

## ***Interactive comment on “The limits to northern peatland carbon stocks” by Georgii A. Alexandrov et al.***

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We are pleased to see that Referee agrees that the results of the study are worth publishing. We also acknowledge the importance of Referee’s comments for presenting the results of the study in a more precise and coherent way. Below is our response to Referee’s questions and recommendations.

Response to the questions asked by Referee:

1. (1) P1, L.23 : Where do northern peatlands start? Is it >40 North or >45
- (2) Here we refer to the article of Loisel et al. (2017) and keep in mind the peatlands located north of 45 N.

C1

(3) “... northern peatlands, namely the peatlands distributed across the northern mid- and high-latitude regions located north of 45°N, ...”

2. (1) P1, L.25: 864-2240 PgC – Is that already your result or is it from a different study?

(2) These numbers were calculated from the range of estimates of carbon accumulation rates associated with peat growth and the range of estimates of peatland area reported by Yu (2011) and cited in this paragraph. It is a starting point of our research aimed to explore limitations to peatlands growth that do not allow them to remove 2000 PgC amount of carbon from the atmosphere.

(3) The changes made in the manuscript hopefully make it clear that this is a simple extrapolation based on the estimates reported by Yu (2011).

3. (1) P3, L.3: What is the density of draining system?

(2) The density of draining system is the length of draining streams per unit area.

(3) “...the potential peat depth, is determined by the amount of effective rainfall, drainage system density (the length of draining streams per unit area) and the hydraulic conductivity ...”

4. (1) P3, L.4: What is the impeded drainage model?

(2) The impeded drainage model is the model based on the Dupuit-Forchheimer theory of groundwater movement (aka hydraulic theory) and a few additional assumptions (see Supplementary Information to our previous work, <https://media.nature.com/original/nature-assets/srep/2016/160420/srep24784/extref/srep24784-s1.doc>). The basic idea of the model is that the high level of water table in a peatland is maintained due to impeded drainage: it takes long time for water coming with precipitation at the central part of a peatland to reach the draining streams.

C2

(3) “To calculate the potential peat depth, we apply an equation derived (see Supplement) from the impeded drainage model used in our previous study (Alexandrov et al., 2016)?”

5. (1) P3, L.6: Why is  $h_{max}$ , the maximum height of the water table above the level of the draining system, dependent from the fraction of the area occupied by peatlands?

(2) Both  $h_{max}$  and  $f_p$ , the fraction of the area occupied by peatlands, depend on  $K$ , the hydraulic conductivity: equation (S6) and equation (S10) in the Supplement (<https://www.biogeosciences-discuss.net/bg-2019-76/bg-2019-76-supplement.pdf>). The “observed” value the fraction of the area occupied by peatlands,  $f_{p,obs}$  makes it possible to estimate  $K$ : equation (S11). Substituting  $K$  given by equation (S11) to equation (S6) gives the equation (S12), where  $h_{max}$  depends on  $f_{p,obs}$  and  $g$ , the average height of the watershed above the level of the draining system. That is to say, excluding  $K$  from the equation for  $h_{max}$  leads to including  $f_{p,obs}$  into this equation.

(3) This part of the text is rewritten.

6. (1) P3, L.26: How much is the minimal depth of the peat layer which is used to classify a land unit as peatland?

(2) The minimal depth of the peat layer which is used to classify a land unit as peatland is a source of uncertainty in the estimates of peatland area. We relied on the WISE30sec data set (Batjes, 2016) of soil properties and diagnosed peatland extent by fraction of grid cell covered by soils of histosol type. Hence, the minimal depth of the peat layer is assumed to be 40 cm (according to FAO definition of histosols).

7. (1) P4, L.12: What is the non-conservative and what is the conservative interpretation of  $f_{p,obs}$ ?

