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Proglacial wetlands: an overlooked CO_2 sink within recently deglaciated landscapes

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Abstract

Glacial retreat has uncovered vast landmasses in the European Alps over the last 150 yrs. Soil formation in these areas is considered to be slow due to low temperatures, lack of moisture, and short growing seasons. Previous studies have however focused solely on dry soils, omitting any water saturated locations. Our research shows that these water saturated locations are key locations of CO_2 uptake and have a significant role in carbon storage in the proglacial valley, despite their small surface area. Loss-on-ignition analyses showed certain wetland soils contained up to 85% carbon, suggesting these wetlands can become peatlands over time, storing large amounts of carbon. CO_2 flux measurements showed atmospheric CO_2 uptake in wetlands of all measured ages, even as young as 5 years after deglaciation. As little moss or plant cover was generally observed at locations <50 yrs, the autotrophic microbial community likely plays an important role in these young systems. Non-saturated locations showed a much larger variation in CO_2 fluxes, with both emission and uptake of CO_2 being observed across ages. Overall, our research shows that wetlands are hotspots of biological activity and pedogenic processes in proglacial areas and should therefore receive more attention in proglacial research.

1. Introduction

Proglacial valleys or glacial forefields form where glaciers have retreated. Since 1850, 60% of glacier volume in the European Alps has been lost, and many small glaciers will disappear completely in the next decades [1]. Owing to prolonged glacial scouring, the newly revealed

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Preprint. Discussion started: 3 September 2025

surfaces are typically composed of bedrock or glacial deposits, with no evidence of prior soil development. Over time, these surfaces are colonized by microbes, mosses and vascular plants and show soil development. Proglacial areas can be used for space-for-time studies, where the soil age is calculated from glacial retreat maps. The age information of these so-called chronosequences can be used to study natural processes over time without the need for experiments and incubations.

The buildup of organic carbon in proglacial soils is a net result of in- and outfluxes of particulate, dissolved and gaseous carbon compounds. Previous studies on soil carbon along proglacial chronosequences have focussed primarily on the particulate and dissolved contributions (e.g. [2–4]). Studies on gaseous carbon fluxes have predominantly focussed on aquatic systems inside proglacial valleys (e.g. [5,6]) and are geared towards research on methane rather than CO_2.

Gaseous carbon fluxes consist predominantly of CO_2 in these young soils, as methane and volatile carbon compounds are only produced in significant quantities in more developed soils. The one previous study on proglacial CO_2 fluxes that we are aware of, reports CO_2 effluxes from soil respiration [7]. Soils can however also take up atmospheric CO_2. The majority of CO_2 uptake by soils is a biological process, performed by microbial and plant communities. These consume atmospheric CO_2 either via photosynthetic or chemoautotrophic pathways and form cell biomass or other carbon compounds, which over time contribute to the formation of soil carbon.

What determines the CO_2 uptake rates in proglacial soils is not well understood. Several factors may limit effective carbon metabolisms in both the microbial and plant communities, such as macro- and micronutrient limitations, temperature, light exposure, physical disturbances, and water availability. Often, several of these factors are lumped together in the soil age. What exactly contributes to the soil age being an explanatory factor, and whether this holds for different locations within a proglacial valley, is often not further explored, nor is the interaction with CO_2 uptake rates. Recent work on proglacial areas and their carbon cycling has predominantly been focussed on Asian glacier regions [8,9] or Arctic regions [10,11], which however have a different climatic regime than the European Alps. We therefore aim to enhance the knowledge on European alpine proglacial regions.
Furthermore, we sampled both water-saturated and non-saturated (dry) soils in proglacial areas. Up to now, proglacial wetlands have been ignored or purposely left out of any proglacial soil dataset, because water-influenced soils were considered too disturbed to be taken into a chronosequence approach. We however show that proglacial wetlands are

https://doi.org/10.5194/egusphere-2025-4113
Preprint. Discussion started: 3 September 2025

hotspots of atmospheric CO_2 uptake and carbon storage and that trends with age can be observed for both wetland and dry soil locations.

