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

Referee 1:

Overview Ref 1: Maier et al studied the distribution and mechanisms controlling SOC distribution along a geochemical gradient of soil parent materials. The manuscript is overall well-written and the analyses are appropriated. The study compared plant inputs, soil characteristics and parent material in explaining the SOC stocks along the geochemical gradient and pointed out that “Parent material geochemistry – and not plant input - as the primary element shaping soil organic carbon stocks in European alpine grasslands”. Please find below my major and minor concerns.

Our response: We appreciate the positive assessment and support from Reviewer #1 and their clear summary of the most important points in our manuscript. We also thank the reviewer for their comments that have helped us greatly improve the manuscript. We have provided a detailed point-by-point response below and highlight, text that we will add to the revised manuscript version in red.

Ref1C1: From the experimental results to European alpine grasslands. Because the experimental setting is along the geochemical gradients of soil parent materials, so the sites are selected to represent the difference in parent material. Comparisons among selected sites showed that parent material is important. Is it fair to conclude that parent material is more important than input for (entire) European alpine grasslands? Would the conclusion be different if you select the experiment sites across a plant input gradient?

Our response: Thank you very much for your valuable comments. Following up on the first part of the reviewer’s comment, we do not yet have a definite answer to the generalizability of our results to the entirety of European alpine grasslands. However we will provide an answer to this question by performing a GIS-driven exercise for the revised version of the manuscript, identifying which grassland regions of the Alps fall within our geologic and climatic boundary conditions. This will entail the production of maps and the extraction and calculation of numerical values from the extent of the European Alps that show 1) the above treeline alpine grassland/meadow area underlaid by the major rock groups to which our soil parent materials belong to, 2) the area covered by the approximate ranges of our MAT and MAP ranges of our sampling sites i.e. approximately 2 ± 1 °C and 1210 ± 100 mm, respectively. The main information and insights gained from these analyses will be added into our discussion and conclusion sections in order to discuss how representative our results are regarding the entirety of European alpine grasslands extent. We will add the resulting coverage data into our supplement and potentially also add the resulting maps.

Furthermore, we will add the following text to our methods section in the revised manuscript describing how we will undertake these calculations and spatial evaluations under subsection 2.3.8. that we will name ‘Calculation and mapping of geologic and climatic boundary conditions’.:

To understand the generalizability of the results from this study to all European alpine grasslands, we analyzed the extent to which our geologic and climatic boundary conditions apply within QGis (3.40.5-Bratislava). This entailed the production of maps and the extraction and calculation of numerical values that show 1) the above treeline alpine grassland/meadow area underlaid by the major rock groups our study’s soil parent materials belong to, 2) the area covered by the MAT and MAP ranges of our sampling sites, i.e. 2 ± 1 °C and 1210 ± 100 mm.

Alpine grassland/meadow data was extracted from Marsoner et al. (2023)’s detailed land use/landcover map for the areas included in the European Strategy for the Alpine Region, with a spatial resolution of up to 5 m and a temporal extent from 2015 to 2020. It was created by aggregating 15 high-resolution layers resulting in 65 land use/cover classes. The overall map accuracy was assessed at 88.8%. Herein, Alpine natural grassland was defined as being > 2000 m elevation. For the calculation of elevation, the European Digital Elevation Model (EU-DEM), version 1.1 was used (European Union, 2016). European geology coverage was taken from the European Geological Data Infrastructure (EGDI) 1:1’000’000 (OneGeology-Europe / EGDI, n.d.). Swiss geology coverage was extracted from BAFU 1:500’000 (Federal Office of Topography swisstopo, 2025). MAP data (30 arc sec, ~1km, based and a temporal extent from 1970-2000) was derived from WordClim Version 2.1 (Fick & Hijmans, 2017) and MAT data (30 arc sec, ~1km, and a temporal extent from 1981-2010) from Climatologies at high resolution for the earth’s land surface areas (CHELSA) (Karger et al., 2017; Karger et al., 2018).

