<u>Point by Point Reviewer Response</u>

Reviewer 1

General comments:

What's the paper about: In this ms Swenson et al attempt to estimate C-balance of five managed raised bogs in Ireland. The five sites differ in their hydro-physical and ecological characteristics, as defined by the National Parks and Wildlife Servies of Ireland. The strength of their study is in their attempt to estimate total C-balance of each site based on measurements of various aspects of ecosystem carbon balance during the same season, including: ecosystem CO2-gas flux, ecosystem CH4-gas flux, aquatic fluxes of dissolved organic and inorganic carbon and CO2 gas efflux from open water in drainage ditches. Furthermore, they provide a literature compilation and review of studies that have measured ecosystem CO2 and methane flux in boreal and temperate, managed and intact, peatlands. They use the global synthesis to explore global patterns between the fluxes and mean annual water table. They discuss their sites in light of the global patterns and argue that the most practical advice to policy makers on C-sequestration potential of restored peatlands should involve insights into the impact of water table and vegetation composition on C-fluxes - two aspects that are actually manageable at sites. Some caution should be taken when interpreting their annual sums of different component fluxes, as most are modelled based on point measurements throughout the year and in some cases models were used to extrapolate beyond the data range used to develop the empirical model! Lots of assumptions used in some cases.

Response: The authors agree that more cautionary notes should be given to exptratolating beyond data collection periods. For the specific assumptions that have been pointed out in the detailed comments, responses are below. The request for more statistical information on the models and the apparent need for a clearer description of the modeling process has been included in the main body of the manuscript as well as in the supplemental section.

Manuscript changes: More caution has been given to extrapolating the modelled CH_4 and CO_2 flux data beyond the data collection periods. The request for more statistical information on the models and the apparent need for a clearer description of the modeling process has been included in the main body of the manuscript as well as in the supplemental sections.

Detailed Comments: 1. This is a bit lengthy ms, but given it has a synthesis review, maybe ok for length. Journal can decide if to have it split into ms a and b or one ms when published. ALternatively there may be enough material here to write two separate more focused ms: one using actual observed data, focusing on observed trends and one on estimated/modelled trends in light of the global synthesis work.

Response: Agreed that the manuscript is too long, and some parts can be shortened, particularly the discussion section on comparisons to literature. It probably works better as one manuscript (if the Editor agrees).

Manuscript changes: As per comments from Reviewer 2, much of the global synthesis discussion has been cut from the text as the Figs. 11 and 12 can speak largely for themselves. Figures 11 and 12 have been moved to the results section. This keeps the discussion section more focused and shortens the manuscript as a whole.

2. Title may be worth modifying to include "implications for restoration efforts" in it - or something along the way. Also use of "restored and cutover" is a bit confusing. It sounds like both sites are undergoing restoration, just for different amounts of time. Perhaps reword to be more clear: "raised bogs at different stages of restoration".

Response: The cutover area is not really undergoing restoration as such. Thus, it doesn't make sense to include "*different stages of restoration*" in the title.

Manuscript changes: Title has been changed to: *Carbon balance of a restored and cutover raised bog: Implications for restoration and comparison to global trends*

3. Keywords: may be add DIC, DOC, global synthesis, carbon balance

Response: Good suggestions.

Manuscript changes: DIC, DOC and carbon balance has been added to the key words.

4. Abstract - you mention measuring along 5 different ecotypes, but only two are listed. Describe all 5 then. Also reword to include all 5 ecotype descriptions, avoid use of specific category name (ex. Sub-central) and just use general description in Abstract. Don't think that category name adds info for non-Irish readers or those unfamiliar with NPWS classifications.

Resonse: OK, this comment and comments 6 and 7 suggest that Reviewer 1 is getting confused on the site description. We agree that this needs to be clarified both in the abstract and the main body of the paper. However, the Reviewer is asking to include details of all five the ecotypes in the abstract, but then not to use the names. To fully describe the 5 different ecotypes, without using the names would be far to wordy for an abstract.

Manuscript changes: A much clearer and still concise description of the study site is included in the abstract. Names of specific ecotypes have been removed from the abstract. All of the ecotypes have not been described individually, but this general description has been included: "were measured for five distinct ecotypes ranging from those with high quality peat forming vegetation down to communities indicative of degraded, drained conditons." Also, a brief but clear description of the site has been added in the abstract.

5. line 105: unidentified acronym occurrence? NECB.

Response: OK

Manuscript changes: "net ecosystem carbon balance" (NECB) has been added to define the acronym.

6. lines 120-125. Objectives state two main research sites: 1960 cutover and 2009 cutover, but in Abstract and rest you discuss 5 sampling sites of different "eco-types".

Response: Yes, the description of sampling locations and study site needs to be clarified. Five ecotypes were located in areas with two different site histories.

Manuscript changes: A clearer description of the ecotypes and site history has been included in both the abstract and the main body of the text. The wording in the objectives was changed to "for five distinct peatland ecotypes, which are located in two adjacent areas with contrasting site histories."