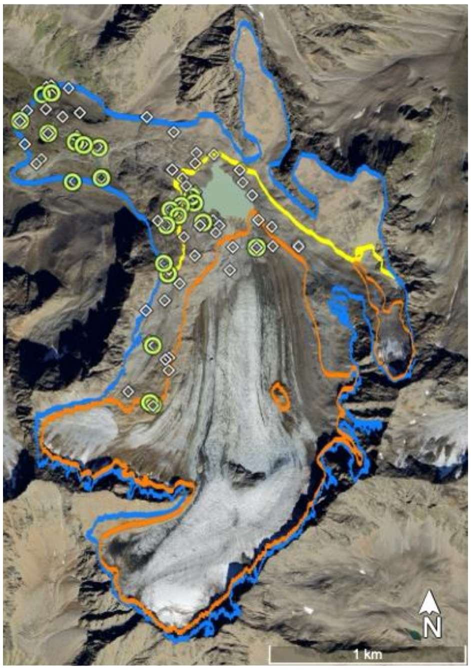

Fig. 1. Map of the proglacial area of the Bachfallenferner glacier, Austria. Glacial outlines of the years 1850 (blue), 1969 (yellow), and 2015 (orange) are shown. More outlines are available (GLIMS) but not included in the figure. Soil and wetland sampling locations are indicated with white diamonds and green circles, respectively. Geographic coordinates at the centre of the image are 47.0737° N, 11.0769° E. Background imagery from Google Earth©, imagery date 8 Sept 2023.

https://doi.org/10.5194/egusphere-2025-4113
Preprint. Discussion started: 3 September 2025

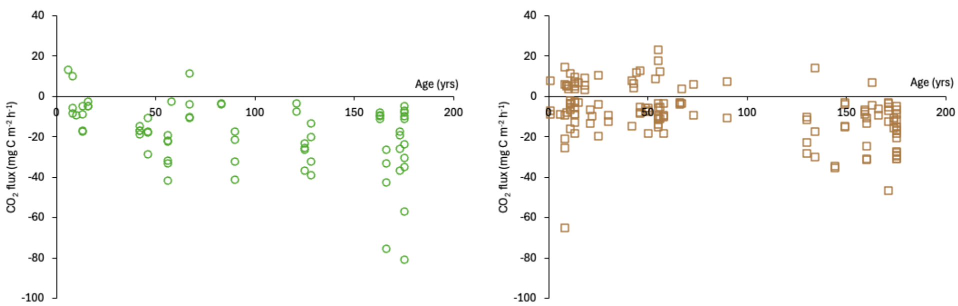

Fig. 2. CO_2 fluxes of the proglacial wetlands (left, in green) and soils (right, in brown) plotted against age. Positive (> 0) fluxes indicate emissions to the atmosphere, negative (< 0) fluxes indicate atmospheric CO_2 uptake. Fluxes were upscaled to per hour values, for details see Appendices (Material and methods).

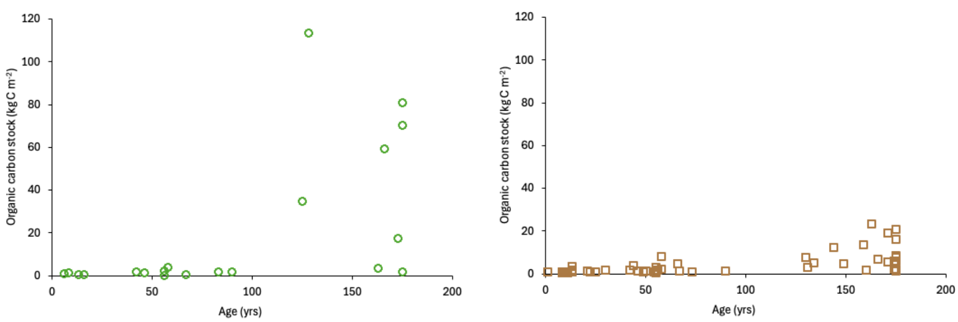

Fig. 3. Organic carbon stocks of the wetlands (left, in green) and soils (right, in brown), calculated as the cumulative stock of all soil horizons that were present, plotted against age.

