

Interactive comment on “Carbon dynamics and changing winter conditions: a review of current understanding and future research directions” by M. Haei and H. Laudon

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Dear Associate Editor,

We appreciate the comments of the two anonymous referees on our manuscript. We find the comments very valuable and will do our best to incorporate them in the text and make changes accordingly. The manuscript will also go through an additional language editing.

As pointed out by both referees, we will improve the entire text by writing more specifically about where, which season and whether it is carbon flux or concentration. We

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will incorporate the relevant material from the references suggested by both referees into the text and add the references to the reference list. However, one reference deals mainly with permafrost which is not in focus for this paper, and we may not include it (see below). As suggested by Referee #2, we are going to change the structure of the paper and remove the titles Introduction, Methods, Results and Discussion. Instead of the three first main titles, we will insert new titles/sub-titles (more details below). For the discussion section, we will still keep the sub-titles but modify the text as recommended by both referees. We believe that by doing so the manuscript will be very much improved and hope that the editor finds our responses and proposed changes suitable and satisfactory.

Below please find a detailed point to point response to the referees' comments.

Anonymous Referee #1

- General: This manuscript reviews the literature pertaining to effects of winter climate on ecosystem C dynamics. This topic is timely and a review will well serve the scientific community. This paper has good content and cites relevant studies. However, I found the writing to be vague in many places when discussing C fluxes and the season. As written it is often difficult to discern which season is being referred to when discussing a response variable. In addition, the pool of C being referred to is sometimes vague (e.g., in some cases you mention C concentrations, but it is not clear if you are referring to soil, soil solution, etc.).

We thank the anonymous referee #1 for the valuable comments. Throughout the manuscript, we will specifically clarify the seasons, carbon fluxes versus concentrations, and whether it refers to soil, soil solution, streams or through the snow-pack. The manuscript will also be language edited which will hopefully contribute to its clarity. However, the referee has already pointed out a number of language issues which we will consider to improve the text.

- There are a couple of references that the authors might consider adding to this

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manuscript.

Both references Reinmann et al. 2015 and Hufkens et al., 2012 are now incorporated in the manuscript. Please find more details in response to the specific comments on these references.

- Please see my detailed comments below.

- Introduction: 15765 L8: "DOC has also" to "DOC also has"

We will change this accordingly.

- Methods: 15767 L10: "Exiting" to "Existing"

This typo will be corrected accordingly.

- Results: 15769 L11: I might change "decreased in both snow removal. . ." To "were lower in both snow removal. . ." Because the ambient plots were unaltered and as such their DOC fluxes were unaltered.

Good point. This will be changed as suggested.

- 15769 L13-15: Why is this temperature distinction important?

Very good question! Since we have not highlighted the temperature changes for the other field studies, it is not important to mention this here. We will hence remove this information from the text.

- 15769 L16-17: I think this is a case where either and or should be used in place of neither and nor to prevent use of the double negative.

This will be corrected accordingly.

- 15769 L15-20: Is it important to draw distinctions in experimental design and questions posed between these studies? The former was simulating snowmelt compared to irrigation post-treatment. Also, I could be recalling incorrectly, but wasn't the response observed by Henschel et al. after 1 f-t cycle that was followed by sustained frost?

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We will rephrase the text to avoid misunderstanding. However, we suggest keeping the details of the design to highlight the similarities/differences between the experiments. We hope that the text will help the reader to compare the effects of permanent frost and impacts of repeated freeze-thaw cycles. The text would then read as: "In the soils of the German temperate forest, a cycle of two-week freezing/one-week thawing increased the DOC concentrations at -8 and -13°C (but not at -3°C), but repeated freeze-thaw cycles did not have significant impacts."

- 15770 L27-28: Does rising levels of CO₂ mean higher rates of soil respiration? If so, I think that should be explicitly stated.

Yes, it is meant rates of soil respiration and will be clarified in the text.

- 15771 L3: "A three times decrease"?

This will be rephrased to "by a factor of ~ 3 ".

- 15772 L6: The same area as what?

We assume that the referee refers to Page 15771 L6 and will remove this part of the text to avoid misunderstanding.

- 15771 L14-16: Is there a biome component to this story? i.e. are there differences in response to soil frost across biomes?

Very good point! We will modify the text and add to the text that this was mostly observed in the temperate biome.

