BC contributed to total C_{org} which is particularly important at initial soil formation stages, where microorganisms could have used BC as a C source whereas other C_{org} sources provided by vegetation were still scarce or simply lacking.

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Table 1. General properties of the sites and samples.

Site	Year of exposure	Exposure time (yr)	Horizon	Depth (cm)	Skeleton (wt-%)	Soil type (WRB)	Vegetation*
S1	1870	140	A	0–6	41	Humi-skeletic Leptosol	4
S2	1880	130	A	0–10	64	Humi-skeletic Leptosol	4
S3	1900	110	A	0–5	54	Humi-skeletic Leptosol	3
S4	1910	100	A	0–1	55	Humi-skeletic Leptosol	3
S5	1940	70	A1	0–1	7	Humi-skeletic Leptosol	2
S6	1960	50	A	0–3	64	Skeletic Leptosol	3
S7	1960	50	A	0–4	26	Skeletic Leptosol	2
S8	1950	60	O/A	0–12	63	Skeletic Leptosol	2
S9	1935	75	O	0–3	44	Humi-skeletic Leptosol	2
S10	1930	80	A1	0–2	49	Humi-skeletic Leptosol	3
AS1	1870	140	A	0–5	n.d.	Humi-skeletic Leptosol	2
AS2	1880	130	A	0–5	n.d.	Humi-skeletic Leptosol	2
AS3	1890	120	A	0–5	n.d.	Humi-skeletic Leptosol	5
AS4	1890	120	A	0–5	n.d.	Skeletic Leptosol	2
AS5	1900	110	A	0–5	n.d.	Skeletic Leptosol	7
AS6	1910	100	AC	0–5	n.d.	Skeletic Leptosol	2
AS8	1920	90	AC	0–5	n.d.	Skeletic Leptosol	6
AS9	1930	80	AC	0–5	n.d.	Skeletic Leptosol	4
AS10	1940	70	A	0–5	n.d.	Humi-skeletic Leptosol	2
AS11	1945	65	A	0–5	n.d.	Humi-skeletic Leptosol	3
AS12	1945	65	A	0–5	n.d.	Skeletic Leptosol	3
AS13	1950	60	A	0–5	n.d.	Skeletic Leptosol	3
AS14	1950	60	A	0–5	n.d.	Humi-skeletic Leptosol	3
AS15	1965	45	A	0–5	n.d.	Skeletic Leptosol	2
AS16	1965	45	(A)C	0–5	n.d.	Skeletic Leptosol	3
AS17	1970	40	AC	0–5	n.d.	Skeletic Leptosol	3
AS18	1970	40	AC	0–5	n.d.	Skeletic Leptosol	3
AS19	1975	35	(A)C	0–5	n.d.	–	3
AS20	1975	35	(A)C	0–5	n.d.	–	3
AS21	1975	35	(A)C	0–5	n.d.	–	3
AS22	1980	30	(A)C	0–5	n.d.	–	0
AS23	1980	30	(A)C	0–5	n.d.	–	3
AS24	1990	20	(A)C	0–5	n.d.	–	0
AS28	2007	3	C	0–5	n.d.	–	0
AS29	2007	3	C	0–5	n.d.	–	0

n.d. = not determined;
*0 = no vegetation; 2 = Pioneer grass communities (*Geo montani-Nardetum* and *Poion alpinae*); 3 = *Epilobietum fleischeri* with single willow shrubs and Alpenrose; 4 = Green alder scrub (*Alnetum viridis*) (*Alnus viridis* and tall perennial herbs, *Salix* spec., *Poa* spec., *Deschampsia caespitosa*, *Avenella flexuosa*, *Nardus stricta*, *Festuca* spec., *Phleum rhaeticum*, *Anthoxanthum alpinum*, *Calamagrostis villosa*); 5 = Grass heath on moister soils (grass species e.g. *Festuca violacea*, *Calamagrostis villosa*, *Phleum rhaeticum*, *Poa alpina*); 6 = Boulder plant communities, partially *Epilobietum fleischeri* (*Epilobium fleischeri*, *Adenostyles leucophylla*, *Rumex scutatus*, *Dryopteris* spec., *Athyrium* spec., *Gymnocarpium dryopteris*, *Polystichum lonchitis*); 7 = Rock vegetation (e.g. *Agrostis rupestris*, *Silene rupestris*, *Sempervivum arachnoideum*)

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Table 2. Spectral and chemical properties of the investigated samples.