2. Results and discussion

Given the well documented glacial retreat in the proglacial area of the Bachfallenferner (Fig. 1)[12], each location in this area can be given an age via linear interpolation between recorded glacial extents. For clarity, we use the word ‘soil’ for the surface material at each location, also for undeveloped deposits without signs of pedogenesis. ‘Dry’ is used for each location that is not water-saturated, regardless of its water content. Younger soil locations are

https://doi.org/10.5194/egusphere-2025-4113
Preprint. Discussion started: 3 September 2025

generally characterized by a lack of vascular plant and moss cover, whereas the older locations have a lush appearance with abundant grasses and other plants (Fig. B1). The first moss coverage is already observed in the first decade, although the percentage surface cover remains low (Fig. B2). Grasses and other plants appear from ca. 50 years onwards (Fig. B2). A similar pattern is observed in other proglacial areas[13], although some regions show the development of a rich vascular plant cover much earlier [9,14].

In this study, we sampled and measured in both dry and water-saturated (wetland) locations. Previous work on carbon and/or CO_2 cycling in proglacial areas has been focussed on either streams and lakes (e.g. [5,6,15]) or on dry soils (e.g. [4,13]. Generally, the presence or absence of wetlands in the proglacial valley is not mentioned, although Bernasconi et al. (2011)[13] very briefly mention they observed groundwater seepage in sampling locations that have a higher clay content than the average. Given the high input of glacial meltwater, snowmelt, and precipitation, proglacial areas are very likely to contain and sustain wetlands, both near streams and in small, local depressions or groundwater seepage locations. Further research, preferably using remote sensing, is required to quantify the surface area of wetlands in proglacial areas and to upscale our findings.

Microbial and/or plant communities can use atmospheric CO_2 either via photosynthetic or chemoautotrophic pathways. We report CO_2 uptake in most of the measured locations (Fig. 2). In wetland locations, the net CO_2 flux was negative (indicating uptake) in 95% of the measurements. In the dry locations, 18% of the fluxes were positive, mostly in soils up to 100 years old. In many soil locations in the proglacial area of the Bachfallenferner, the plant community is limited (<50% plant surface in 60% of the dry soil locations, and in 38% of the wetland locations, Fig. B2). It is therefore likely that the soil microbial community plays a key role in the CO_2 uptake. Earlier studies on the microbial community in proglacial environments showed that chemolithoautotrophy (non-light dependent CO_2 uptake) was an important trait in the presented microbial communities[11]. Research in very young deglaciated soils revealed that carbon fixating microbial genes could be found in soils directly after deglaciation (0 yrs old), with an increase in copy numbers within the first decade [8]. However, other studies also showed that genes for heterotrophy (carbon cycling) were present in very young soils [16], indicating that both carbon uptake and degradation can occur rapidly after glacial retreat. Soil moisture was one of the explanatory variables of the microbial community composition along the chronosequence investigated by Khan et al. (2023)[8].

The positive net CO_2 fluxes (indicating CO_2 emissions) that we observed predominantly in young dry soils are expected to be the result of microbial decomposition of soil carbon.

https://doi.org/10.5194/egusphere-2025-4113
Preprint. Discussion started: 3 September 2025

Guelland et al. (2013)[7] found net CO2 emissions for each of their sampled locations within the Damma glacier proglacial area, despite the presence of plants only in their older sites. Soil respiration in young sites (<50 yrs) mainly had pre-aged, burned, allochthonous carbon as C-source, whereas the CO_2 from older soils was the result of degradation of in situ produced carbon. The presence of old or allochthonous carbon would explain the CO_2 emissions we also find in our youngest sites. Incubation studies with added plant litter showed decomposition occurred in soils of 10 years old, to the same extent as in 70- and 120-years old soils, thus indicating that a microbial community capable of the mineralisation of organic carbon is present within 10 years [17]. We measure net CO_2 uptake in older and in wet locations. CO_2 production likely does occur in those locations but is masked by simultaneous CO_2 uptake. To detangle the two, detailed incubation studies and/or isotope measurements are required. Potentially, soil carbon can form complexes with weathered minerals in older soils, protecting it from degradation and lowering emission rates [7,17].