- 15771 L17: What is meant by "frost induced organic carbon"?

We will rephrase the text to avoid misunderstanding.

- 15772 L7: Here, and other places in this paragraph I think it would be useful to specify that you are talking about DOC concentrations (if that is indeed what you are referring to) so as not to be confused with actual mass of DOC being lost in streams. I think this

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is an important distinction to make because higher concentrations do not necessarily mean greater losses of DOC.

Good point. We will specify this throughout the text.

- 15772 L15-18: I find this sentence a little confusing and perhaps inconsistent with the preceding text. Here you indicate that DOC export is higher DURING warmer winters, but the preceding text covers DOC export during several different seasons, depending on the study. I think this needs to be clearer here and it might be useful to discuss some sort of seasonality that might exist in the response of DOC export and/or some sort of bias in season(s) sampled by previous studies. This is also a good place to specify what is meant by 'export' of DOC...i.e. mass vs. concentrations.

Good point. We will split the preceding paragraph into two. The first paragraph will focus on winter season and the second one dealing with spring snowmelt. We will also specify what is meant by export. These changes would hopefully make the sentence "In summary..." more reasonable.

- 15772 L19: Using "continuous" here makes it seem like automated chambers were used, is this what is meant?

We will rephrase the text to avoid misunderstanding.

- 15772 L21: Perhaps change to "After measuring rates of soil respiration for 17 months in northern China..." See next comment.

- 15772 L21-25: I'm not sure these 2 sentences are necessary because it seems a bit out of place to start discussing soil warming during the growing season when the rest of the paper has dealt with winter manipulations. Also, in the context of this manuscript, I'm not sure how useful it is to say that winter rates of soil respiration are not different between ecosystems. That seems a bit ancillary here and perhaps just a nuance of the study cited. The use of "between" twice in the second sentence is confusing.

We agree with the referee and will remove these sentences from the text. Therefore
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the sentence mentioned in the last comment will be removed.

- 15772 L25-27: Again, the wording of the description of the soil respiration study (i.e. "In a one season CO₂ efflux measurement") conveys something different than what I think is meant here. You can also simply say that soil CO₂ efflux declined throughout the winter.

We will modify the text as suggested.

- 15773 L2-5: I don't think these two sentences add anything useful to the paper...it is pretty well established that growing season rates of soil respiration are higher than those during the winter.

We agree with the referee and will remove this part from the text.

- 15773 L7-8: What is meant by "turning warmer spring to seasons with increased net CO₂ uptake"?

We will clarify this by rephrasing the sentence to "... and led to an increase in net CO₂ uptake in warmer spring seasons".

- 15773 L10: Change to "the Sierra Nevada Mountains"

This will be changed accordingly.

- 15773 L11: Concentrations where?

We will clarify in the text that it is about beneath snow CO₂ concentrations.

- 15773 L16-17: Lower rates of R_s when?

We will add in the text that it is related to winter season.

- 15773 L18-19: Total C or labile C?

It was meant total C and will be clarified in the text.

- Discussion: 15773 L26: Important for CO₂ production during winter? Growing sea-

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son? Because fluxes during multiple seasons are discussed throughout the paper I think it is important to specify the season you are referring to each time.

Good point. We will add the information on the seasons throughout the paper.

- 15774 L4-5: C concentrations in what? Soil? Soil solution? Streams?

We meant C concentration in soil and will specify this in the text.

- 15774 L26: Are you referring to the soil C pool here?

Yes, and this will be clarified better in the new version of the manuscript.

- 15774 L27-28: Losses during winter? During each event?

We meant after multiple event. This will be clarified in the text.

- 15775 L1: If I recall correctly Campbell et al. did not measure most of these fluxes during the winter, but during the growing season. Further, that study was looking at a sustained soil frost, not F-T cycles. I think it is important throughout to explicitly indicate which season you are referring to.

Since the Campbell et al. paper dealt with C release during snowmelt, we will remove this part. Instead, we will incorporate this into the section entitled "Extreme conditions".

- 15775: For this first paragraph you might want to look at Reinmann et al. 2015, Ecosystems who discuss short-term impacts of soil frost on aboveground respiration and tree growth/C storage.