7. lines 142-145: Again there seems to be a mismatch in site description - here you say two sites were uncut and three cut, but in objectives on lines 120-122 it seems to suggest both sites were cut, just one left to recover since 1960 and the other site only since 2009. So please clarify your site descriptions. May be clarify that you have two main research sites and 5 sub-sites within them and how they all differ with respect to their management history. Also add reference to table 1 early in this paragraph.

Response: Agreed, this can be clarified as per the above comments. The term *recently restored* is used in the last paragraph of the Introduction, this might imply that the bog had been harvested (and has now being restored) whereas it just been drained in preparation for being cut (but not actually harvested). The site history needs to be clarified earlier on.

Manuscript changes: See previous comments.

8. lines 164 - you had trees on your sites? please include % cover in Table one or description. How large are they on average and species type, stem density

Response: Yes, there were trees on the site as a whole. For example, the weir catchment area contained "lightly forested drains along a bog road (<10%)" Line 276. However, all of the ecotypes were treeless. Line 164 reads "open areas, excluding any large trees". In this case, "excluding any large trees" is a qualifier describing the open areas i.e. there were no trees at our monitoring sites.

Manuscript changes: "excluding any large trees" is changed to "excluding any trees"

9. LIne 167: collars were installed to represent ecolocigal variability - such as what?

Response: Again, it seems that the site description needs to be clearer in the manuscript. Within the ecotype definitions, there can be variability for the specific species coverage.

Manuscript changes: See above changes to line 7.

10. lines 211: which light levels, not clear? Please list PPDF under which measured. Where measurements corrected for PAR reduction due to chamber transmittance reduction?

Response: The light sensor was located inside of the chamber during measurements, so there was no need to correct for chamber transmittance as the light level was directly measured.

Manuscript changes: The phrases "generally under full ambient light, 1-2 light other partial shading light levels, and a completely shaded measurement" and "located inside the chamber" have been added to the manuscript.

11. NEE modelling, section 2.5: modelled NEE to account for diurnal variability - based on what? did you measure diurnal variability in data? Line 243: PPFD used from which chamber? or outside? lines 245 and Table S3: when reporting stats it is insufficient to just present R2 values. Show also n-values and estimated coefficients. Also describe how many data points were used to fit the model and how many to test/validate the model fit? Did you do that?

Response: The gross primary production (that is CO_2 uptake by photosynthesis) is the largest component of net ecosystem exchange. In practically every system, the gross primary production is strongly controlled by the light intensity, which obviously has diurnal variations. Thus, the hourly light intensity (measured in the field at the weather station) was input into models of NEE, which results in expected diurnal fluctuations of the modelled results. Measurement of light intensity is described in Lines 186–191 of the manuscript.

All of the field data was used to calibrate the models. Validation was not done explicitly.

Manuscript changes: Further, statistical information is included in Table S3. Supplemental section S1 has been revised to show a clearer description of the modeling process, including (among other things) a description of the number of data points used to fit the models.

12. Methane modelling: be very cautious in your "modelling" attempts and interpretations - you fit an empirical model to a small subset of observations and then attempt to use that to predict fluxes outside of the data range used to develop your empirical model. I don't think this is statistically sound, although I appreciate your attempt and sympathize with instrument malfunction. So highlight this limitation in your text and discussion. Line 265 - "collar average" probably should read "overall average from measurements at all collars".

Response: This is a good point. More cautionary notes should be included in describing the limitations of this data. All of the methane field measurements were used rather than "a small subset." "Collar average" is the correct terms here.

Manuscript changes: More cautionary notes have been included in describing this data throughout the manuscript.

13. Section 2.7, lines 278: - is that a valid assumption?

Response: This is a big assumption, that the aquatic carbon losses were the same for each of the ecotypes, but it is an assumption that we had to make due to resource limitation. (It would be an interesting topic for a future research project.) Many studies that have measured other aspects of the carbon balance have made bigger assumptions about the magnitude of the DOC losses. For example, Wilson et al., 2016b estimate DOC losses from a peatland "based on guidance provided by IPCC [report]" rather than field measurements. In this case, the DOC/DIC flux was at least measured directly on-site.

Manuscript changes: None.

14. Lines 307-312: you discuss CO_2 evasion from drainage ditches, what about openpond water on your bogs? Any present? what proportion? how much would the open ponds add to CO_2 efflux from open water?

Response: These are valid questions, but in this case, the only open water areas at the study site were associated with drainage ditches.

Manuscript changes: None.

15. Line 315: likely mean "DIC" instead of "DOC"?

Response: No, this is correct. Here the DOC flux is calculated differently for the carbon balance of the system, which includes all carbon losses from the catchment area and for the global warming potential, which is the greenhouse gas effect. This is because some of the DOC lost from the system may be stored in longer term sediment and not contribute to the GWP.

Manuscript changes: None.