(2) The variety of possible interpretations is parameterized using the equation (S18) in the Supplement. The difference between the conservative and non-conservative in-

C3

terpretations of  $f_{p,obs}$  could be illustrated by the following example. Let us consider a grid cell the 36% of which is covered by peatlands. Does it mean that peatlands cover 36% of each watershed within this grid cell? Or does it mean that only 48% of watersheds are occupied by peatlands, and the peatlands cover 75% ( $0.48 \cdot 75 = 36$ ) of each of these watersheds? In other words, we cannot say for sure whether the grid cell contains many small peatlands, or few large peatlands. Under the conservative interpretation,  $f_{p,obs} = 36\%$  suggests that peatlands cover 36% of each watershed within this grid cell (many small peatlands). Under the non-conservative interpretation,  $f_{p,obs} = 36\%$  suggests that only 48% of watersheds within the grid cell are occupied by peatlands, and the peatlands cover 75% ( $0.48 \cdot 75 = 36$ ) of each of these watersheds (few large peatlands). The conservative interpretation of  $f_{p,obs}$  leads to smaller estimate of  $p_{max}$  as compared to the non-conservative interpretation.

(3) This part of the text is rewritten.

8. (1) P5, L.11: Why 875 PgC? What is with the 665 PgC – 1258 PgC? What is your main result?

(2) The main result of this study is the expedient estimate of carbon stock that could be accumulated by northern peatlands by the end of the current interglacial. This estimate is equal to 875 PgC and falls within the range of uncertainty that starts from 750 PgC to 900 PgC ( $= 875 \pm 125$  PgC), and derived from the Yu's model (Yu, 2011). The validity of this estimate is supported by the estimates of potential carbon stocks obtained by a completely independent method under different interpretations of the data on the geographic distribution of peatlands: this estimate,  $875 \pm 125$  PgC, falls within the range of uncertainty associated with accuracy of the data on the geographic distribution of peatlands.

(3) This part of text is rewritten.

9. (1) P4, L.21: “peat C addition” do you mean C accumulation?

C4

(2) We use the words “peat C addition” to denote the amount of carbon that enter to catotelm. Peat accumulation is the difference between peat addition and peat decomposition.

(3) The words “peat C addition” are changed to “annual C input to catotelm.” “This model suggests that the growth of carbon stock in peatlands is limited by the ratio of annual C input to catotelm to the decay constant.”

10. (1) P5, L.20-21: Why 1000 PgC? It seems a bit arbitrary to me.

(2) It is not completely arbitrary. According to Allen et al. (Nature. 2009 Apr 30;458(7242):1163-6. doi: 10.1038/nature08019), cumulative anthropogenic emissions of 1000 PgC are expected to result in 2oC carbon-dioxide-induced warming above pre-industrial temperatures (confidence interval: 1.3–3.9 oC). Hence, if cumulative anthropogenic emissions will not exceed 1000 PgC, then there is a chance that there will be no dramatic changes in climate leading to a massive destruction of northern peatlands.

(3) “This assumption, perhaps, is not relevant to the scenarios of dramatic changes in the Earth system, jeopardizing peatlands development, that might take place if cumulative carbon emissions exceed 1000 PgC (Allen et al., 2009; Millar et al., 2017).”

11. (1) P5, L.21: What happens to the peat C storage if carbon emissions exceed 1000 PgC?

(2) According to Millar et al. (Nature Geoscience, 10: 741-747.), 90% of CMIP5 models suggest that 468 PgC of cumulative carbon emissions after 2015 lead to warming by 1oC above 2010-2019 level under RCP2.6 scenario of radiative forcing. Hence, if cumulative carbon emissions exceed 1000 PgC (545 PgC from 1850 to 2015 plus 468 PgC after 2015), then one cannot exclude the risk of dramatic changes in climate leading to a massive destruction of northern peatlands.

(3) The text is revised.

C5

12. (1) How does the orbital forcing affect peatland C uptake?

(2) We did not consider the effect of orbital forcing on peatland C uptake in the reported numerical experiment. The purpose of this experiment was to show how additional long-term carbon sink provided by northern peatlands may affect the level of atmospheric CO<sub>2</sub> concentration to which Earth system will return after the end of anthropogenic CO<sub>2</sub> emissions.

13. (1) P6, L.2: “in relevant time frame” – Can you give a number, what a relevant time frame is?

(2) The next reductions in northern summer insolation that may lead to glacial inception will occur 1500, 16000, and 53000 years after present. It is unlikely that atmospheric carbon dioxide concentration will return to the level typical for interglacial periods within next 1500 years. Hence, the next 5-15 thousand years is a relevant time frame for reducing the atmospheric carbon dioxide concentration to the level that is typical of interglacial periods.