Site	Luminance (L^*)	Munsell colour Hue	Value	Chroma	C_{org} ($g\,kg^{-1}$)	N ($g\,kg^{-1}$)	C/N Weight ratio	O/C Atomic ratio	H/C Atomic ratio	BC[1] $g\,C\,kg^{-1}$ C_{org}	BC[1] ($g\,kg^{-1}$)	B6CA %
S1	57.9	2.5 Y	5.6	1.5	7.1	0.6	12	0.7	1.0	49.7	0.4	27.8
S2	40.2	0.8 Y	3.9	1.1	64.1	3.0	22	0.5	0.8	43.2	2.8	22.8
S3	51.6	2.3 Y	5.0	1.4	30.3	1.0	29	0.4	1.3	33.1	1.0	27.7
S4	39.0	1.4 Y	3.8	1.5	54.5	1.2	47	0.7	1.7	25.8	1.4	20.7
S5	57.1	2.5 Y	5.6	1.1	31.7	0.8	42	0.6	1.1	40.2	1.3	26.1
S6	48.1	1.4 Y	4.7	1.8	37.0	1.1	34	0.3	1.6	27.9	1.0	33.6
S7	43.2	1.6 Y	4.2	1.7	64.5	4.3	15	0.6	1.6	23.0	1.5	21.6
S8	45.1	1.7 Y	4.4	1.2	89.7	3.8	24	0.6	1.5	25.9	2.3	14.8
S9	39.4	0.5 Y	3.8	1.4	131.0	7.0	19	0.7	1.6	42.8	5.6	13.5
S10	38.4	1.4 Y	3.7	1.3	47.9	1.3	36	0.9	1.6	44.9	2.1	14.5
AS1	47.5	1.6 Y	4.6	1.5	61.2	4.6	13	0.6	1.8	43.1	2.5	26.3
AS2	48.1	2.2 Y	4.7	1.8	18.1	1.2	15	0.5	1.6	48.8	0.8	19.5
AS3	58.3	2.9 Y	5.7	1.5	7.3	0.3	23	0.7	0.3	54.5	0.4	43.9
AS4	54.8	2.3 Y	5.3	1.7	9.4	0.4	24	0.8	0.4	49.9	0.5	38.5
AS5	47.2	1.9 Y	4.6	1.7	14.2	1.4	10	1.0	0.7	58.1	0.8	28.4
AS6	62.2	3.1 Y	6.1	1.3	3.2	0.7	4	1.3	2.2	136.7	0.4	49.9
AS8	63.9	2.5 Y	6.2	1.6	3.9	0.4	10	0.2	1.7	n.d.	n.d.	n.d.
AS9	62.6	3.4 Y	6.1	1.4	5.3	0.6	9	1.2	1.5	44.7	0.2	28.8
AS10	49.5	2.0 Y	4.8	1.8	29.9	1.1	28	0.5	0.8	61.4	1.8	23.6
AS11	49.4	2.1 Y	4.8	1.7	11.6	0.8	14	0.7	0.5	46.6	0.5	24.4
AS12	43.8	1.8 Y	4.3	1.6	12.6	0.7	19	0.7	0.4	30.2	0.4	24.1
AS13	47.6	2.2 Y	4.6	1.3	11.5	0.4	30	0.5	0.9	27.1	0.3	25.3
AS14	58.5	2.7 Y	5.7	1.4	18.1	0.3	58	0.6	1.4	23.7	0.4	22.0
AS15	49.7	2.3 Y	4.8	1.6	18.3	0.3	57	0.8	1.6	48.0	0.9	16.6
AS16	61.7	2.7 Y	6.0	1.2	4.9	1.4	3	1.2	1.4	46.4	0.2	24.3
AS17	58.6	2.2 Y	5.7	1.6	6.0	1.0	6	0.3	1.2	50.1	0.3	23.2
AS18	59.1	2.6 Y	5.8	1.5	9.3	0.4	25	0.8	0.9	35.6	0.3	20.4
AS19	69.6	2.4 Y	6.8	1.4	2.3	1.0	2	0.2	1.4	n.d.	n.d.	n.d.
AS20	59.9	3.0 Y	5.8	1.5	4.1	1.3	3	0.0	1.8	67.7	0.3	22.3
AS21	54.7	3.1 Y	5.3	1.5	4.0	0.7	5	0.0	0.1	n.d.	n.d.	n.d.
AS22	59.7	3.7 Y	5.8	1.4	2.9	0.3	10	0.3	2.1	69.2	0.2	22.7
AS23	64.7	4.2 Y	6.3	1.3	2.6	0.2	11	0.6	0.3	73.7	0.2	22.9
AS24	63.8	3.8 Y	6.2	1.4	2.9	0.4	7	0.0	2.2	n.d.	n.d.	n.d.
AS28	62.5	4.3 Y	6.1	1.3	1.9	0.7	3	0.9	0.4	117.9	0.2	22.6
AS29	60.3	4.5 Y	5.9	1.2	2.1	0.3	8	0.7	2.8	n.d.	n.d.	n.d.