Egli et al. (2010)[4] found a correlation (R2 = 0.51, $p < 0.05$) of soil organic carbon content with age, with an apparent knickpoint around 50 years. However, their limited number of sampled locations younger than 50 years makes it difficult to accurately assess trends in the youngest soils. Temme et al. (2016)[18] did not find a significant relationship between soil age and organic carbon content, but did observe the same divergence between soils > 50 and <50 years old, with the <50 years old soils containing no detectable organic carbon. We hypothesize that the difference between these two age groups is related to the contribution of vascular plants to the soil carbon stock. Our CO_2 flux results show that carbon is taken up in part of our soils of <50 years, presumably by the microbial community. The uptake rate however increases when the plant surface cover increases (Fig. 2, Fig. B2). Bernasconi et al. (2011) show that the microbial carbon content of their proglacial soils increased with age in the top 5 cm, showing that microbes do still contribute to soil organic matter in later stages, in addition to plant carbon inputs. Li et al. (2022)[9] observed a linear increase in soil organic carbon content with age (0.13 – 1.3 % over a 90 yrs sequence), as well as a decrease in pH with age. We also observed a relationship between age and pH (Fig. B3). Interestingly, the soils measured in that study had a soil moisture content of 68 – 85%, except for the youngest soil (40%). Although not saturated, these soils are likely closer to our wetland sites than the dry soil locations within the Bachfallenferner proglacial area. The combined work of Smittenberg et al. (2012)[3] and Guelland et al. (2013)[7] showed increasing carbon stocks with age in the Damma proglacial area, along with increased CO_2 emissions, but no significant correlation between the two. They showed the presence of plants seemed to increase soil CO_2 emissions due to enhanced root inputs, although the relationship seemed complex and dependent on several factors.

https://doi.org/10.5194/egusphere-2025-4113
Preprint. Discussion started: 3 September 2025

Besides the effect of age, we also see a clear distinction between wetland and dry locations. Wetland locations have significantly higher CO_2 uptake rates (Fig. 2) than dry soils of the same age. They also become CO_2 sinks much earlier: the majority of the wetlands is an atmospheric CO_2 sink directly after glacial retreat, whereas the dry soils are often CO_2 sources in the first 100 years (Fig. 2). In the oldest locations (170-175 yrs old), the CO_2 uptake rates of the wetlands is on average 2.2 mM h^{-1}, whereas it was 1.4 mM h^{-1} in dry soils. The carbon stock is very high in certain wetlands, but low in others (Fig. 3). Possibly, the time of carbon buildup in the wetland locations does not always correspond to the deglaciation age. Deposition or erosion of fine material in these wet sites may have 'reset' the clock on soil carbon stock buildup. Several of the older wetland locations have up to 70-80 mass % carbon in the topsoil (Supplemental file 2), indicating that the wetlands could turn into peatlands over time. Plant communities appear earlier in wetlands than in dry soils and also cover a higher surface % (Fig.A; Fig. B2). However, also before vascular plant and moss communities are established, wetlands have a higher CO_2 uptake rate. This supports the hypothesis that the microbial community is more abundant and/or active in proglacial wetlands compared to non-saturated soils. A higher water content can benefit the microbial community by an increased water and nutrient availability, due to enhanced (diffusive) transport. A study on litter decomposition in proglacial soils showed a positive correlation between microbial mineralisation of litter and the soil moisture content [17], suggesting a higher water content indeed promotes microbial activity. In addition, our results show a correlation between the water and carbon content of the soils (R^2 = 0.65, Fig. B4), not only for wetland but also for locations classified as dry soils. As no other studies on proglacial wetlands exist, we cannot compare this with previous findings. A study on wet locations just outside the terminal moraine of a proglacial area in New Zealand[19] shows peat formation in saturated soils. Potentially, the wetlands we observe will turn into peatlands over time. The correlation we observe between water content and carbon stock is likely a result of enhanced plant and microbial activity (and therefore carbon uptake and storage fluxes) in wetter soils, but it should be noted that a higher carbon content also increases the water holding capacity of the soils, and the correlation is therefore likely explained by both biological and physical reasons.