The previous section 2.3.8. ‘Statistical analyses’ will become the new subsection 2.3.9., with the same title.

In response to the second part of the comment, we would like to highlight that our analysis compared a range of soils developed on different parent materials, that also varied in maximum potential plant input (standing above- and belowground biomass stocks). The chosen locations are all located between 2000–2300 m.s.l., similar topographic position (slope and exposition, which will be added to Table 1) and cover a mean annual temperature range of 1.4–2.8 °C and a mean annual precipitation range of 1050–1300 mm. Our sampling sites cover alpine grasslands located on five geochemically distinct geologies of the European alps, according to geological maps (Federal Office of Topography swisstopo, 2020; Federal Institute of Geosciences and Natural Resources, 2020). The conclusion made in the paper, based on the selection of our five sites, that also varied in plant input, therefore remains the same, that parent material geochemistry was more important than plant biomass stocks in relation to SOC stocks.

Newly added references:

Marsoner, T., Simion, H., Giombini, V., Egarter, V.L., Candiago, S.: A detailed land use/land cover map for the European Alps macro region, Sci. Data, 10(1), 468, 10.1038/s41597-023-02344-3, 2023.

European Union, Copernicus Land Monitoring Service. European Digital Elevation Model (EU-DEM), Version 1.1. https://land.copernicus.eu/pan-european/satellite-derived-products/eu-dem/eu-dem-v1., 2016.

OneGeology-Europe / EGDI. (n.d.). Surface lithology of Europe (harmonized pan-European geology) [Web Map Service]. European Geological Data Infrastructure (EGDI). Retrieved August 5, 2025, from https://maps.europe-geology.eu/

Federal Office of Topography swisstopo: Lithological map of Switzerland 1:500000, https://map.geo.admin.ch, 2025.

Fick, S.E., Hijmans, R.J.: WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology, 37(12), 4302–4315. https://doi.org/10.1002/joc.5086, 2017.

Karger, D.N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R.W., Zimmermann, N.E., Linder, P., Kessler, M.: Climatologies at high resolution for the Earth land surface areas. Scientific Data. 4 170122. https://doi.org/10.1038/sdata.2017.122, 2017.

Karger D.N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R.W., Zimmermann, N.E, Linder, H.P., Kessler, M.: Data from: Climatologies at high resolution for the earth's land surface areas. EnviDat. https://doi.org/10.16904/envidat.228.v2.1, 2018.

Ref1C2: Soil fertility vs. soil mineralogy model. The authors build random forest models with 42 samples and multiple explainable variables. Do these models face overfitting issues? What insights can we gain from these analyses, especially differentiating soil fertility vs. mineralogy? I feel the rationale is not very well justified. Why not have plant input as an explainable variable, and why not plant input, fertility and mineralogy together explain SOC variations?

Our response: Thank you for this critical feedback. The main incentive of our decision to design two separate prediction models for SOC with distinct sets of variables is to investigate whether SOC is more related to stabilization mechanisms (mineralogical variables) or to fertility parameters that may govern C input (fertility variables). Clay can be seen as both a proxy variable for C stabilization potential (Georgiou et al. 2022) and also as a proxy for the retention of water and nutrients in the soil, thus contributing to overall soil fertility (Kleber et al., 2015; Yu et al. 2022). Since clay content is a proxy for both and multifunctional in that sense, we decided to leave it in both models. If both predictor variable sets were merged into one prediction model, this would most certainly result in overfitting, due to the very low degrees of freedom of the model (not enough observations). Although we already allude to clay as a proxy for the retention of nutrients (lines 240–242) in the methods of our manuscript, we do not explicitly address the reasoning behind the inclusion of clay in both of our models. We will therefore add the following statement after line 246:

"Clay is included in both models to act as a proxy for nutrient retention and water holding capacity of the soil (Yu et al. 2022), in the case of the soil fertility model, and as a proxy for SOC stabilization potential in the soil mineralogy model, as has been commonly done in SOC prediction models (Abramoff et al. 2021, Georgiou et al. 2022)."