[1] Black carbon was calculated by multiplying BPCA-C data with a conversion factor of 2.27 (Brodowski et al., 2005).

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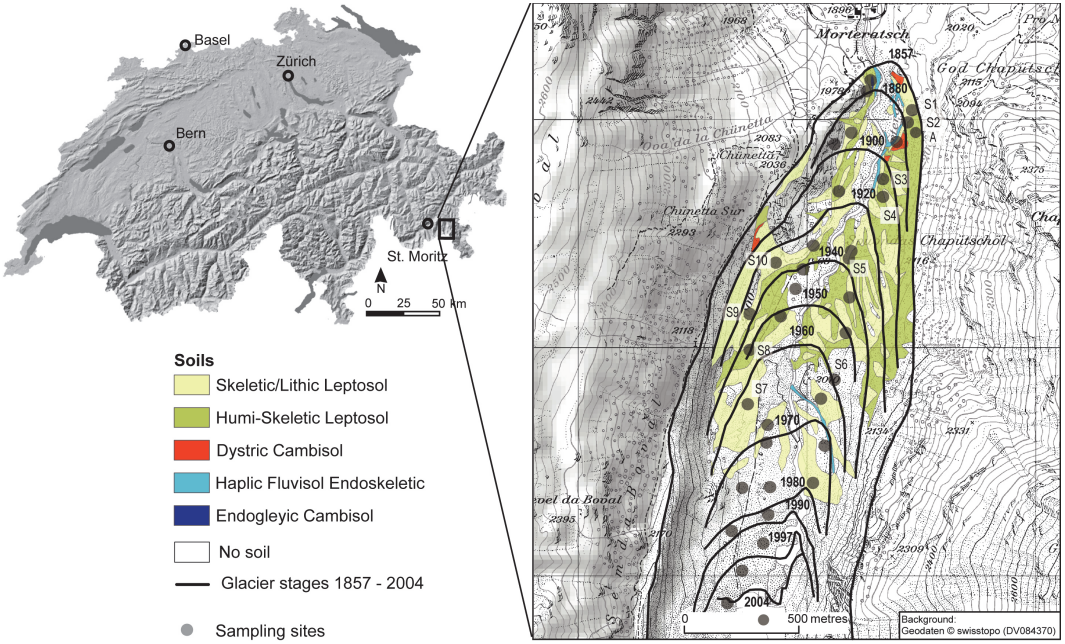

Fig. 1. Location of the Morteratsch glacier forefield with isochrones of glacier retreat, major soil units and position of the topsoil sampling sites, which were analysed in detail regarding soil chemistry and mineralogy (S1–10; Mavris et al., 2010).

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BC contributes to organic matter in young soils in the Morteratsch area

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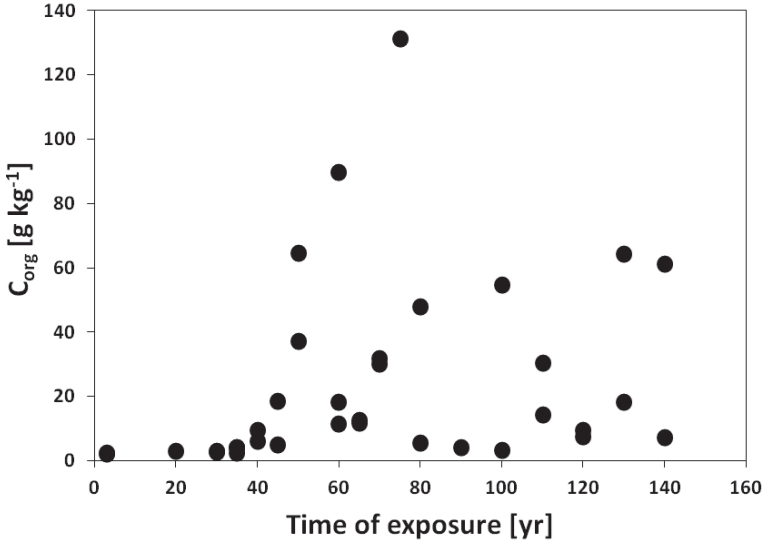

Fig. 2. C_{org} concentrations (in g kg^{-1}) in all samples as a function of surface exposure time.