(3) “in relevant time frame, that is, in 5-15 thousand years,”

14. (1) P6, L.7: What are limits to peatland growth?

(2) The limits to peatland growth are the peat depth values that cannot be exceeded in given climatic and geomorphologic conditions.

15. (1) P6, L.10-16: Why is the cumulative carbon removal associated with the natural development of peatland ecosystems limited? The cumulative carbon removal associated with the natural development of a peatland ecosystem is limited by the height of the water table that could be maintained due to impeded drainage above the level of draining streams. Therefore, cumulative carbon removal associated with the natural development of peatland ecosystems is limited by the given climatic and geomorphological conditions.

Response to recommendations made by Referees:

C6

1. (1) Abstract: Please insert one or two statements about the methods, which you applied in this study. Also, include a statement about your results, where you specifically mention the amount of carbon which could be set off by peatland growth.

(2) done

(3) “The limits to northern peatland carbon stocks, evaluated based on the gridded data on the depth to bedrock and on the fraction of area covered by soils of histosol type, suggest that  $875 \pm 125$  PgC is the most expedient estimate of potential carbon stock in northern peatlands at large.”

2. (1) I would recommend changing the title of the manuscript into “The potential of northern peatlands for carbon sequestration”

(2) We would like to keep a “connotation” to the paper “The limits to peat bog growth” by Clymo (1984), and to highlight the fact that the cumulative amount of carbon that northern peatlands could remove from the atmosphere is limited by the geomorphological conditions in present climate.

(3) Based on the overall idea of the suggested title, we think it would be reasonable to change the title as follows, “The limits to growth of northern peatland carbon stocks”.

3. (1) Page 1, Line 10: Maybe write “continuous” instead of “persistent”

(2) We used “persistent” instead of “continuous”, because “persistent carbon sink” is a common collocation appeared in a number of research articles on carbon cycle (e.g., Pan, Y. D. et al. A large and persistent carbon sink in the world’s forests. *Science* 333, 988–993 (2011)).

4. (1) P1, L.12: Rewrite the sentence. E.g. “The evaluation of the carbon sequestration potential of northern peatlands show that atmospheric carbon dioxide concentration can be significantly reduced. Northern peatlands have the potential to be the second largest CO<sub>2</sub> sink after the world’s oceans.”

C7

(2) Here we were trying to say that over the next 5 thousand years after the end of fossil fuel burning, not only oceans but also northern peatlands will be removing carbon dioxide from the atmosphere.

(3) This part of the text is rewritten.

5. (1) The introduction needs a better structure. The different paragraphs need to be connected better and the research gap should be mentioned more clearly.

(2) Done

(3) We moved the paragraph that seemingly was breaking the logic flow to the proper place in the end of Introduction.

6. (1) Page 1, Line 17: You mention the study by Loisel et al. (2014). Please also include the new study by Treat et al. (2019) in your introduction

(2) Done

7. (1) P1, L.17 : I suggest to use the word “knowledge” instead of “wisdom”

(2) We think that “notion” would be good.

(3) “. . . largely confirm the conventional notion of the carbon (C) sink provided by northern peatlands . . .”

8. (1) P1, L.21 : I suggest to use the word “previous” instead of “later”

(2) Here we use ‘later’ in sense of ‘coming after something else’. Hence, it cannot be replaced by “previous”.

(3) To avoid possible misunderstanding, we revise this sentence as follows, “In the early Holocene, both the rate of peatland expansion and the rate of carbon accumulation appear to be highest (Yu et al., 2010) as compared to the later Holocene periods.”

9. (1) P2, L.13: I suggest to use the word “rise” instead of “elevation”

C8

(2) Done

10. (1) Methods: You could start with an equation for the maximum depth of peat before introducing the maximum carbon stock in a grid cell

(2) Done

11. (1) I suggest to make subchapters to explain the different model parameters. The first subchapter could include the maximum carbon stock in a grid cell, whereas a second subchapter includes the extrapolation from the grid cell to the entire northern peatland area and a third subchapter explains the differences between a conservative and non-conservative interpretation of fp

(2) done

(3) The estimate for the entire peatland area is merely a sum carbon stocks in the grid cells located north of 45N, and hence is explained in one sentence, "The sum of the potential carbon stocks for all cells north of 45°N gives the less-conservative estimate of the potential carbon stock in northern peatlands."