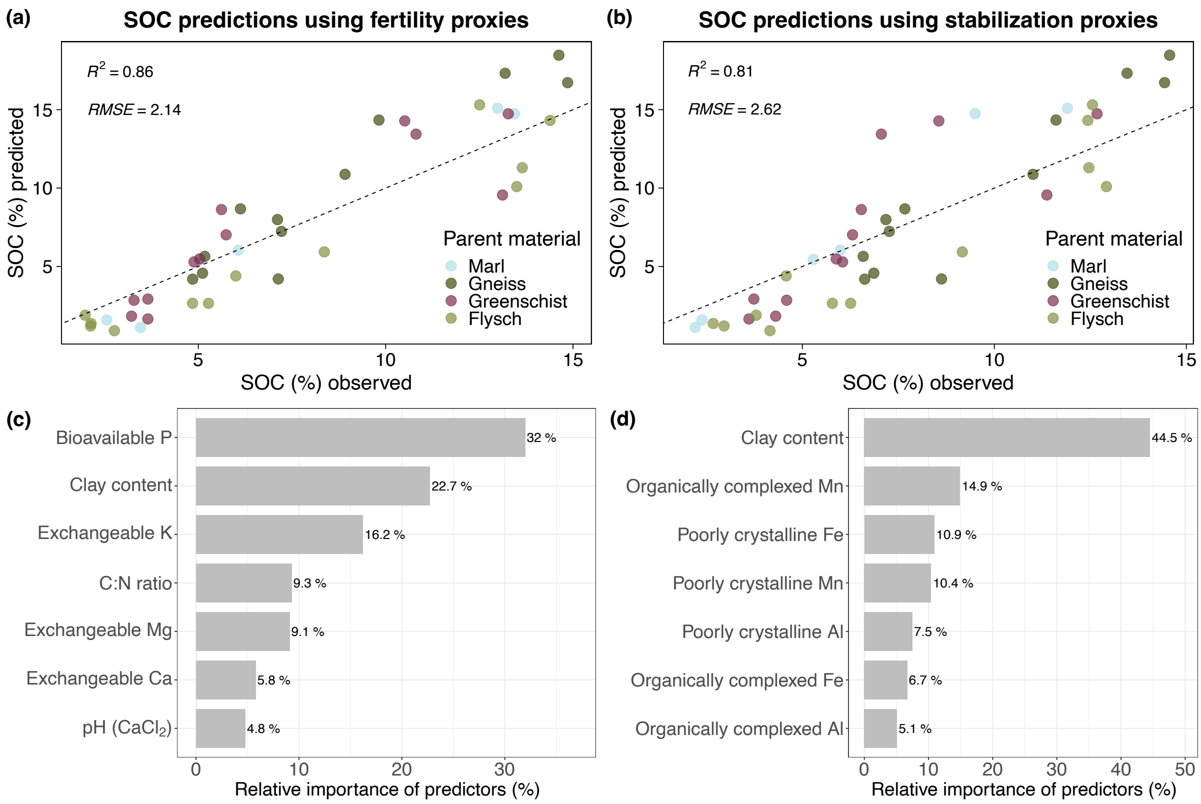
Plant input in our study is not measured directly - we use total plant biomass and above-/belowground plant C stocks as proxy for potential biomass inputs. Furthermore, as is shown in Fig. 3 of the manuscript, the plant biomass C stocks do not consistently coincide with SOC stocks. We were mainly interested in soil-driven variables as predictors for SOC rather than trying to produce the best possible model for SOC (%) prediction.

We would nevertheless like to mention this in the manuscript explicitly in the methods section 2.3.7 'Calculation of plant biomass and soil organic carbon stocks' after line 212:

'Plant biomass OC stocks will be interpreted as a proxy for potential plant biomass C input, as plant input rates were not measured directly within this study'.