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BC contributes to organic matter in young soils in the Morteratsch area

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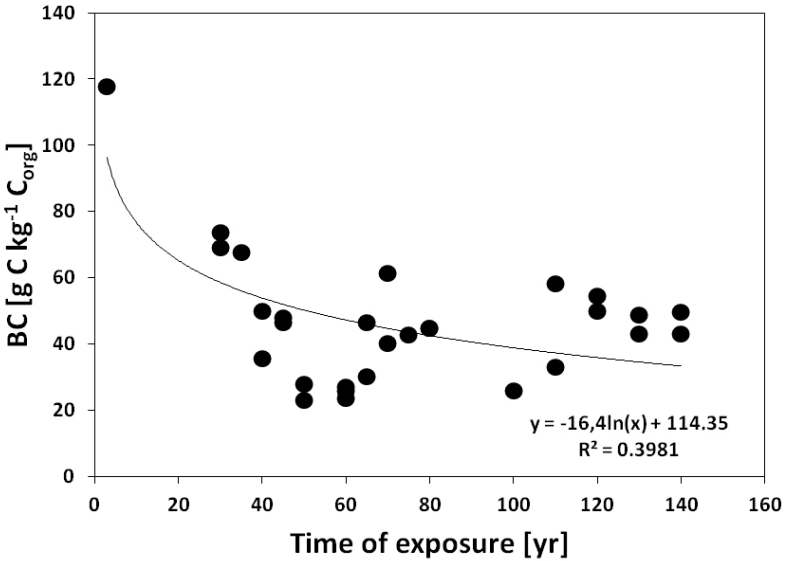

Fig. 3. Relative proportion of BC in total organic carbon as a function of time for all samples except outlier AS6.

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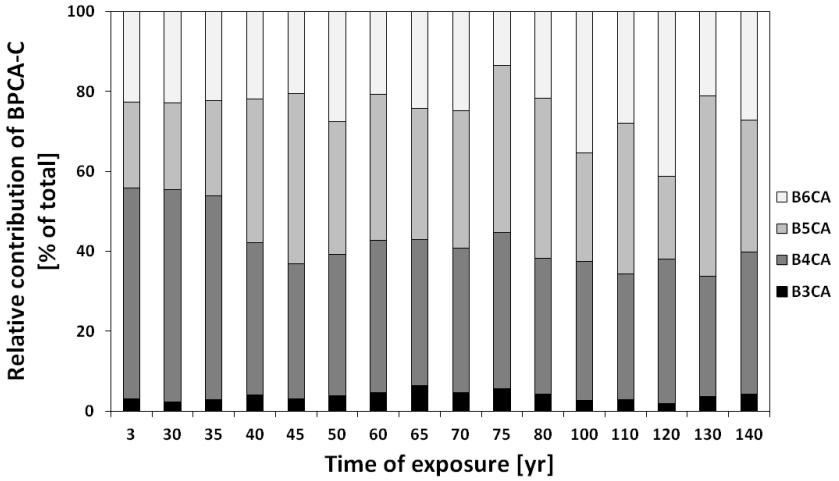

Fig. 4. Average patterns of benzene rings in proportion to total BPCA-C for times of exposure.

