Author responses to comments for Maier et al. Biogeosciences preprint manuscript

Reviewer 3, Frank Hagedorn:

Overview Ref 3: The manuscript by Maier et al. represents a comprehensive assessment on SOC storage in alpine grassland soils, clearly demonstrating that parent material geochemistry plays a dominant role in controlling SOC stocks; an aspect often overlooked in the current literature.

Our response: We appreciate Frank Hagendorn's support for our manuscript and his constructive feedback on an important topic that helped improve the discussion. We have provided a detailed point-by-point response below and highlight, text that we will add to the revised manuscript version in red.

Ref3C1: Although alpine soils are known to be particularly stony, it remains unreported if and how coarse stone fragments have been incorporated in the estimates of SOC stocks. The authors state that soil sampling was conducted using Kopecky cylinders (100 cm^3) within soil profiles and Edelman augers to bedrock depth. Although this method permits estimation of bulk or fine earth density within the cylinder volume, it does not capture larger stone fragments present throughout the profile. In stony soils, typical for alpine environments, omitting these coarse fragments can lead to substantial overestimation of SOC stocks (Poeplau et al., 2017). Given the frequent absence of direct measurements of coarse fragments, many studies apply corrections to SOC stock estimates based on field-derived stone content data. It is therefore recommended that the authors clarify whether such corrections were applied, and if not, to discuss the implications for their SOC stock estimates.

Our response: Thank you very much for your valuable comments. We did account for the coarse fragments in the estimates of SOC stocks, by using the suggested SOC stock calculation from Poeplau et al. (2017). However we acknowledge that our description of the SOC stock calculations should be more clear. We would therefore like to adapt our methodology description in section 2.3.7. In our manuscript the stocks were corrected for the stone content as follows: We subtracted the coarse fragment fraction from the soil mass, yet used the 'full' soil volume, to compute the SOC stocks. Our estimates therefore take the coarse fraction mass and volume into account as to attempt to not overestimate SOC stocks (lines 217-220 and equation (2)). We will however discuss the SOC stock estimates. For further transparency, we will provide the average ± SE of coarse fragment content per horizon and site in Table 4 of the revised manuscript. Upon double checking we also realized that the equations we are quoting from Poeplau et al. (2017), were in fact not their eq. 3 but their equations 7 and 8, thus we will correct this in the revised version. We will define the terms used in equation (2) and adapt the description of eq. 2 and 3. as follows from line 218 onwards to, clarify how we accounted for the coarse fragments:

'To account for coarse fraction contained in our soil samples in our SOC stock estimations, respective SOC horizon stocks (SOC_{stockj}) were calculated in two steps following Eq. 7 and 8 proposed by Poeplau et al. (2017). In a first step, what they call the fine soil stock for a respective horizon (j) is estimated (FSS_j), (Eq. 2), where the $mass_{finesoil}$ is the mass of the total sample without the mass of the coarse fraction, $volume_{sample}$ is the total volume of the sample including the coarse fragments and $depth_j$ is the thickness of a respective horizon. In a second step SOC stocks are calculated for a respective horizon (SOC_{stockj}) (Eq. 3), where the $SOC_{concfinesoil}$ is the OC concentration of the fine soil multiplied with the previously calculated fine soil stock FSS_j (i.e. the total sample without the mass of the coarse fraction). Whole profile SOC stocks were calculated by summing all horizon specific SOC stocks per sampling site.

Ref3C2: Additionally, reporting the slope of each soil profile is important for enabling surface-area-based corrections of SOC stocks (Prietzel & Wiesmeier, 2019).

Our response: Thank you for this comment. We will add the slopes of each soil profile to Table 1.

Ref3C3: Accurate sampling methods and SOC stock estimations are essential for enabling meaningful comparisons across ecosystems and for supporting upscaling efforts. A critical discussion of the uncertainties associated with SOC stock estimates would be valuable, even though these uncertainties do not undermine the manuscript's central finding that parent material geochemistry is a key control on SOC storage.

Our response: Thank you for this comment. We will provide an additional segment in the discussion on the uncertainties associated with SOC stock estimates based on the coarse rock fraction, the potential influence of geogenic organic carbon (see response to reviewer 2's comment on Line 342, **Ref2C42**) and the general difficulty to identify representative and relatively undisturbed plots in high alpine environments.

We first of all suggest to remove the text currently placed at lines 306–309, from the sentence beginning with "These findings are linked to the SOC stock calculation methodology, […]". We would however like to add the sentiment of these lines into our discussion, before line 405 in the following way:

In our study, as a result of our calculation methodology (horizon specific sampling and analyses instead of fixed depth increments), the magnitude of a horizon-specific and whole profile SOC stocks depend on the thickness of individual soil horizons and their respective OC contents (see Sect. 2.3.7). Thus, thick horizons (such as Bw) can harbor more C as part of the profile stock even if C concentrations are lower than in thinner (topsoil O or A) horizons (Fig. 2, Sect. 2.1). If SOC stocks were normalized to the same depth increment thickness, the trends reported here would potentially change. Furthermore, SOC stock estimates can vary significantly depending on the calculation method applied. For example, Poeplau et al. (2017) show that

discrepancies in estimated SOC stocks between methods increase with increasing rock fragment content. In soils with rock fragments comprising > 30 vol %, they revealed that SOC stocks may be overestimated by as much as 100%. Since our sampling took place in steep terrain with strongly varying rock fragment contributions of 1.6 ± 0.9 in the Dolomite's Oh, up to 52.5 ± 2.6 for Greenschist's Cw horizon (see Table 4.), we calculated SOC stocks by taking these varying contributions into account by applying the calculation methodology as suggested by Poeplau et al. (2017) (Sect. 2.3.7), as to not overestimate SOC stocks. In addition to uncertainties related to the SOC stock calculation methodology, spatial heterogeneity of SOC further introduces uncertainty. Due to the formation of microenvironments, soil-forming processes can vary at very small scales (Körner, 2003; Kemppinen et al., 2024). We aimed to minimize this effect by collecting composite samples which consisted of 10 individual samples per horizon and plot (Method section 2.2). Even with these measures–adjusted SOC stock calculation method and composite sampling–inherent uncertainties associated with spatial heterogeneity of SOC will remain part of studies that estimate SOC stocks at a regional scale.

Newly added references:

Kempinnen, J., Lembrechts, J.J., Van Meerbeek, K., Carnicer J., et al.: Microclimate, an important part of ecology and biogeography, Glob. Ecol. Biogeogr., 33(6), 313834, 10.1111/geb.13834, 2024.