12. (1) I suggest you discuss your methods in the discussion section with a separate subchapter and strictly separate between methods and results, so that no results appear in the methods section

(2) Done

(3) No results appear in the methods section. The discussion section is rewritten.

13. (1) P3, L.9: Change the sentence to " : : hmax is the maximum height of the water table above the level of the draining system: : ." (2) done

14. (1) P4, L.1-11: This part would better fit into the discussion where you could have a subchapter discussing your methods and your model.

(2) This part is an explanation of our approach to addressing uncertainty. We rewrite

C9

the text to clarify this point.

(3) This part of the text is rewritten.

15. (1) P4, L.13: 1258 vs 665 PgC. This is a result and should therefore be in the results chapter (2) done

16. (1) P4, L.14: Please replace "one cannot expect: : ." with "it cannot be expected: : ." (2) done

17. (1) P4, L.18: Please replace "one may assume: : ." with "it can be assumed: : ." (2) done

18. (1) P4, L.23: 875 PgC. This is another result and should therefore be in the result section (2) done

18. (1) The results section needs to be rewritten completely with a focus on your own results. (2) done

19. (1) P5, L.5: Add the year of publication after Yu (2) done

20. (1) P5, L.10: Add the year of publication after Yu (2) done

21. (1) P5, L.10: Please change "one could find" into "it is reasonable to agree: : ." (2) done

22. (1) Please provide a more in-depth discussions of your methodological approach, e.g. show the benefits but also limitations of your model and compare your results of potential C accumulation with e.g. C accumulation during the Holocene. I suggest making several subchapters. One where you discuss the benefits and limitations of your model, including the uncertainty of your estimation. Another subchapter where you compare your results with previous studies (as you did in the results section) and a third subchapter where you discuss the implications of your results on the global C cycle (basically your actual discussion).

C10

(2) The uncertainty of estimates is explained in the methods section (sub-section 2.3), because we apply an original method for characterizing the uncertainty of our estimates.

(3) The section Discussion is rewritten.

23. (1) P5, L.14: Change the first sentence into: “The potential for northern peatlands to store carbon were estimated for the first time: : :”

(2) Yes, “potential for growth” and “limits to growth” have the same meaning, and “potential for growth” sound more positive. However, we would like to keep here a “connotation” to the paper “The limits to peat bog growth” by Clymo (1984) cited in the next phrase.

24. (1) P5, L.15f: Change the following sentence into: “We adapted this methodology to global scale and additionally included geomorphological aspects of peat bog growth: : :”

(2) We changed this sentence proceeding from general idea of this recommendation.

(3) We adapted this methodology for use at the Earth system scale based on the gridded data (Hengl et al., 2014) representing geomorphological aspects of peat bog growth.

25. (1) P5, L.18 : Write “Our estimate: : :” instead of “Moreover, this: : :”

(2) We deleted “Moreover”.

(3) “This estimate,  $875 \pm 125$  PgC, corresponds to the present climate. . .”

26. (1) P5, L.18: Delete “somewhat”

(2) done

27. (1) P5, L.19: Change the following sentence into: “This assumption, however, might not be relevant for scenarios of dramatic changes in the Earth system that will

C11

take place if cumulative carbon: : :”

(2) done

28. (1) P5, L.21f: Change the following sentence into: “Nevertheless, if cumulative carbon emissions do not exceed 1000 PgC, the northern peatlands play an important role in global carbon cycle recovery”

(2) done

29. (1) P5, L.26: Replace “plain” with “other” (2) done

30. (1) P6, L.1-4: You should also discuss the conditions and timeframe under which such a scenario can happen. Also, if you make such a strong statement, there should be a better explanation of this Earth system model of intermediate complexity.

(2) It is not a statement; it is rather a report about the numerical experiment that demonstrates the role of northern peatlands in global carbon cycle recovery and calls for further numerical experiments. That is why it is presented in discussion. The Earth system model of intermediate complexity, CLIMBER-2, is described in the cited paper.

31. (1) P6, L.3 replace “won’t” with “will not be able to” (2) Done

32. (1) Please add a reference list for the supplement (2) done

33. (1) S1.1: Please rephrase the first sentence. (2) done

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