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Interactive comment on "Strong warming of subarctic forest soil deteriorated soil structure via carbon loss – Indications from organic matter fractionation" *by* Christopher Poeplau et al.

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The manuscript by Poeplau et al., investigates the effects of long-term soil warming on SOC fractions. Their carbon content as well as their relative distribution in response to warming are being discussed for two different soil depths and ecosystems. As I myself am working on warming effects on soil microbial communities in connection to biogeochemical cycles, I was very pleased to read about warming effects on the abiotic components of soil. Especially long-term in-situ warming experiments are rare and extremely valuable to study the mechanisms and concepts behind various warming effects. I completely agree with the authors that strong systematic gradients in SOC

content (in the same soil) can provide an important framework to improve our understanding of SOC dynamics. I believe that this study adds some very valuable aspects the research field of soil warming. This paper and some there presented ideas could also provide the basis for hypotheses that could be targeted in other future mechanistic studies. The manuscript is well written and structured. Most parts of it are easy to follow, however I hereby want to suggest some minor and detailed revisions in order to improve the manuscript in terms of its readability and understandability.

Answer: We thank the reviewer for these very positive statements and many helpful comments that helped to improve the manuscript.

Personal comments: Out of personal interest, I would like to ask if you have a suggestion to why both ecosystem types approach to more or less the same SOC content in response to long-term warming (Fig. 4 and 5)? The levelling off of (absolute) SOC losses from different soil types (with different native C contents) to a sort of threshold level is very interesting to me.

Answer: Indeed, this is interesting, but we have to keep in mind that the soil type is not that different, it is the land cover that differs. We added the following sentences to section 4.4: 'Finally, SOC contents in both ecosystems approach a similar baseline in the highest warming intensity. This might indicate that the specific amount of biogeochemical persistent SOC does not depend on land cover or vegetation type, but is rather controlled by mineralogy.'

I also like the idea of decreasing pore space with warming (due to aggregation loss). I myself often observed a decrease in microbial biomass with warming, which I now start considering to link to the suggested decrease in pore space and microhabitats. Therefore, one can see the need of better exploring structural soil changes upon warming in order to better interpret biotic responses.

Answer: Yes, we fully agree and hope to go into more detail regarding soil structure (of undisturbed soil columns) in the future.

Out of curiosity I also want to ask if you observed any changes in the vegetation cover after several years of soil warming? And if yes, if there is data on plant communities available or a paper covering that aspect? As far as I know, changes in vegetation with warming are quite often observed and I wonder about associated impacts on SOC contents and fraction distribution. E.g. if observed effects like the loss of aggregation could be associated with a change in the vegetation structure? Out of personal interest, is the light ultrasonic treatment more effective and more representative for natural conditions than the slacking treatment?

Answer: There is one paper out on phenology in the grassland (Leblans, Niki, Bjarni D Sigurdsson, Sara Vicca, Yongshuo Fu, Josep Penuelas, Ivan Janssens (2017). Phenological responses of Icelandic subarctic grasslands to short-term and long-term natural soil warming. Global Change Biology 23(11), 4932-4945. doi: 10.1111/gcb.13749) and the consortium has gathered quite some data on vegetation dynamics and biomass, much of it is however still unpublished or not available in a form that it can be properly used, and currently there are two PhD students working on those NPP issues, aboveground and belowground in both ecosystems. However, we agree that vegetation responses should be mentioned to some extent, because they are likely to drive SOC dynamics. We now added the following sentences to section 4.1: "In fact, root biomass in 0-10 cm decreased in both ecosystems (data not shown), leading to weak positive correlations (R^2=0.37 for forest and R^2=0.29 for grasslands) of SOC and root biomass. Also aboveground plant litter tended to decline in both ecosystems. This suggests that SOC losses were partly driven by decreasing C input with warming and not by increased microbial activity alone. However, a clear picture on absolute C inputs in the experimental plots is not available yet, since it needs to consider NPP and biomass turnover at the same time." Regarding the slacking: This is a very good question and slacking is usually done in the context of aggregate size fractionation or any questions related to aggregate stability. So in our case, slacking and an aggregate size fractionation would have been interesting as well (and is currently done by other groups working on the ForHot experiment). However, this was not clear before we started the

fractionation work in the grassland and the beauty of this study is that we could repeat the exact same method for the forest.