Previous research on CO_2 emissions from proglacial areas has strongly focussed on streams and lakes, which can emit CO_2 that is either locally produced or CO_2 that is transported along with (melt)water. Glacial runoff is known to transport methane [10,20], but an earlier study that measured the CO_2 flux from glacial runoff water did not show consistent fluxes. Values fluctuated between uptake and emission of CO_2, in the range of -20 to +20

https://doi.org/10.5194/egusphere-2025-4113
Preprint. Discussion started: 3 September 2025

mmol m^{-3} day^{-3}[20]. As we measure consistent uptake of CO_2 from our wetlands, we expect allochthonous CO_2 inputs to be limited.

Although trends in the CO_2 flux and carbon storage with age and wetness can clearly be observed, not all variation can be explained by these factors. We attempted to further explain the observed CO_2 fluxes and carbon stocks with other environmental factors such as slope and the topographic wetness index. However, none of these increased the predicting value of our simple model ($R^2 < 0.4$). A surprising apparent decoupling between carbon fluxes and soil characteristics was also observed by Guelland et al. (2013)[7], who attributed this to the high heterogeneity in proglacial areas. More research on proglacial systems would allow for better correlative studies and modelling on larger, combined datasets. The data of this study have been deposited in a public repository (see Methods) to encourage such future analyses.

Overall, our data indicate that proglacial wetland areas play an important role in CO_2 uptake and carbon storage. Wetlands take up atmospheric carbon as early as 5 years after glacial retreat and can locally store more carbon than dry soils in their vicinity. Although wetlands occupy only a small proportion of the proglacial landscape, they appear to be disproportionately important for carbon sequestration. Despite this, they have been completely overlooked in previous proglacial research. The factors controlling soil carbon storage and CO_2 fluxes in proglacial environments remain poorly understood. Our limited dataset underscores the need for more comprehensive investigations in proglacial systems, which are rapidly expanding due to ongoing glacier retreat, and the need for a larger research focus on alpine wetland areas.

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4. Author contribution statement

SvG and AT designed the sampling campaign and setups, with the help of NJ and CvR. AT and NJ created the CO_2 loggers and chambers. Fieldwork was performed by CvR and RP, with the help of NJ, AT and SvG. Scripts for data analysis were created by AT, NJ and RP. Glacial extent modelling was done by AT and RP. Laboratory work was done by CvR and RP. Data analysis was done by SvG with the help of AT and RP. The manuscript was written by SvG with help from AT and revisions by NJ, CvR and RP.

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The authors declare no conflict of interests.

6. Data availability statement

All data, R scripts and field observation questionnaires generated and used for this study are openly available in the Zenodo repository [link, will be created and included upon publication].

https://doi.org/10.5194/egusphere-2025-4113
Preprint. Discussion started: 3 September 2025

Appendices

Appendix A: Material and methods

Site description and selection of sampling locations

The Bachfallenferner proglacial area is located in Tyrol, Austria and is part of the Stubai Alps mountain range. Geologically, it is part of the Ötztal-Stubai Massif and characterized by metamorphic rock (paragneiss and mica schists)[21]. The proglacial area covers an altitude from 2920 (next to the current glacier) to 2440 m. The current glacier is ca. 1.9 km long, has a ca. 1.45 km^2 surface area, and reaches to a maximum altitude of 3100 m (status 2023).