16. LInes 321-322: Sentence makes no sense? what are you saying? "... from the sum of model error and error of input field variables"?

Response: This sentence is describing the model statistics.

Manuscript changes: This sentence has been re-worded for clarity. Also, partially because of this confusion expressed by the Reviewer here and partially because the modelling of ER was redone as per comments by Reviewer 2, the statistics have been redone using simpler and more straight forward methods.

17. Lines 338: report st.dev on mean annual total from Ballyroan.

Response: OK

Manuscript changes: These details have been added to the manuscript.

18. lines 340: 1978-2007 average taken from where? also report stdev on mean annual value.

Response: OK.

Manuscript changes: The mean annual temperature is changed to the 30 year average 1981-2010 based on Walsh, 2012 as per comments by reviewer 1. Walsh (2012) does not report the stdev so this is not included.

19. Figure 4: hard to tell two blue colours apart, likewise for yellow and orange. suggest to change.

Response: OK

Manuscript changes: The colors have been changed in Figure 4 to improve readability.

20. Figure 4 -7 - either show all modelled and observed fluxes like you do for CH4- fluxes in Figure 5a (IWOULD HIGHLY RECOMMEND, OTHERWISE YOU SHOWTOO MUCH MODELLED RESULTS but little observed values used to derive the modelled values!) or as monthly bar plots or cumulative plots like you do for terrestrial CO2- fluxes in Fig 4. This is also probably where you can reduce your figure numbers. Fig 5b probably belongs to Supplement where you describe your model fitting.

Response: Moving Fig. 5b to the supplemental section is a good suggestion. Otherwise, this comment is a little perplexing: on the one hand, Reviewer 1 mentions reducing the number of figures; on the other hand, Reviewer 1 asks for more figures showing modelled and measured results. As the GPP and ER were modelled separately for each of the 29 collars, it would be confusing/misleading to show the entire field dataset and modelled results in a single plot. The modelled and measured data is shown together here for one particular collar as an example. For all 29 collars, 77 such plots (3 for each collar) would be needed, which may be excessive even for the supplemental section (although if the Editor thinks this is valuable, these plots can be included). The r^2 values, although not statistically sufficient by themselves, demonstrate the modelled data correlation with field data in a much smaller format.

"like you do for CH4- fluxes" Showing all of the modelled and measured CH_4 flux data was possible because the field data from all collars was lumped together before modelling.

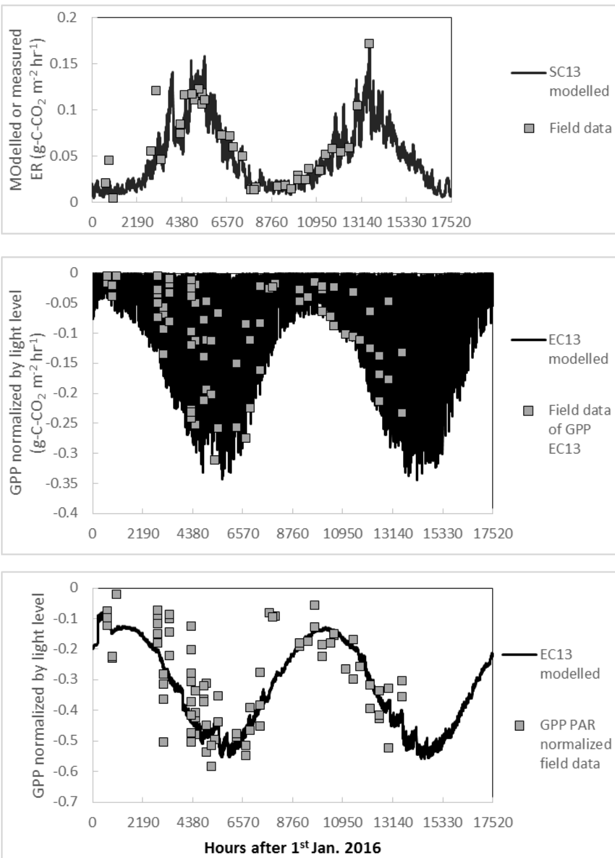

Figure caption. This figure shows the modelled and measured data for collar EC13 for ER (top), GPP (middle), and for clarity (because GPP drops to 0 every night with light level), GPP normalized by light level to show the seasonal fluctuations independent of light level (bottom).

Manuscript changes: Fig 5b has been moved to supplemental section. Otherwise, no changes has been made unless the Editor requests plots like the example above to be in the supplemental section.

21. Section 2.4 name - CO2-gas flux measurement, not GHG.
Response: Yes, that is better.

Manuscript changes: The section heading name changed to "CO_2 and C_{H4} gas flux measurements"

22. Aquatic carbon losses: Fig 7: how do you know point around 2 mg/L is an outlier for DIC to assume a constant flux throughout the year? Seems too few points to make such assumption.

Response: This is a fair point, but it is just an assumption and has a very minor effect on the overall results, as this is the smallest component of the C balance. Based on Dixon's Q test, this point can be excluded as an outlier to 95% confidence.