Thank you. We checked the reference and will add the relevant information on fine root/soil frost to the section on field and laboratory experiments. Some information on the competitiveness of plants will also be added to the "carry-over" section.

- 15775 L19-21: The wording in this sentence is kind of odd. You might just say that "There are almost always differences. ..."

This will be corrected accordingly.

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- 15775 L27-28: I think you should elaborate on this point. How might soil type and organic matter content influence the response to soil frost?

Good point. We will add to the text that differences in soil texture can influence the water holding capacity and soil susceptibility to freezing.

- 15776 L18-24: Can you take this to the next step and indicate whether this has an impact on annual export vs. the timing of export?

We will explain in the text that the consequences on carbon export are mainly determined by changes in discharge rather than concentrations.

- 15778 L1-2: "shifts to soil temperature to soil moisture" does not entirely make sense, should it read "then to soil moisture"?

This will be corrected accordingly.

- 15778 L13: Is this due to the effects of snow cover on soil frost?

Yes, and this will be mentioned in the text.

- 15778 L26: Snow "disappearance" to "snowmelt"?

This will be changed accordingly.

- 15779 L14: change to "towards THE south"

This will be changed accordingly.

- 15780 L14: Remove "to" from "reach to"

This will be corrected accordingly.

- 15780 L16: "rises" to "rise"

This will be corrected accordingly.

- 15781 L3-6: "leafing" to "leaf-out". Perhaps provide a citation for each of these re-

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sponses?

We will make the correction and add the references.

- 15781 L8-9: See Hufkens et al. 2012 in GCB who discuss effects of spring warming and a late frost on sugar maples in the northeastern U.S.

We have now checked this reference and will add the relevant information to the text.

- 15782: It is hard to see how the modeling paragraph fits in because there is not much of a focus on the winter processes. Could you add a few sentences to tie that in? I think discussing modeling prospects is important, but it would be great to tie it in a little more to winter processes. Do models explicitly model or take into account winter?

This aspect was also discussed with the editor in an earlier correspondence. As the referee mentioned the winter processes has not been explicitly accounted for in the models. We will re-structure this section to highlight this aspect at the beginning of the paragraph.

- 15782 L25: Add a colon after “consider.”

A colon will be added here.

- Figures: Fig 1: Align letters in pictures and make them the same font size.

We will make these changes in the figure.

Anonymous Referee #2

- General comments: Ecosystems which experience long or deep winters also tend to contain large standing stocks of organic carbon, mostly in soils. Climate warming, especially at high latitudes, is expected to be more pronounced in winter than in summer, and there is potential for significant impacts of winter warming on long-term ecosystem function and carbon dynamics. The subject matter of this review is therefore timely and important, and one which would be of significant interest to BG readers. I think the au-

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thors are correct in saying that winter processes have been understudied, and this ms does present a useful collation of the available research. However, at present, there is little in the way of synthesis and the presentation is lacking. The text jumps back and forth between different processes and ecosystems with no clear development of ideas or arguments. Part of the problem is that the review is presented as Methods, Results and Discussion sections. No new data are presented (there is no meta-analysis) which is perfectly OK, but then it doesn't make sense to me to have a methods and results section – the results section mostly just lists the results of previously published papers and isn't necessary (but do summarise the results of the literature search e.g. search terms, numbers of papers published on each topic etc.). The ms would be significantly improved, and would have much greater impact, if instead it was structured around describing the important concepts and/or processes which govern C cycling responses to winter conditions (for example main sections on “Projected winter climate change” or “Mechanisms of DOC export from soils” etc). Each section would then explain the concept or process, how it works, why it is important, what the main uncertainties are etc. This has partially been done in places, e.g. section 4.1, and I really like figure 2. However, the take home messages from the literature need to be much more strongly emphasised, and some substantive conclusions provided at the end of the manuscript (over and above highlighting the need for more research). In general the language should be more precise and specific – there are quite a few instances where the authors make ambiguous statements. I've given examples below so it is clear what I'm talking about, but I haven't made exhaustive minor edits because I expect the text will have to change substantially to address the issues above.

