Stocks, origin, and future trajectories of hidden soil organic carbon in paleosols of blockfields in the high alpine permafrost region

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Permafrost is warming because of global temperature increase, which alters the carbon cycle in these environments. While research has primarily focused on arctic permafrost, we are lacking data on the timing and magnitude of potential C accumulation and release in the alpine permafrost zone. These environments contain blockfields on mountain tops (>2900 m) with and without patterned ground, which are mainly vegetation free and therefore thought to be free of soil organic carbon (SOC). Motivated by the fact that coarse and fine material separates with freezing and thawing, we aimed to test whether alpine blockfields without vegetation are indeed SOC-free or whether they contain hidden carbon which might represent a CO_2 source upon climatic warming. By sampling vegetated soils at the same or slightly lower elevation, we wanted to test how SOC stocks in blockfields will develop under climate warming in the near future.

On four mountain tops (2900 to 3200 m a.s.l.) in the periglacial zone of the Eastern Swiss and North-Western Italian Alps, we removed up to one-meter-deep thick stone layer and excavated eleven soil profiles. While one location was completely vegetation free, the three other locations were influenced by active patterned ground with non-vegetated and sparsely vegetated patches within the same blockfield.

At each site, we found dark and fine material beneath a stone cover of a few decimetres up to a meter. Preliminary results of the vegetation free location show a hidden SOC stock of 0.8 to 1.1 $kgC \cdot m^{-2}$ and narrow CN ratios of 9.0 to 10.1. Bulk soil ^{14}C dating revealed an age of 4,000 to 12,900 years right beneath the stone cover (0-20 cm) and at greater depth (>80 cm) respectively. In agreement with our finding, Pintaldi et al. (2021) observed "hidden" SOC stock beneath active patterned ground on a mountain top plateau in North-West Italy. There are two possible origins of the hidden carbon: 1) soot deposition by natural and anthropogenic processes throughout the Holocene and 2) carbon accumulation during warmer climatic conditions during the early to middle Holocene.

A first estimate of the soot deposition in high alpine environments indicates that soot input cannot explain the observed SOC stocks. OC concentrations from an ice core drilled at Fischerhorn glacier (Jenk et al. 2006) allows to calculate the input by soot deposition. Mean OC concentrations for the ice core were 33 $\mu gC \cdot kg^{-1}$ ice which would yield a soot deposition of about 70 $gC \cdot m^{-2}$ over 5000 years. Even when assuming the highest OC concentration of 80 $\mu gC \cdot kg^{-1}$ originating from wood combustion during mid-19th century, the soot input would range only around 165 $gC \cdot m^{-2}$ over 5000 years. Both estimates are far too little to explain the observed stocks of hidden SOC around 1 $kgC \cdot m^{-2}$.

We therefore presume that the hidden SOC primarily originates from SOC accumulation in a warmer climate during the early to middle Holocene. During the Holocene Thermal Maximum (5,000 to 11,000 years BP) temperatures were 0.5 to 3.1 °C higher compared to today's conditions in the Alps (Badino et al. 2018; Heiri et al. 2003) which was associated with an upward shift of the treeline and a retreat of glaciers. Reconstructions of the treeline in the Western Italian (Badino et al. 2018), Central (Tinner and Theurillat 2003) and Central Eastern Alps (Nicolussi et al. 2005) show a 100 to 300 m higher tree line ecotone compared to the current situation. During this time, most high elevation peaks were also ice-free (Bohleber et al. 2020). Around 4,000 years, reconstructions indicate a drop in temperature by about 1.8 °C (Badino et al. 2018), a lowering of the treeline below present-day elevation (Badino et al. 2018; Nicolussi et al. 2005) and an elevation dependent development of the current neoglaciation (Bohleber et al. 2020). This strongly suggests that our sampled sites at 2900–3200 m a.s.l. carried a vegetation cover leading to soil development and carbon accumulation during the Holocene Thermal Maximum. Thereafter, soils became possibly covered by blocks due to reverse vertical sorting during the colder period from 4,000 years to present day. We will characterize the chemical composition of the hidden SOC to gain further insight into its origin.