Manuscript changes: None.

23. Fig 8: what's WHB and EHB?

Response: These points need to be labeled on Fig.1

Manuscript changes: These points have been labeled on Fig.1

24. Section 3.4: not sufficient to report only p-values for statistical results, report also associated n used, mean and st.dev. Lines 404-406: was spatial variability accounted for in your analysis?

Response: OK, on the stats. It is not clear what is meant by spatial variability; this is exactly what is being described here i.e. difference between collars within the same ecotype.

Manuscript changes: Additional statistical information added throughout this section, where applicable. It is not always appropriate to include n, mean, and stdev for every statistical analysis.

25. Figure 9a: - units unclear gC-CO2? CO2-equivalent? so Fig a and b are the same, with a in g/m2/yr and b in tones/ha/yr? why include both?

Response: The carbon balance and the global warming potential (GWP) as shown in Fig. 9a and 9b, respectively, are fundamentally different quantities with correspondingly different units. Although the change in units may be confusing, the units chosen are standard units for reporting these types of measurements.

Manuscript changes: None.

26. line 416: "carbon flux" probably mean "CO2 flux", same comment on lines 424. lines 416-417: unclear - so you looked at environmental controls for each collar separately? why not together per eco-type?

Response: The phrase “carbon flux” is not used. The phrase “carbon balance” is the correct wording here and refers to multiple aspects of the carbon balance, including CO_2 flux. The data are presented together by ecotype in Fig. 4, Fig. 6, and Fig. 9. As data (flux & divers) is available in detail at each collar, there is no reason not to include these comparisons.

Manuscript changes: This section has been changed to describe the patterns in collar CO_2 flux instead of patterns in carbon balance data, to reduce confusion.

27. Section 3.5 - again stats should show n, mean, stdev together with p-value, else meaningless.

Response: This is a good suggestion.

Manuscript changes: The additional statistical information is included throughout this section.

28. lines 428-433: don't get this paragraph.

Response: The percent genus cover within the collars is compared to the GWP, C-balance, and CH_4 flux.

Manuscript changes: This paragraph is quite short and seems fairly clear. Updated statistical information has been included, which may help. Also, the updated version of Fig. 10, which is referenced in the paragraph, may help clarify.

29. Fig. 10: What if you colour points by ecotype? would be nice to see how they fit on the scatter, if group or not. in plots a and d - units are in gC, so does this C include CH4-carbon? Legend says data was averaged over 2 years - why? was there no interannual variability?

Response: Yes, good idea to colour by ecotype (and would also address comment 26 somewhat). Data was averaged over the two years for clarity in the plots because these plots are focused on spatial rather than temporal variability; the longest data set available was included. Yes, in the first draft of the manuscript the carbon balance includes all aspects of the carbon balance. However, a and d of this plot have been changed in the revised manuscript to include only CO_2 flux (NEE) only rather than carbon balance.

Manuscript changes: The collars were coded by ecotype as per the Reviewer's suggestion in this plot. Plots a and d of this figure 10 have been changed in the revised manuscript to include only CO2 flux (NEE) only rather than carbon balance.

30. Discussion: Lines 436-437: well, I would be cautious with such as statement, as nowhere in your paper do you present simultaneous measurements of all components of c-balance you meausured. If you do have observation days where you have all of the fluxes measured on the same day - those would be your key days to focus on and show when trying to figure-out contribution of each component flux to overall C-flux. Such comparison, even if only on few days would be more valuable than that gapfilled modelled comparisons to field-based research.

Response: This is a fair point with being cautious about this statement, as the word "simultaneously" is a little misleading. This line could be re-stated to be more precise. However, adding in description about specific days where all the fluxes were measured together with all of the other data (flows etc.) would probably not help the structure of the paper (and would make it a lot longer).

Manuscript changes: *The word "simultaneously" has been removed from this paragraph. Instead, this line has been changed to "*concurrently quantified annual fluxes of all major aspects of the C balance"

31. lines 449-452: so did Nilsson et al also take a single measurement in a year and assume DIC to be constant? If not, how many they took and how the differences in sampling between their study and yours impacts the results. Think of n-sampled.

Response: Agreed that more discussion is needed on the causes of differences between studies although it is unlikely that the differences observed are due primarily to the number of samples.

Manuscript changes: Further discussion is included on the differences between these study sites and results. See also to response to comment 32 below.

32. LInes 458: lower than Dinsmore and Nilson by how much? make it easy on the reader, so less likely to flip back and forth. show both values or state % difference.

Response: Yes, this paragraph is a bit burdensome with a lot of data comparisons. The comparison between studies has been put into tablular format to be easier to read format. Then, this paragraph can be focused more on the differences in methods, etc. causing the variation in results (Partially, addressing Comment 31).

Manuscript changes: A table of the various components of the carbon balance from these other two studies is included in Section 4.1 (now section 4.2 in the revised manuscript). This paragraph is also substantially shorter than previously.