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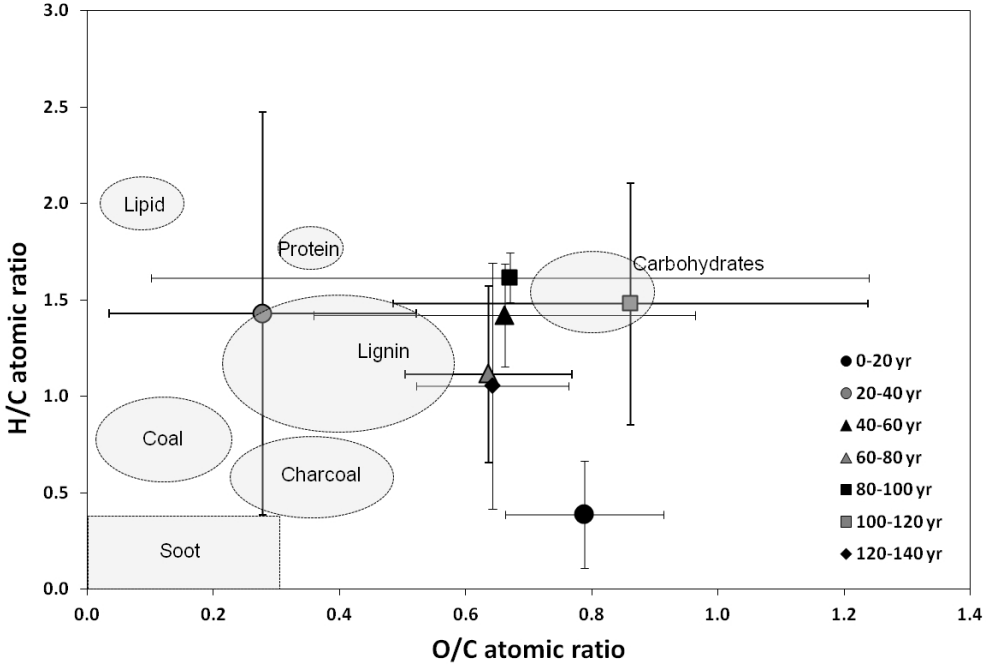

Fig. 5. Van Krevelen diagram showing the H/C and O/C atomic ratios of soils (mean values ± SD of age classes). Grey shaded areas indicate areas of organic compounds after Kim et al. (2003) and Hammes et al. (2006).

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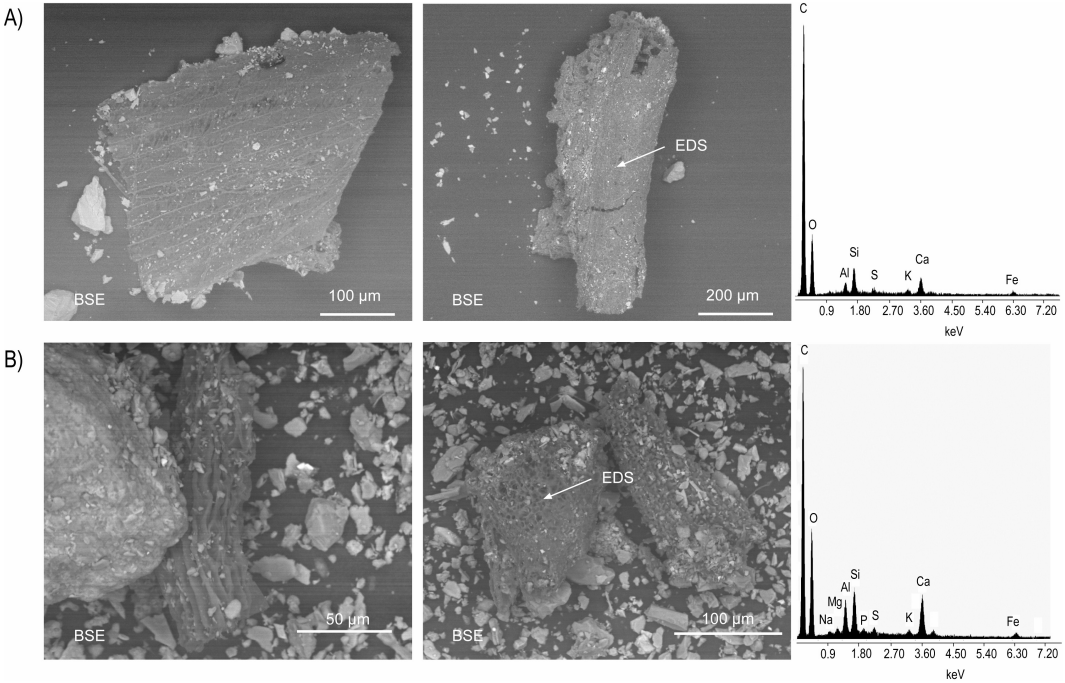

Fig. 6. Environmental scanning electron microscopy (ESEM) and energy-dispersive spectroscopy (EDS) on organic particles with a density $< 1\,g\,cm^{-3}$. **(A)** Exposure age three years (AS29); **(B)** exposure age 20 yr (AS24). BSE = back-scattered electrons.

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