Sampling locations targeting dry soil were selected prior to the field campaign using conditioned Latin Hypercube sampling[22]. We used this method to select sampling locations spatially randomly while also ensuring that the distribution of selected ancillary variables matches their distribution of the entire proglacial area. We used slope steepness (calculated using slope in ArcGIS 10.3) and the Topographic Wetness Index as ancillary variables. Our sampling setup included both sloping and flat parts of the proglacial area, but excluded sites located directly within riverbeds or lakes, or those too steep to access safely. These assessments were made in the field.
Wetland sampling locations were selected based on Google Earth imagery of 23-09-2021. We manually searched for locations that appeared to be wetlands or small lakes. In the field, we visited each of these locations to confirm that these were indeed wetlands. If so, they were added to the sampling locations list. There were no exclusion criteria for wetlands, as we wanted to sample the entire range of different wetland characteristics. Wetlands were defined as water saturated locations with no more than 3 cm deep surface water and a surface water coverage of < 50%. If the water was deeper or occupied more surface area per m^2, we classified the locations as ponds and therefore excluded them. Most locations did not have surface water coverage (see Fig. B2).

Determination of glacial retreat year and age

The year that the glacier retreated from each location in the current proglacial area was determined by linear interpolation between the glacial extents available from the GLIMS dataset, similarly to the method described in Temme and Lange (2014)[23], complemented with the manually digitized extent in the year of measurement (2023). When the glacier readvanced, and then retreated again, we took the most recent retreat year, with entails the assumption that soil formation was completely reset by the temporary glacial scouring and transport.

https://doi.org/10.5194/egusphere-2025-4113
Preprint. Discussion started: 3 September 2025

Soil sampling, site observations, and flux measurements

All described sampling locations were visited between 6 and 10 August 2023, between 10:00 and 17:00. Soil sampling and flux measurements of a single location were done within 3m distance of each other. Site and weather observations were noted for each location following a standardized protocol. Vegetation and surface cover descriptions were based on visual assessments. Pictures were taken of each deployment location for later verification where necessary.

Flux measurements were taken using a static chamber approach, similar as described by Bastviken et al. (2015)[24], using CO_2 mini loggers (SenseAir, Sweden). The sensors were activated in the morning, left running throughout the day, and shut down and read out in the evenings. They were set to record CO_2 concentration (ppm), moisture (%) and temperature (°C) every 30 seconds. The sensors were not field calibrated, as only the linear decrease or increase was used in later analyses. The static chambers itself consisted of see-through plastic boxes with a volume of 22L (39x28x28 cm, Ikea Samla). Chambers were not covered to allow light penetration for photosynthesis and phototrophy. Pottery clay was used as a seal between the chamber and the soil, except for locations with surface water, where the chambers were placed directly on the wetland surface. Chambers were anchored down by placing rocks on top of the chambers to weigh them down. At each location, two chambers were deployed within 1-2 m distance and left for 10 - 20 minutes to measure, after which they were aired out and the measurements were repeated.

Soil sampling and horizon description were done with the use of a standardized questionnaire containing a subset of categories from the FAO guidelines for soil description (questionnaire available at Zenodo [link]). Soil samples of each soil horizon were taken with a soil knife and sampled into plastic zip bags, which were stored in the dark at ±10°C until transport to the laboratory. If present, above ground biomass and larger rocks (>3 cm) were removed from the samples before they were placed in the sample bags. Roots, if present, were not removed. Wetlands were measured, sampled and described in an identical way to non-wetland locations.

Determination CO_2 flux from concentration data

CO_2 fluxes were calculated from the CO_2 concentrations measured over the 10 – 20 minute chamber deployments. To prevent human bias in selecting datapoints for flux calculations, we created an R script that automatically determined the best fit linear regression, based on a minimum of 10 datapoints, representing 5 minutes (one measurement every 30 seconds).

Flux measurements for which the highest linear regression had an $R^2 < 0.7$, were excluded from the resulting flux table. All linear regression plots were manually checked to exclude obvious errors in the measurements. The script can be found at Zenodo [link]. Note: when neither emission nor uptake occurs, the flux value is very close to zero. However, such low flux values rarely show up in the dataset since their nearly horizontal regression lines often had $R^2 < 0.7$.

The resulting fluxes, in units of ppm CO_2 h^{-1}, were converted into μM m^{-2} hr^{-1}, using an assumed value for air pressure inside the box (calculated using the elevation and the average temperature inside the chamber over the measurement interval), the box volume and ground surface area, as well as the molar mass of carbon.