33. SECTION 4.2 - I THINK THIS BELONGS TO RESULTS - this section should be split with synthesis plots shown in results and their discussion left in Discussion. ALso how data was collected and filtered should be in methods.

Response: That is a good suggestion and agrees with Reviewer 2.

Manuscript changes: The figures 11 and 12 have been moved to the results section and relevant pieces have been moved to the methods section or kept in the discussion. On the whole, the discussion section has been shortened and re-written for clarity, as per response to Reviewer 2.

34. lines 532: how dry is "too dry"? also Briones et al reference is missing.

Response: The reader can go to the relevant reference if interested in this question*: Briones, M. J., McNamara, N. P., Poskitt, J., Crow, S., and Ostle. N. J. Interactive biotic and abiotic regulators of soil carbon cycling: evidence from controlled climate experiments on peatland and boreal soils. Global Change Biology, doi: 10.1111/gcb.12585, 2014.*

Manuscript changes: This line has actually been removed from the manuscript. This line was deemed to be an unnecessary tangent. As this is the only line that references Briones et al., 2014, the reference was not included in the reference list.

35. Fig. 11 - add lines to legend

Response: OK

Manuscript changes: Lines were added to the legend in Fig. 11.

36. lines 568-574 discussion - so how many points were from EC-derived NEE and how many from chamber derived-NEE? how do they fit on your Fig 11/12. Is there a difference between the two? (ex. one method consistently lower, but trends same, or one falls on one end of trend and the other at the other end?

Response: The primary difference between the use of these two methods is for the land use type as described in the text. The curious reader can pull out this information in the Supplemental tables, but this plot with numerous symbols already, may become overcrowed with this information.

Manuscript changes: None.

37. line 577: "inter" probably should read "winter"

Response: Yes.

Manuscript changes: “inter” changed to “winter”

38. Fig 12: you specify your data points with numbers 1-5. I assume that relates to your ecotypes - so which is which? add to fig description.

Response: Yes, this needs to be added.

Manuscript changes: The numbers 1- 5 have been specified in the figure caption.

39. Lines 606: "managing water table" - that’s repeat of point 1).

Response: That is a fair point.

Manuscript changes: The words “managing water table” were deleted from line 606.

40. line 608: "... the impact of these things must be considered." which things? and their impact on what?

Response: Yes, this line is "vague" as per Reviewer 2, and can be clarified.

Manuscript changes: This line has been changed to "the impact of these actions on C balance, CH_4 flux, and GWP must be considered"

41. Lines 621-624, follow discussion about impact of Sphagnum presence on GWP. So what has the study of Junkurst and Fielder to do with Spagphum-GWP?

Response: OK, further discussion can be included on the Sphagnum effect on GWP. Junkurst and Fielder is a little off topic here. This reference may be removed.

Manuscript changes: As per above responses the entire discussion section has been streamlined and clarified. These particular line referring to Junkurst and Fielder have been removed.

42: Lines 628-635 - unclear what you're trying to say. Are you attempting to say that peatlands lifespan is more than 100 years, so their assessment should be based on longer time scales? So how long?

Response: This sentence needs to be clarified, but is important. Peatland **preservation** is beneficial (in terms of greenhouse gasses) despite methane emissions because of long term sequestration and storage of carbon out balances methane emissions. However, for peatland **restoration,** the greenhouse gas impact depends on the time scale that restoration works effect the eco-hydrological trajectory. For example, if restoration works only impact the short term (decadal) eco-hydrological trajectory, then methane emissions may be proportionally more important to consider for the overall greenhouse gas budget.

Manuscript changes: These lines have been clarified.

43. Lines 649: what's Marginal and Facebank ecotype? references?

Response: Yes, this is unclear.

Manuscript changes: These lines were ultimately removed from the manuscript along with the undefined and Irish specific terms "facebank" and "marginal". These lines were removed simply to shorten and streamline the discussion section as they were not central to the overall points of the discussions section.

S1. GPPmax is assumed constant throughout what? which metrics from Wilson et al 2007 where used? how many data points were used for model development at each point? why biological zero is assumed at 0C? what reference you have for this? Label your equations consequitively and consistently. SHow your model comparisons, how good each fit is. Why model fit to all collars - so did you check they all behave the same? where are the results?

Response: Section S1 describes the modelling process. The number of questions surrounding this section suggests that this entire section could be clarified. Yes, some assumptions were made. However, not too many major assumptions were made because several different empirical models were fit to the field data and then compared. The actual biological zero has a minor impact on the model results. An exponential increase with temperature is quite common to be applied in biological systems at the temperature ranges of the Irish climate. *Why model fit to all collars - so did you check they all behave the same?* Quite the opposite, I did not assume that all collars behave the same way because of ecological and hydrological differences between collars. Thus, empirical models were fit to the field CO_2 flux data from each of the 29 collars individually.