Specific comments: Short comment to the title: I am not sure if you can really call it a "deteriorated" soil structure. I would rather use the term "changed" or "affected" because it does not imply a judgement. Also. The authors sometimes refer to boreal systems throughout their manuscript. However, I much better like the term subarctic in the context of the study site. Throughout the manuscript, I found an inconsistency in terms of SOC terminology as it is stated on page four and also within the use of associated units. In order to improve the readability and the understandability of the text, I would also welcome to be more specific and explicit when writing about SOC changes e.g. SOC contents, concentrations, fractions, mass et cetera. For detailed comments about alternative phrasing suggestions see below.

Answer: We changed the title of the manuscript. Following suggestions also of the other reviewer, we now removed soil structure from the title, mentioned the very specific soil type (Andosol) and included that two different ecosystems were evaluated: "Strong warming of a subarctic Andosol depleted soil carbon and aggregation under forest and grassland cover". Regarding the word 'boreal', we have replaced it by subarctic or deleted it where appropriate. The suggestion on being more specific about the use of SOC was also realized (see below). Page 1: Line 14: Five different SOC fractions were isolated and their re-distribution as well as the amount of stable aggregates was assessed to link SOC to soil structure changes.

Answer: We agree and used the suggested sentence in the abstract.

Line 16: Soil warming had depleted SOC concentrations in forest bulk soil by...

Answer: We agree but used contents instead of concentrations.

Line 24:...indicating an indirect protective effect of SOC on aggregates...

Answer: Here, the rationale was actually the other way around. We now slightly

changed the sentence to clarify this: '...indicating an indirect protective effect of aggregates >63 μm on SOC.'

Line 25: Topsoil changes in total SOC content and fraction distribution...

Answer: Changed accordingly.

Line 27:...in the response of subsoil SOC content and fraction distribution...

Answer: Changed accordingly.

The authors write in the abstract that no ecosystem effect was observed. However, this was confusing to me, as in my understanding Tab. 3 shows significant effects.

Answer: In the abstract, we are referring to the interactive effect of warming and ecosystem, not to the ecosystem effect (interaction effect is also given in the table). The question was, if the two ecosystems responded differently to warming. We modified the sentence to clarify that: 'However, no ecosystem effect on the warming response of subsoil SOC content and fraction distribution was observed.'

Line 32: Could you please specify if the stated temperature increase refers to air or soil temperature?

Answer: This is air temperature and we added that information.

Page3 Line 3: I believe that the statement about permafrost soils is out of place here as no permafrost is occurring at the investigated site.

Answer: We agree and deleted this part of the sentence. It now reads: 'The highest SOC stocks are located in high northern ecosystems (Tarnocai et al., 2009).'

Line 32: It was a bit hard to understand to how many samples you refer in your manuscript. Could you please state the explicit number of samples taken? Also, are all mentioned five transects situated in the investigated forest? Please also indicate the number of samples in your graphs.

Answer: The information was given above, when introducing the design of the experiment. However, it seamed a bit hidden because also the other reviewer did not see that. We therefore added that information again when describing the sampling procedure. The sentence (L30) read as follows: 'In late April 2018, i.e. almost exactly 10 years after the warming was initiated, mineral soils of all permanent forest plots (six warming intensities, five replicates each) were sampled.'

Page 4 Line 6: Distinct responses to warming were thus expected. Could you make an explicit statement what you were expecting?

Answer: Instead of going into more details here and setting up hypotheses in the middle of materials and methods, we decided to delete this small sentence. The method description reads more fluent now.

Line 15: Unit is missing for SPT (1.8 g cm3 -1)

Answer: Changed accordingly.

Line 33: Out of personal interest - what is the variability to the average mass recovery?