To test the release of CO_2 from hidden paleosols, we measured CO_2 fluxes in the field using a CO_2

chamber installed onto the fine earth after stone removal. Results showed an average release rate of 2.6 ± 3.7 mg·CO_2-C·m^{-2}·h^{-1} from the four sites during the summer season. Rates were about a magnitude higher from the adjacent sparsely vegetated soils (27.7 ± 20.5 mg·CO_2-C·m^{-2}·h^{-1}). In conjunction with higher SOC stocks and younger ^{14}C ages (around 1,500 years) at slightly lower elevations measured at one of the sites, this indicates that upward plant migration has a strong impact on SOC cycling and leads (again) to carbon sequestration in the soil.

In summary, we show that high alpine blockfields in the permafrost region store a small amount of old carbon, which is now hidden below thick stone layers, and which most likely originates from past vegetation in these environments during warmer climates in the Holocene. In-situ soil CO_2 flux measurements give evidence that these paleosols are currently releasing small amounts of (possibly old) CO_2 to the atmosphere. Colonization with upward migrating plants will, however, lead to C sequestration in the soil. Further studies are needed to explore how widespread these paleosols are and to assess the magnitude of C losses and gains in high alpine terrain. The comparison of vegetated and non-vegetated plots presents the possibility of modelling the timing of carbon loss and uptake in these environments.

References

Badino, F., Ravazzi, C., Valle, F., Pini, R., Aceti, A., Brunetti, M., Champvillair, E., Maggi, V., Masero, F., Perego, R., and Orombelli, G. 2018. 8800 years of high-altitude vegetation and climate history at the Rutor Glacier forefield, Italian Alps. Evidence of middle Holocene timberlinerise and glacier contraction. Quaternary Science Reviews, 185: 41–68. doi.org/10.1016/j.quascirev.2018.01.022

Bohleber, P., Schwikowski, M., Stocker-Waldhuber, M., Fang, L., and Fischer, A. 2020. New glacier evidence for ice-free summits during the life of the Tyrolean Iceman. Nature Scientific Reports, 10: 20513. doi.org/10.1038/s41598-020-77518-9

Heiri, O., Lotter, A.F., Hausmann, S., and Kienast, F. 2003. A chironomid-based Holocene summer air temperature reconstruction from the Swiss Alps. Holocene, 13(4): 447–484. doi.org/10.1191/0959683603hl640ft

Jenk, T.M., Szidat, S., Schwikowski, M., Gäggeler, H.W., Brütsch, S., Brütsch, B., Wacker, L., Synal, H.-A., and Saurer, M. 2006. Radiocarbon analysis in an Alpine ice core: record of anthropogenicand biogenic contributions to carbonaceous aerosols in the past (1650–1940). Atmospheric Chemistry and Physics, 6: 5381–5390. doi.org/10.5194/acp-6-5381-2006

Nicolussi, K., Kaufmann, M., Patzelt, G., van der Plicht, J., and Thurner, A. 2005. Holocene tree-line veriability in the Kauner Valley, Central Eastern Alps, indicated by dendrochronological analysis of living trees and subfossil logs. Vegetation History and Archaeobotany, 14(3): 221–234. doi.org/10.1007/s00334-005-0013-y

Pintaldi, E., D`Amico, M., Colombo, N., Colombero, C., Sambuelli, L., De Regibus, C., Franco, D., Perotti, L., Paro, L., and Freppaz, M. 2021. Hidden soils and their carbon stocks at high-elevation in the European Alps (North-West Italy). Catena, 198: 105044. doi.org/10.1016/j.catena.2020.105044

Tinner, W., and Kaltenrieder, P. 2005. Rapid responses of high-mountain vegetation to early Holocene environmental changes in the Swiss Alps. Journal of Ecology, 93(5): 936–947. doi:10.1111/j.1365-2745.2005.01023.x