Manuscript changes: This section has been re-written and clarified. *where are the results?* See response to Comment 20. More field data could be included at the Editor's request as described above.

S2. Equation S10 - which one is that?

Response: This section has been re-written and clarified as per above comment.

Manuscript changes: As above.

S3. Tables S1 and S2 - kind of useless statistically. Please add estimated parameter coefficient's stats - p and t-values, also model stats such as R2, n-observations.

Response: That is fine.

Manuscript changes: More statistical information has been included in these tables.

S3. Table S3: p-values? n? F-stats? data ranges used to fit model? all needed to make sense of reported R2.

Response: That is a good suggestion.

Manuscript changes: More statistical information has been included in Table S3.

S4. methane modelling - what worries me most. you fit an empirical model to limited data range and then use that to extrapolate beyond that data range. Don't think that's good statistical practice. Be cautious of such things. If there's a physiologically based model to work with - try that instead. Was effect of Temp similar to that of ER - show? "Temporal variation in fluxes was extrapolated in this model" - what are you trying to say?

Response: This is a good point that more caution needs to be added around the model results. Though, perhaps the purpose of modelling methane fluxes for this study needs to be clarified a bit more in the paper. The purpose of this model was not to predict the methane flux at a particular point in time. Rather, the purpose of this model was to estimate annual methane fluxes. Essentially the average methane flux at each collar was scaled by a factor to account for the fact that the field data was not collected over the entire year. The model was used to predict that factor. Further, the major hole in this data is that methane measurements were only collected during one of 2 years. This limitation in the data **needs** to be highlighted more explicitly in the manuscript. The assumption that the methane flux was the same is partially verified by the fact that the model gave very similar results for both years. This is the other purpose of this model.

"limited data range" This phrase is used several times by the Reviewer; I am not entirely sure of the meaning. If the Reviewer is referring to a limited data **collection period**, than this is a fair comment. However, if the Reviewer is referring to a limited **data range**, than, it seems that the reviewer is mistaken. The modelled results were not extended beyond the data range.

I am not aware of an appropriate physiologically based model to use in this case because methane fluxes from peatlands can be highly variable both within and between sites.

"Temporal variation in fluxes was extrapolated in this model" Yes, this needs to be clarified.

Manuscript changes: More caution needs to be applied when presenting methane modelling results, particularly for 2016 when no field data was collected. Also, the purpose methane modeling has been clarified in the manuscript.

Also was there any model validation done for any of your modelling activities?

Response: No, in this case, all of the field data was used in calibrating the models.

Manuscript changes: None.

Reviewer 2:

General Comments:

General comments: The manuscript reports the results from a two year study at two peatlands in Ireland: an abandoned (but not rewetted) and a rewetted peatland. In both sites, a full carbon balance (CO_2, CH_4, DOC and DIC) was measured and calculated. The authors indicate that the abandoned site was a strong annual carbon source and that the rewetted site was a small carbon sink. The authors also compare their results with literature values (a very nice literature review is included in the Supplementary material). The manuscript is well written (although it would benefit from a spell-check and does feel a little long), tightly focused (except Discussion) and the results are clear. However, the Discussion section is disjointed and requires some surgery, and I also have some concerns in regard to the models used but this may just need clarification by the authors rather than any major reconstruction.

Response:

The Reviewer comments that the paper is a "little long" and the Discussion section is "disjointed and requires some surgery." I agree with this comment in general. After a fresh read-through, I think that the discussion section gets a little off topic from the study results by including lengthy discussions of data from literature. The comparison to literature data is valuable, including Figures 11 and 12 and the extensive tables of literature data in the Supplemental Section 3. However, the discussion text surrounding these figures can be greatly shortened, while the figures would remain understandable and useful. After some major revisions, the discussion section has been shortened from 3013 words to 1975 words in length and we feel that is much clearer and to the point. The overall important points of the discussion section have remained largely the same; the text has been clarified, shortened, and restructured.

Further, the Reviewer comments, "I also have some concerns in regard to the models used but this may just need clarification by the authors rather than any major reconstruction." The only "concern" raised explicitly is the number of fitting parameters (an in comment below on Tables S1 and S2) and for "clarification," the Reviewer requests that the SE of model fitting parameters be included. Additional statistical information on the modelling has been included in the Tables S1 and S2. The Reviewer raises a valid point; the ecosystem respiration model, in particular, arguably had too many empirical fitting parameters. This model was replaced by a simpler model with fewer fitting parameters, as described in more detail in the response to the comment on Table S1 and S2.

Manuscript changes:

The discussion section has been shortened and streamlined by cutting out much of the text describing the comparison to literature. The Figures 11 and 12 has been left in the body of the text, but moved to the results (as in comment on Section 4.2, below).

The model used for ecosystem respiration has been redone using a simpler model, which was taken directly from Wilson et al., 2016a.

Specific comments:

L2 "Add C after carbon and use thereafter in abstract" "Add methane before (CH4)" "Not necessary to add "losses""

Response: These are good suggestions.