Answer: We added standard deviations to the given recoveries: 'Average mass recovery was 97$\pm$2%, average C recovery was 99$\pm$21%'. Of course, mass recovery was less variable.

Page 5 Line 11: Would you assume a positive or negative correlation between the poured bulk density and SOC in the SA fraction?

Answer: We changed the sentence slightly into: '...and hypothesized that _i would be negatively correlated to SOC content in the SA fraction in particular.'

Line 31: Do you think that absolute SOC losses are higher in topsoil because of a higher "native" C concentration?

Answer: This is likely because relative SOC losses were similar (or even higher in the subsoil). We however do not speculate about this here, because this is not the

discussion part.

Page 6 Line 1: Please state here that you talk about SOC contents in bulk soil.

Answer: Done.

Line 11: The depletion of SOC content lead to a changed relative distribution...

Answer: Done.

Line 12: The ANOSIM revealed... Please state here that you talk about topsoil findings.

Answer: Done: 'The ANOSIM revealed that a warming intensities of 5.8 and 17.5°C were necessary to significantly change topsoil SOC distribution (Tab. 2).'

Line 13:...fraction distribution was only significant from the unwarmed reference at a warming intensity of 5.8C. I was wondering about the + 2.7°C treatment (see Tab. 2)?

Answer: That is correct, in the subsoil significant differences were also found for 2.7°C. This was now included.

Line 15:...SOC in the POM and SA fractions, which were strongly depleted with warming (Fig 1). Please mention here, that this was the case in both depth increments.

Answer: In fact, in this specific sentence we are talking about the topsoil only. We therefore started the sentence now with 'In the topsoil. . .'.

Line 28:...the relative mass proportion of rSOC was expected to increase...

Answer: Done.

Line 30: Could you please give the p-value for the mentioned regression between rSOC and total SOC in the SC fraction?

Answer: Done. It was $p<0.001$.

Line 36: Could you please state the p-value for the significant negative relationship between the proportion of SOC in SA and the proportion of SOC in DOC

Answer: Done. It was $p=0.002$.

Page 7 Line 5: You mention similar SOC contents for subsoil forest and grassland soils. Is there more information about that e.g. an ANOVA?

Answer: We agree that similar is a vague term and actually the ANOVA (as presented in Tab.3 gave significant differences between ecosystems also in the subsoil. We have now rephrased the sentence to be more precise. It now reads as follows:'Also, the difference between ecosystems in subsoil SOC contents was less pronounced than in the topsoil.'

Line 14: You mention that POM in forest soils responded more negatively to warming than POM in grassland soils. Was this normalized to their respective C contents?

Answer: It is inferred from the slope of the regressions in Fig.4, which shows that forests start at a higher level than grasslands and both end up with a similar amount. So yes, it is true in absolute and relative terms.

Line 17: I would have appreciated it, if you mentioned earlier on that the warming in the grassland soils was only 6 years compared to the 10 years of warming in the forest.

Answer: This was mentioned in material and methods. Now on page 5, lines 12-14.

Line 20:...we found a strong negative correlation of bulk soil SOC content and poured BD. Please also give the R2 here.

Answer: Done.

Line 34: According to Tab. 1 the relative change in topsoil SOC content is -3.6% not -2.7% as stated.

Answer: This is correct. Numbers were mixed up here. Changed accordingly.

Line 36: Do you think that the + 5.8°C is a realistic warming intensity for soil or air temperatures?

Answer: To be clear about this difference, we modified the section, which now reads as follows: 'Considering that an air temperature increase of up to 11°C until the end of the century is within the possible range of IPCC climate change projections (IPCC 2013), we assume that a soil warming intensity of up to 5.8°C can be considered realistic. For example, Zhang et al. (2005) showed that soil temperature increase (+ 0.6°C) generally followed the air temperature increase (+ 1°C) in Canada during the 20th century. At a warming intensity of 5.8 °C, the investigated soil lost 29 % (topsoil) and 37 % (subsoil) SOC in ten years.