We appreciate the anonymous referee #2 who highlights very important points. As recommended, we will modify the structure of the manuscript and remove the sections Introduction, Methods, Results and Discussion, and instead insert new titles and sub-titles into the text. However, we are going to keep most of the sub-titles of the Discussion section in the original manuscript, but modify the content following the referee comments. The suggested titles and sub-titles are listed below: 1 Background 1.1

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Carbon in northern ecosystems 1.2 Winter climate change 2. Studies on winter carbon dynamics 2.1 Field and laboratory experiments 2.2 Time-series and literature search 3 Current knowledge 3.1 Empirical experiments versus time-series 3.2 Field and laboratory studies 3.3 Time-series 4 Insights from existing studies 4.1 Mechanisms of carbon release in frozen soils 4.2 Field-scale snow-cover manipulations and laboratory soil incubations 4.3 Time-series 4.4 Carry-over effect 4.5 Future winter climatic changes 4.6 Shoulder seasons 4.7 Extreme conditions 4.8 Modelling 5 Future research challenges

Throughout the manuscript, we will be more specific with our statements (following referees' comments) and an extra language editing will hopefully improve the text.

- A recent review of the effects of thawing on soil gas fluxes should be cited (Kim et al. 2012)

We agree with the referee and will add this into the text.

- Specific comments:

- Introduction P. 15764 L. 23-26: This information on terrestrial C stocks in "northern ecosystems" needs to be more specific – how are you defining northern ecosystems? I would suggest giving values for carbon stocks. There are also more recent relevant estimates of terrestrial C stocks than those available in Hobbie et al 2000 (e.g. (Hugelius et al. 2014))

Thank you for your suggestion. We will modify the text accordingly and add the newer reference to the text.

- Results P. 15768 L. 16-17. Sentence beginning "Most field and laboratory studies: : :"
Do you mean an increase in DOC in the soil solution? Or delivery of DOC to the aquatic system? Does "field studies" include long-term observational data? It is also not clear what the increased DOC is in response to. Are you referring to increased severity of freezing or the effect of a single freeze thaw event compared to unfrozen conditions? The following sentences go into details, but the meaning of the first sentence of the

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paragraph should be clear.

We are going to change the first sentence to "Most field and laboratory studies indicate an increase in soil DOC concentrations in response to soil frost, but some observations depart from this trend." This change will hopefully make this paragraph clearer. Some additional minor modifications will also be done throughout this paragraph to address the above questions.

- Discussion P15773 L.22-24.This is another example of a general statement which is ambiguous. The clause "showing that cold soils and soil frost generally enhance organic carbon concentrations" could mean any number of different things; enhanced organic C concentrations in soils, in soil pore water, in streams etc. I'm also not sure that all available/relevant studies on carbon in both organic and inorganic forms have been included (e.g. Bokhorst et al. 2008; Nowinski et al. 2010; Grogan 2012)

The changes based on general recommendations of both referees will hopefully clarify this section. The suggested references Bokhorst et al. 2008 and Grogan 2012 will also be included. Thank you.

- References Bokhorst, S., Bjerke, J.W., Bowles, F.W., Melillo, J., Callaghan, T. V. & Phoenix, G.K. (2008) Impacts of extreme winter warming in the sub-Arctic: growing season responses of dwarf shrub heathland. *Global Change Biology*, 1–10.

Grogan, P. (2012) Cold Season Respiration Across a Low Arctic Landscape: the Influence of Vegetation Type, Snow Depth, and Interannual Climatic Variation. *Arctic, Antarctic, and Alpine Research*, 44, 446–456.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J.W., Schuur, E. a. G., Ping, C.L., Schirmer, L., Grosse, G., Michaelson, G.J., Koven, C.D., O'Donnell, J. a., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J. & Kuhry, P. (2014) Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences*, 11, 6573–6593.

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Kim, D.G., Vargas, R., Bond-Lamberty, B. & Turetsky, M.R. (2012) Effects of soil rewetting and thawing on soil gas fluxes: A review of current literature and suggestions for future research. *Biogeosciences*, 9, 2459–2483.

Nowinski, N.S., Taneva, L., Trumbore, S.E. & Welker, J.M. (2010) Decomposition of old organic matter as a result of deeper active layers in a snow depth manipulation experiment. *Oecologia*, 163, 785–792.

Thank you. The references will be incorporated into the text and added to the reference list. We may not include Nowinski et al. 2010 with focus on permafrost.

Interactive comment on *Biogeosciences Discuss.*, 12, 15763, 2015.