Manuscript changes: The recommended changes have been made in the manuscript abstract.

L4 Harvested suggests a renewable fuel source. Peat removal for fuel is anything but sustainable. Please replace harvesting here (and throughout the manuscript) with either "extraction" or "mining".

Response: OK, yes, this is a good suggestion.

Manuscript changes: The term “harvested” has been changed to “mined” in the manuscript when in reference to peatlands impacted by peat extraction.

L5 Please define what you mean by “historically abandoned”

Response: OK, this is potentially confusing.

Manuscript changes: “historically” has been changed to “a*bandoned x years ago”*

L6/7 What do you mean by “high quality”?

Response: That is a good question; high quality is referring to the site most similar to the ecology and hydrology of undisturbed open raised bog habitat in Ireland.

Manuscript changes: As per Reviewer 1’s comments, the site description has been clarified in the abstract.

L7 Calluna vulgaris

Response: The *Calluna vulgaris* refers to a species of plant. In the manuscript the Calluna Cutover refers to specific ecotype.

Manuscript changes: The named of specific ecotypes have been removed from the abstract to reduce confusion, as per Comment 1 from Reviewer 1.

L14 Why upper cases for Temperate and Boreal?

Response: Indeed.

Manuscript changes: Temperate and boreal has been changed to lower case throughout the manuscript where appropriate.

L15 “: : :in this study and was: : :”

Response: Ahh, there is an extra word in this line.

Manuscript changes: The word “was” has been removed from this line.

L18 Add C after carbon and use thereafter in the manuscript

Response: Agreed.

Manuscript changes: The suggested change has been applied to the manuscript.

L26 95% is very high – 80 to 85% is generally cited

95% refers to the percent of raised bogs that have been degraded in Ireland rather than the total amount of peatlands, this has been clarified in the manuscript.

L31 Throughout the manuscript, you use intact, natural, near-natural and pristine interchangeably

- please select one and keep to it.

Response: This is a good suggestion.

Manuscript changes: The term “intact” has been used in reference to peatlands which have not been mined or drained. The term “natural” has been used in reference to those peatlands which are not actively being used for agriculture, intensive grazing, mining, forestry, etc.

L54 Consider Fritz et al. (2011) New Phytologist. 190, 398-408.

Response: I was not aware of this publication. The findings from this publication are somewhat contradictory with this line of the introduction.

Manuscript changes: This line has been changed to include the findings from Fitz et al., 2011.

L75 Please use primary source as reference; Myhre et al (2013) Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

Response: Yes, good point.

Manuscript changes: The suggested primary reference is used

L77 I would not be inclined to use specific data here; why Helfter et al. and not McVeigh et al. for instance?

Response: Including specific data here is helpful for putting the present work in context. Helftler et al. is used as a source because they include a table of reported literature values.

Manuscript changes: The use of this source is clarified by adding “literature compilation from Helftler…”

L78 The CH4 values derived by Wilson et al (2016) include rewetted sites, so are not suitable here, however there are lots of CH4 studies you could cite instead, e.g. Laine et al. (2007) Plant and Soil. 299, 181-193; Green and Baird (2017) Mires and Peat. 19, Article 09.

Reponse: That is a good point.

Manuscript changes: The value of CH4 emissions for intact peatlands in this line of the introduction has been removed based on comments on L77 and L78. Assigning a typical CH4 flux value may not be helpful in this line of the introduction because of the high variability reported in literature.

L82 Change methane to CH4; L90 Change methane to CH4

Response: OK

Manuscript changes: The use of “methane” has been replaced by the chemical symbol throughout the manuscript after initially defining it.

L89 Bain et al (2011) is not in reference list

Response: OK

Manuscript changes: This citation has been added to the reference list.

L101 Consider Barry et al. (2016) Aquatic Sciences. 78, 541-560

Response: OK

Maunscript changes: This article has been added as a reference here.

L109 “recovering” is a new term to me. Do you mean rehabilitated?

Response: Recovering means bogs which have had no definite action taken to rehabilitate them. They have just stopped being mined and left. So, the term “rehabilitated” is not correct.

Manuscript changes: In this line “abandoned” has been used in place of “recovering”. In the manuscript, this term has now been defined here as the “spontaneous revegetation of mined peatlands” (From Poulin et al., 2005), which have had no definite action taken to rehabilitate them.

L129 What do you mean by “natural peatland area”? The site is obviously not natural and the surrounding landscape is mainly grassland and some forestry. Delete.

Response: OK, The site is a natural area with a variety of plant communities some of which is peatland in various degrees of degradation.

Manuscript changes: The wording has been changed from “natural peatland area” to “peatland and natural area”.

L130 See earlier comment regarding harvesting.

Response: As in above comment.

Manuscript changes: As in above comment.

L132 Met station location? 1980-2010?

Response: Ok, this could be clarified.

Manuscript changes: The 30 year average (1981-2010) meteorological mean annual rainfall and temp from (Walsh, 2012). Have been used in the site description instead of the shorter period of record from nearby weather stations.