Page 8 Line 17: You write, that the present study did not reveal tipping points. However, if I look at e.g. Fig 1. it seems to me that +5.8âŮęC causes some abrupt changes in SOC contents and SOC proportions in fractions? Please also specify "tipping points for SOC" here (e.g. SOC contents).

Answer: This is correct, it seems like the aggregate break-down kicks-in only after 2.7°C. However, in the mentioned section we discuss bulk SOC content only. We clarified this and also added a sentence on page 9 line 24-25: 'A tipping point for aggregate-breakdown appears to be located between the warming intensities of 2.7 and 5.8°C.'

Line 22: You write that climate change is likely to strongly affect SOC stocks of boreal forests. Generally, I strongly agree to that statement. However, would question the comparability of the relatively young investigated forest on volcanic bedrock material to the biome of naturally old grown boreal forests. Upscaling to the regional or global context might be a slight over interpretation.

Answer: We conducted a soil warming experiment in a subarctic forest and find strong losses of SOC. We do not think that it is an overinterpretation to infer that climate change is likely to affect subarctic forest SOC elsewhere or as a whole. We don't state that this will happen at the same rate as we found, so we think it is ok to leave that statement in the text.

Page 9 Line 17: In the unwarmed reference soil, it accounted for the highest proportion of soil mass and SOC content.

Answer: changed accordingly.

Line 29:...we found a very strong positive correlation of SOC mass and...

Answer: changed accordingly.

Page 10 Line 2: I did not understand the context of the sentence about carbon desorption from the mineral phase. It seemed a bit out of place to me.

Answer: We changed the sentence slightly: 'Desorption of carbon compounds from the mineral phase is likely to be fostered by increased surface area, which is the case when aggregates disintegrate.' – and hope that it is understandable now: break-down of aggregates increases the surface area that is exposed to water.

Line 8: According to your definition on page 4 the unit of SOC content should be (g C kg -1).

Answer: Done

Page 11 Line 7: You might rephrase the sentence to: Changes in SOC concentrations and the relative distribution of fraction masses in the grassland soils have been previously investigated.

Answer: Done.

Line 8 to Line 11: The fact that there is no difference in subsoil SOC dynamics... might indicate that the same mechanisms of SOC depletion were involved in both ecosystems.

Answer: Done.

Line 23: The sentence is very long, maybe you could split it apart.

Answer: We shortended the sentence into: 'Therefore it seems likely that amount and

fraction distribution of SOC drove the ecosystem specific warming response in the topsoil.'

Line 37: You might rephrase the sentence to: Differences in the relative distribution of SOC fractions and their respective SOC concentration in response to warming have only been found in the topsoils of both examined ecosystems.

Answer: We rephrased the sentence as follows: 'Differences in the warming response of bulk SOC and SOC fractions between ecosystems have only been found in the topsoil,. . .'

Specific comments about graphs and tables:

1) Tab. 2: In the table description you write about testing "differences in SOC fraction distribution". Do you mean the relative mass distribution of SOC fractions?

Answer: Well, it is about how SOC is distributed in different fractions (reformulated to 'testing differences in the distribution of SOC in investigated fractions'). Fraction mass is not correct here, because in this paper fractions mass refers to the total soil mass in a specific fraction, not carbon.

2) Fig.1: is missing the a)b)c)d) notation in the individual graphs. Also the unit of the x-axis of a) and b) should be changed to SOC content (g C kg-1).

Answer: Done.

3) Fig.3: For me, the graph would be easier to understand if the title of the x and y axis would be changed to "percentage of total SOC in SA" and "percentage of total SOC in DOC". Also a p-value is missing in the graph as what is the depicted error range (95% confidence interval?).

Answer: Changed accordingly.

4) Fig 4: I am a bit confused if the scatter plots show SOC masses or SOC contents of the fractions in response to warming. What is the depicted error range? Moreover,

some relationships seem rather curvilinear to me than linear.

Answer: It is the carbon content as defined in m&m section, which you might understand as carbon mass actually (g C in the fraction per kg soil). It is confusing, because you can look at the data from different angles and at another point, we are talking about SOC concentration, which refers to g C in the fraction per kg fraction. The error is the 95% confidence interval and that was now added to the caption. Also, we admit that it was a bit oversimplified to use a linear fit in all cases. We now selected the best fit for each case using AIC, deciding between linear and logarithmic fits and also adjusted the statistics section.