In regards to the overfitting question, we re-ran our random forest models to account for spatial autocollinearity by using an adapted leave-one-plot-out cross validation (CV). The leave-one-plot-out CV measure is used to reduce overfitting in regression statistics with limited field observations (Yates et al. 2022). We present the results of these revised models as a revised version of Figure 5., which we will add to the revised manuscript. This revised Figure has the same structure as the current Fig 5. in the manuscript and shows the predicted bulk SOC (%) vs. measured/observed bulk SOC (%). Accordingly, we will change the individual reported numerical values such as the R^2, *RMSE* and the relative importance values of bio-P and clay denoted in the results section 3.4. so that they align with the newly calculated values. Due to the similar results from these revised models, we would leave the discussion section 4.4. as is. We will add the change lines 253–254 of our current methods section 2.3.8. to following to describe the adapted cross validation:

We used an adapted leave-one-out cross validation (i.e., leave-one-plot-out CV) to account for spatial autocollinearity within plots and thus to reduce overfitting (Yates et al. 2022). Iterating through all plots, only one plot and its observations were taken as test data, while the rest of the dataset was used as a training set, until all plots were used once as test data, on which we tested the prediction accuracy of our model.



Revised Figure 5. (a) Predicted bulk SOC (%) values vs. measured/observed bulk SOC (%) values of the soil fertility model. **(b)** Predicted bulk SOC (%) values vs. measured/observed bulk SOC (%) values of the soil mineralogy model. **(c)** Relative importance (%) of the model predictor variables included in the soil mineralogy model. **(d)** Relative importance (%) of the model predictor variables included in the soil fertility model. The dashed line represents a 1:1 regression line.

In comparison to the model structure of that presented in the current Fig 5. in the manuscript, the *RMSE* of both the soil fertility and mineralogy model increased slightly (from 2.02 to 2.14 and from 2.53 to 2.62 respectively) and the R^2 of both models decreased slightly (from 0.91 to 0.86 and from 0.84 to 0.81 for the soil fertility and soil mineralogy model respectively). The most important predictor variables remain the same as those run with the repeated 10-fold cross validation method for both models. However, their relative importance to the models increases from a previous 20.1% to 32% for bio-P for the soil fertility model and from 24.2% to 44.5% for clay in the soil mineralogy model. The sequence of the other individual predictor variables' relative importance remains very similar for the soil mineralogy model, with only Fe_{PP} becoming seemingly more important than Al_{PP}. The sequence of the other individual predictor variables' relative importance varies more for the soil fertility model, yet the magnitude of importance of the individual predictors remains very similar.

Newly added references:

Abramoff, R.Z., Georgiou, K., Guenet, B.: et al.: How Much Carbon Can Be Added to Soil by Sorption?, Biogeochemistry, 152(2), 127–42, https://doi.org/10.1007/s10533-021-00759-x, 2021.

Georgiou, K., Jackson, R.B., Vindušková, O., et al.: Global Stocks and Capacity of Mineral-Associated Soil Organic Carbon, Nature Communications, 13(1), 1, https://doi.org/10.1038/s41467-022-31540-9, 2022.

Yates, L.A., Aandahl, Z., Richards, S.A., Brook., B.W.: "Cross Validation for Model Selection: A Review with Examples from Ecology", Ecological Monographs, 93(1), e1557, https://doi.org/10.1002/ecm.1557, 2023.

Yu, M., Tariq, S.M., Yang, H.: Engineering clay minerals to manage the functions of soils, Clay Minerals, 57, 51–69, https://doi.org/10.1180/clm.2022.19, 2022.

Ref1C3: Soil aggregates. The study found that microaggregate contributes to a large (>50%) portion of bulk SOC, and inferred those sites with metal oxides favored the formation of microaggregate. Are there approaches to provide more direct evidence from this experiment?