Carbon stock, pH and wetness analyses

All collected soil samples were processed within 2 weeks after collection. Field samples were weighed and then dried for 24h at 105°C, after which they were weighed again, to determine the gravimetric water content. The soil pH was measured on a mixture of 5g of the dried fine earth fraction with 45 ml demineralized water. For determination of the soil organic matter content, dried soil was weighed, ashed at 550°C for 4 hours, and then weighed again. No root picking was done.

The carbon stock per location was calculated using the reported horizon depths and the carbon content per horizon, plus assumptions on the bulk density that are specified below. The horizon depth for the C-horizon was taken as 10 cm for each location. This is an underestimation at certain locations and may be an overestimation at some others. As we do not have accurate maximum depths, we however use this 10 cm to ensure that the C horizon has an equal contribution to the carbon stock of each location. An exception are the locations were no sample from the C horizon is collected, and only the shallower horizons were considered for the calculation of the organic carbon stock. These locations are marked in Supplemental file 2 as having less than 10 cm horizon depth.

To calculate the carbon stock per m^2, we further used the approach of Poeplau et al (2017) [25] which accounts for the rock fraction as we reported for each of the field samples. The measured organic matter contents of the fine earth fraction were first multiplied with the stoichiometric fraction (0.58) to get to the organic carbon content. Then, they were multiplied with the fine earth fraction, assuming a soil bulk density of 1500 kg m^{-3} for the fine earth material. It was necessary to make an assumption for bulk density because the loose but rocky material precluded sampling using rings of known volume.

https://doi.org/10.5194/egusphere-2025-4113
Preprint. Discussion started: 3 September 2025

Appendix B: Additional figures

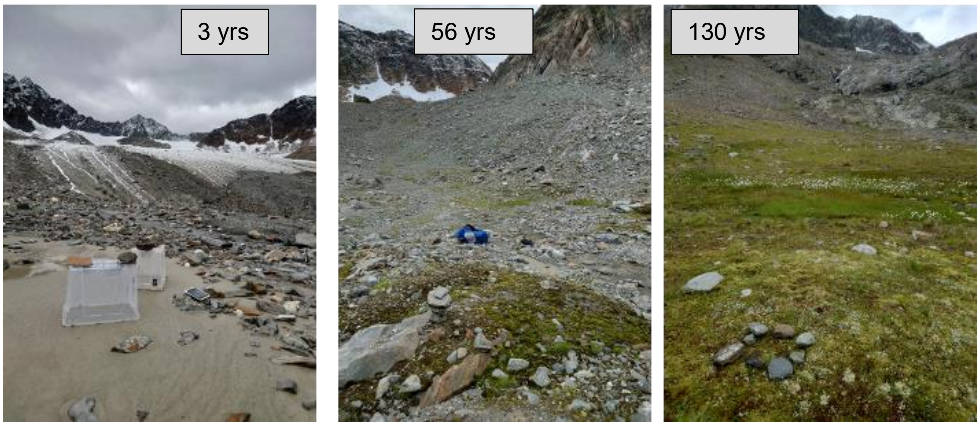

Fig. B1. Wetland locations with time since glacial retreat (age) in the Bachfallenferner proglacial area.

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Fig. B2. Surface cover (in %) as observed at each location, in the upper graph separated into the categories 'Rock, stone and fine earth', 'Plants and moss' and 'surface water'. In the lower graph, the category 'Plant and moss' is further divided into subclasses. The label on the x-axis indicates the age in years and the type of location (S: soil, W: wetland).