5) Fig 5: Please change the title of the the y axis to subsoil instead of topsoil. I moreover have the same small issues with the graphs as mentioned for Fig. 4.

Answer: Changes accordingly.

6) Fig. 6 shows regression models. Please indicate the p-values here. 6a) The unit of SOC content should be (g C kg soil -1). 6b) The unit of SOC concentration should be (g C kg fraction -1). 6c) Please change the title of the x axis to " soil mass in stable aggregates". 6d) The shown relationship looks more curvilinear than linear to me.

Answer: We have added the p-value of <0.001 in the caption once, because this applied to all four regressions. We have changed the axes accordingly and regarding 6D: In fact, the linear fit was the best. The optical impression is a bit misleading, because of three slightly outlying points in the subsoil.

Questions provided by SOIL: 1) Does the paper address relevant scientific questions within the scope of SOIL? Yes, I think so. 2) Does the paper present novel concepts, ideas, tools, or data? The paper shows new interesting data on physical soil structure changes in responses to warming. However, to my state of knowledge, no new tools were involved. The manuscript provides some new concepts and ideas e.g. the proposed mechanism of warming leading to SOC loss (via enhanced microbial activ-

ity) which then results in the loss of stable aggregates. I also very much appreciate the proposed idea that the slope of the regression line between SOC and bulk density might be a useful indicator for aggregation affinity in unmanaged soils.

3) Does the paper address soils within a multidisciplinary context? n.a.

4) Is the paper of broad international interest? The scope of physical soil fractions and their response to warming seems of broad interest. It represents a framework of many biological responses to higher temperatures.

5) Are clear objectives and/or hypotheses put forward? Three objectives are stated clearly on page three and then also addressed in the results and discussion of the paper.

6) Are the scientific methods valid and clear outlined to be reproduced? Yes. Especially the SOC fractionation protocol is described in great detail and could be repeated in ourlab too.

7) Is the soil type/classification adequately described? Yes, most of the general information on soil types is given in the text.

8) Are analyses and assumptions valid? Yes.

9) Are the presented results sufficient to support the interpretations and associated discussion? Yes.

10) Is the discussion relevant and backed up? In general yes. For detailed comments see above.

11) Are accurate conclusions reached based on the presented results and discussion? Yes.

12) Do the authors give proper credit to related and relevant work and clearly indicate their own original contribution? Yes.

13) Does the title clearly reflect the contents of the paper and is it informative? Yes. The title clearly reflects the later proposed mechanism of aggregate break-down which follows SOC loss that was caused by warming. I especially like that the title includes the term “subarctic” and not “boreal”.

14) Does the abstract provide a concise and complete summary, including quantitative results? Yes.

15) Is the overall presentation well structured? Yes, I like the tripartite structure of the paper (1-warming effects on forest SOC and its fractions, 2-forest vs. soil SOC in response to warming, 3- soil structural changes). The focus on those three topics can be found in the introduction, results and discussion part.

16) Is the paper written concisely and to the point? To my understanding the manuscript is mostly concise. However, sometimes the sentences were hard to follow (too long) and not precise enough to understand what the authors meant. This holds especially for “SOC-terminology and SOC units” – see detailed comments above).

17) Is the language fluent, precise, and grammatically correct? Mostly yes. However, some sentences are relatively long and thus hard to follow. This is especially the case in the discussion part.

18) Are the figures and tables useful and all necessary? The figures are nice and useful. For detailed suggestions see comments above.

19) Are mathematical formulae, symbols, abbreviations, and units correctly defined and used according to the author guidelines? Yes. In the context of units, please see detailed comments above.

20) Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated? I think that the sampling procedure (amount of taken samples and analyzed) could be described in more detail.

21) Are the number and quality of references appropriate? Yes.

22) Is the amount and quality of supplementary material appropriate and of added value? Yes

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