Our Response: Thank you for raising this question. We will provide a new figure (see Figure S2 below) to the supplement, that shows the relationship between **(a)** Total Fe concentrations in the bulk soil (g kg^{-1}) vs. the the microaggregates (MA) weight % (wt%) to the bulk soil, **(b)** the sum of iron concentrations from both the pyrophosphate-extractable Fe (Fe_{PP}) and ammonium-oxalate extractable Fe (Fe_{AO}) (i.e. the sum of the reactive metal oxides) vs. the the microaggregates (MA) weight % (wt%) to the bulk soil, **(c)** the sum of iron concentrations from the pyrophosphate-extractable Fe (Fe_{PP}), ammonium oxalate-extractable Fe (Fe_{AO}), and dithionite-citrate-bicarbonate-extractable Fe (Fe_{DCB}) (i.e. all extractable metal oxides- reactive + more crystalline oxy(hydr-)oxides) the microaggregates (MA) weight % (wt%) to the bulk soil.

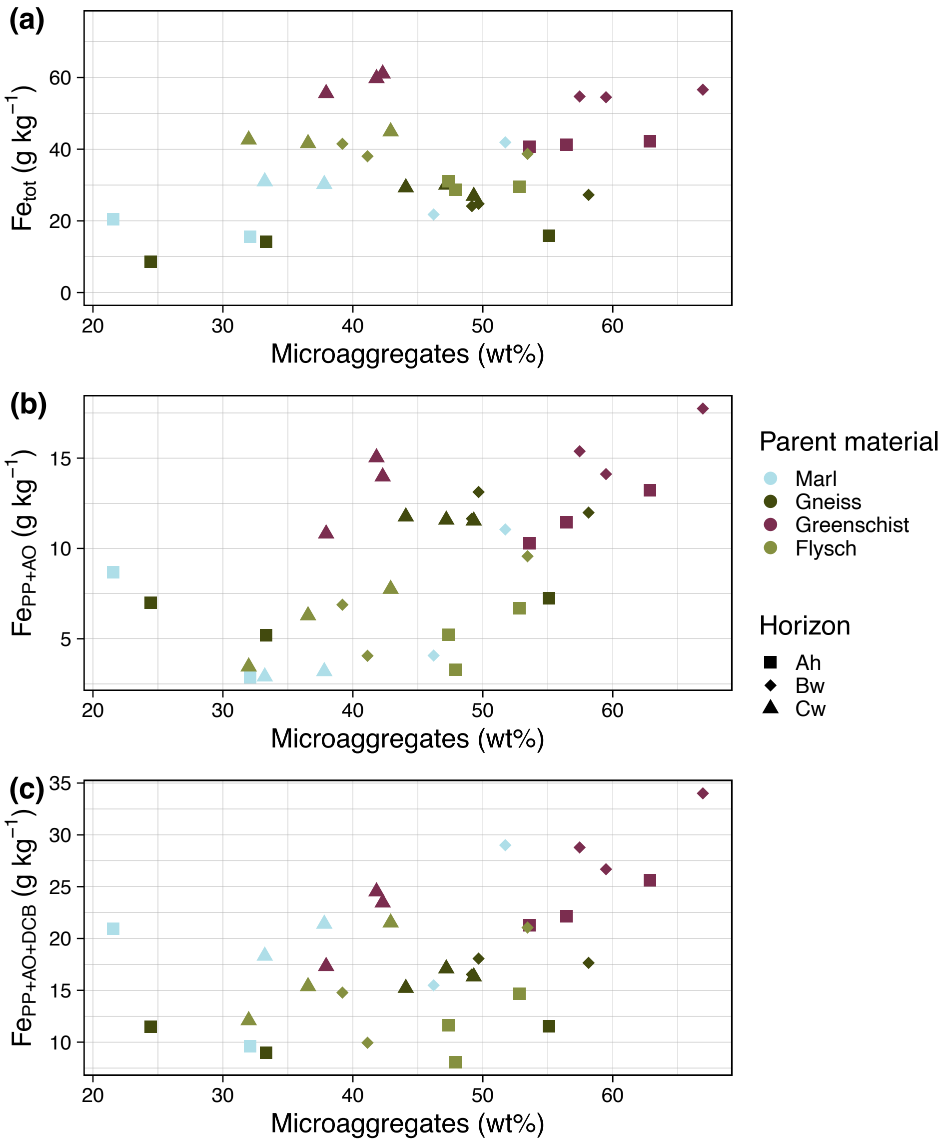


Figure S2. (a) Total Fe concentrations (g kg^{-1}) vs. MA (wt%), **(b)** sum of Fe concentrations from both Fe_{PP} and Fe_{AO} vs. MA (wt%), **(c)** sum of Fe concentrations Fe_{PP}, Fe_{AO}, and Fe_{DCB} vs. MA (wt%) . Observations from the Dolomite site were excluded from this figure as its Oh horizon is organic and showed signs of POM contamination in the MA fraction. Note that the individual panels show different y-axis ranges but share the same x-axis range.

In Figure S2, the role of Fe is shown to be connected to the mass of microaggregates (MA) in the soils. This trend can be seen for different iron phases including the total Fe concentrations within the bulk soil ((a)) as well as the reactive (Fe_{PP+AO}) ((b)) and total Fe pedogenic oxide concentrations ($Fe_{PP+AO+DCB}$) ((c)). While the correlation between Fe_{tot} and MA mass is not significant (Spearman correlation coefficient of 0.16 