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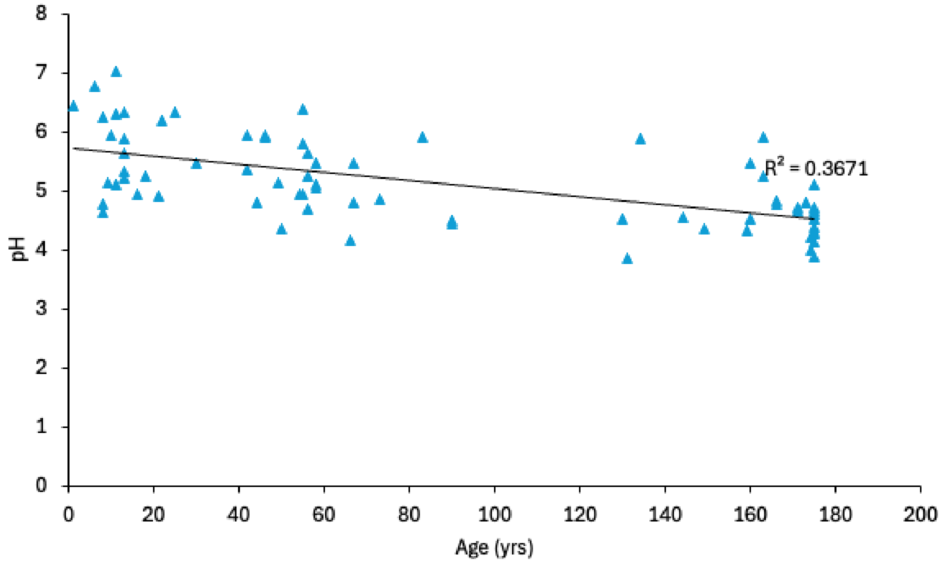
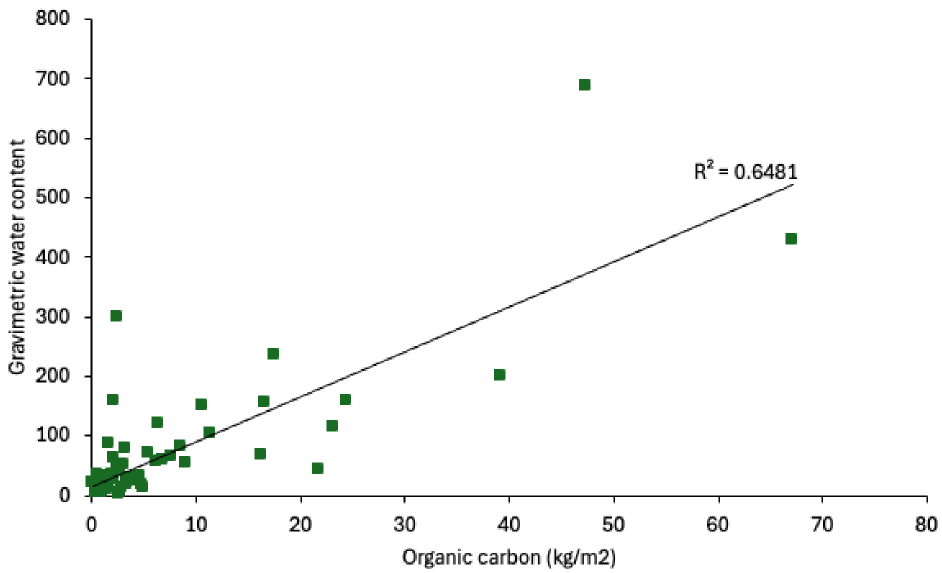


452
453 **Fig. B3**. Correlation between age and pH for the topsoil of all locations (wetland and soil) in
454 the Bachfallenferner proglacial area.
455



456
457
458 **Fig. B4**. Correlation between gravimetric water content and organic carbon stock for the
459 topsoil of all locations.
460

Supplemental file.

Table S1. Overview of CO_2 flux data of all locations. When a certain location has no statistically significant (thus linear $R^2 < 0.7$) CO_2 flux measurements, the CO_2 flux is presented as NS. When no measurement was done, the cell is filled with NA.

Table S2. Overview of soil laboratory data of all locations. The provided soil depth is the sum of all horizons that are taken into account for the organic carbon stock at that particular location. Note: the depth of the C horizon (when sampled for LOI measurement) is always taken as 10 cm, to get an equal contribution of the C horizon, also when the true depth is unknown.