with $p > 0.1$), those between Fe_{PP+AO} and MA mass and $Fe_{PP+AO+DCB}$ and MA mass are positive and significant (Spearman correlation coefficients of 0.53 and 0.48 respectively, with $p < 0.05$). We acknowledge that we cannot derive causation based on correlations, however, the relationship of Fe oxides with microaggregates (Fig. S2) aligns with literature, which explored the importance of reactive metals for aggregation processes (Lehndorff et al., 2021, Campo et al., 2024, Totsche et al. 2018). On the other hand, total and pedogenic oxide Al concentrations do not correlate as well with the MA mass. Further, the concentrations of total extractable pedogenic oxides of Fe compared to Al are on average 2.5 ± 1.1 (SD) times larger. We interpret this as a consequence of the pH range in most of the sampled soils not being low enough to lead to heightened Al mobility. Mn concentrations may have contributed to aggregation processes as well, however its concentrations are much lower than those of Fe (between 12-150 times smaller) and Al (between 11-99 times smaller) and hence its contributions are negligible (data not shown). Based on these findings we assume that Fe may play a more important role for aggregation processes in our examined soils. We would like to add a small statement to the discussion summarizing the correlations from the supplementary Fig. S2 together with a more in depth discussion of literature findings that support our interpretation of a significant role of microaggregates for C stabilization. We also want to discuss the connection of these fractions to pedogenic oxide concentrations. We suggest to slightly change the phrasing discussion of the lines 442–446 and augment the discussion at this location of the manuscript with the discussion of additional literature as follows:

'Wasner et al. (2024) examined a geoclimatic gradient across a diverse range of grassland topsoils and found that the stable microaggregate fraction was the biggest contributor to bulk SOC in C-rich soils. They report that both the SOC quantity in free silt and clay (s+c) and stable microaggregates (MA) fractions were positively correlated to pedogenic oxide contents and texture. The results from this publication support the notion that stable microaggregates can be major contributors to bulk SOC in grassland soils across large environmental gradients. Another publication by Lehndorff et al., (2021) examined the spatial organization of soil microaggregates in a sandy and a loamy Luvisol. They report greater OC concentrations within the microaggregate fractions compared to bulk SOC, and their analyses support the notion that OC forms the core for microaggregate formation and is protected within microaggregate structures. They also found a systemic increase in iron, followed by clay and silicate mineral phases in the microaggregates formed on clay-richer soil, indicating that the inherent soil mineralogy is reflected in the composition of microaggregates. Their data further supports the notion that pedogenic iron aids aggregation processes in the soil by acting as a cementing agent (Campo et al., 2024). The importance and prevalence of iron in microaggregates is therefore shown to be a supporting phase for overall microaggregate stability, and thus ultimately supports the retention of SOC therein. This high relevance of Fe in particular for aggregation processes is also reflected in significant correlations of reactive Fe pedogenic oxides (Fe_{PP+AO}) and total Fe pedogenic oxides ($Fe_{PP+AO+DCB}$) with the MA mass (wt%) for our sites (Spearman correlation coefficients of 0.53 and 0.48 respectively, with $p < 0.05$, Fig. S2). While no significant correlations could be found for reactive or total Al or Mn pedogenic oxides (data not shown). Due to an overall significantly lower amount of total Mn and extractable Mn pedogenic oxide concentrations, we assume the contribution thereof to be rather little to aggregation processes (data not shown). We interpret the insignificant connection of Al pedogenic oxides to MA mass to be related to the pH range of most of our sites, which is above values where Al becomes significantly mobilized and ranges generally between 4.2–6.8, except for the Granite site (3.8 ± 0.2 (SD)).

We would also like to slightly adapt and augment the summary paragraph beginning from line 446 onward:

'[...] a large contribution of MA was found to contribute to bulk SOC, that appear to be supported by the presence of reactive, pedogenic Fe phases. These findings underline the importance of aggregation processes for SOC stabilization in alpine soils developed on different parent materials.'

Lastly, with the addition of these additional correlation analyses we would like to add a brief description thereof in the methods section 2.3.8. from line 232 onwards: 'Spearman correlations were used to examine relationships between select soil biogeochemical variables, as this non-parametric method is appropriate for data that are non-normally distributed.'

Newly added references:

Campo, J., gimeno-Garcia, E., Andreu, V., Gonzalez-elayo, O., Rubio, J.L.: Cementing agents involved in the macro- and microaggregation of a Mediterranean shrubland soil under laboratory heating, Catena, 113, 165-176, https://doi.org/10.1016/j.catena.2013.10.002, 2014.

Lehndorff, E., Rodionov, A., Plümer, L., Rottmann, P., Spiering, B., Dultz, S., Amelung, W.: spatial organization of soil microaggregates, Geoderma 386, 114915, https://doi.org/10.1016/j.geoderma.2020.114915, 2021.

Totsche, K. U., Amelung, W., Gerzabek, M.H., et al.: Microaggregates in Soils, J. Plant Nutr. Soil Sci., 33, 104-136, https://doi.org/10.1002/jpln.201600451, 2018.

Ref1C4: Please double check on figures. There seem swaps. For example, Figure 3a, Gneiss, the crosshatch and solid part seem did not follow the texts. The crosshatch is much big, but in the text, it states that the wood (solid) is bigger. Figure 5 c, should it be the soil fertility model, but in the captions, it states "soil mineralogy model". This swap also affects Figure 5d

Our Response: Thank you for this comment. We will rewrite the Fig. 3 caption to more clearly delineate that the crosshatch pattern represents the woody biomass contribution and that the solid part only represents the herbaceous/non-woody biomass contribution. In the text we already explicitly mention the 80% contribution of woody biomass to total whole profile biomass for the Gneiss site, but we will add a small sentence saying that for all other sites the woody biomass contribution to aboveground biomass C stocks is either zero or < 20 %. We thank you for pointing out the swaps in Figure 5 and will adjust them accordingly.

We will adjust Figure 3 (a) caption as follows: ‘The relative amount of woody aboveground plant biomass is represented by the black crosshatch pattern within the bars, and the solid part of the bars represents the relative amount of herbaceous/non woody biomass [...]’

We will add the following information to line 294: ‘Of which an approximate 80 % consists of woody plant material. For all other sites the woody biomass presence is either zero or < 20 %.