L134 1980s; L140 1970s and 1960s

Response: OK

Manuscript changes: The apostrophe has been removed from all decade numbers.

Fig. 1 The quality of Fig. 1 is poor, although this might be due to the pdf. The legend on the elevation map is hard to determine.

Response: Noted.

Manuscript changes: A higher resolution figure has been used for the final submission.

Table 1. Check font sizes and spelling of Sphagnum and Eriophorum

Response: OK, good catch.

Manuscript changes: These typo mistakes have been corrected.

L188 Where was the sensor located?

Response: Sensor was located inside of the chamber.

Manuscript changes: This detail is added to the manuscript.

L196 Stainless steel collars – as written it appears as if you only had one

Response: Agreed.

Manuscript changes: “collars” instead of “collar” The word was pluralized.

L197 Where was the water trough located?

Response: Along the top edge.

Manuscript changes: Added “along the top edge” to this sentence

L198 What does “constructed in house: : :” mean?

Response: This phrase means that the chambers were built by the authors and department technicians.

Manuscript changes: The phrase “in house” was changed to “in-house” as it should be.

L207 and area, volume of collar/chamber?

Response: The dimensions of the chamber are given above in line 198, but the area and volume can be stated more explicitly.

Manuscript changes: This information has been added to the manuscript.

L208 A constant temperature or a temperature similar to ambient temperature? The former could be 50C for example and fit your criteria but would be meaningless for gas flux calculations and subsequent modelling.

Response: Reviewer 2 seems to have mis-understood the meaning of this sentence. The temperature was kept constant over the chamber closure equal to the initial ambient temperature.

Manuscript changes: The phrase "over the chamber closure time" was added to the sentence as a clarifier.

L213 State flux sign convention used in this study.

Response: Yes, that needs to be included.

Manuscript changes: The following sentence was added after line 213 "For this study, a positive sign convention is indicates a net loss of carbon from the peatland."

L214 describe criteria used for quality checking.

Response: This data was quality checked to ensure that the change in CO_2 concentration over the chamber closure was monotonic, and physical parameters such as temperature and PPFD did not change substantially over the closure.

Manuscript changes: The following sentence describing quality checkin criteria was added to the manuscript: "…quality checked to ensure that the change in CO_2 concentration over the chamber closure was monotonic and that the PPFD did not change by more than 50 μmol m^{-2} s^{-1} over the chamber closure."

L212 How many samples?

Response: "…generally under full ambient light, 1-2 light other partial shading light levels, and a completely shaded measurement."

Manuscript changes: The sentence in the response was added to the manuscript.

L259-260 CH4 fluxes have a strong diurnal variability in some plant types.

Response: The data from Pypker et al., 2013 supports the claim of a low diurnal variability in CH_4 flux compared to CO_2 flux for bog species. This line (259-260) was removed because it does not seem necessary here. The point is that CH_4 measurements taken during the daytime only were used to represent the overall CH_4 fluxes. By contrast, the CO_2 flux is strongly controlled by light level and thus had to be modelled on a shorter (hourly) time step because light level is obviously changing throughout the day.

Manuscript changes: The first sentence of section 2.6 (Line 259-260) was removed because it is not really necessary for the method description.

L337 Unusual long-term dates; 1980-2010 more usual.

Response: This is the data range available at the nearby weather station.

Manuscript changes: The data used for annual rainfall comparisons to study period was from the Ballyroan (oatlands) Met Éirrean daily rainfall station with a period of record from 2001 to present. The average annual temperature value was changed in the manuscript to the 1980 to 2010 average temperature based on Walsh (2012).

Fig. 2b Degree symbol missing on y axis.

Response: Good catch.

Manuscript changes: The suggested changes are made to the figure.

Fig 5b The use of a 1:1 line would provide better information as to the performance of the model

Response: That is a good idea.

Manuscript changes: The suggested changes are made to the figure.

Figs. 4,6, 9 and 10 Check spelling of plant names.

Response: OK

Manuscript changes: Plant name spelling mistakes are corrected in the figures.

Section 3.4 Only use “significant” when related to statistical comparisons.

Response: Yes, that is already the case. Every instance of the word “significant” in the manuscript refers to statistical comparisons.

Manuscript changes: None in response to this comment but more statistical information is included in the text in line with Reviewer 1’s comments. This makes the use of the term significant is clearer.

L407 GWP

Response: Yes, Good catch.

Manuscript changes: One instance of “GPW” changed to “GWP.”

L407 tonnes (and thereafter)

Response: Yes, Good catch.

Manuscript changes: Two instances of “tons” changed to “tonnes” in the manuscript.

Fig. 10 Given that MAWT is used as a predictor variable in the models, these observations are not independent (especially as the collars were lumped together for modelling) and I am far from convinced as to their value in this manuscript.

Response: Hourly water table (as opposed to MAWT) data was used as a parameter in modelling NEE, but not CH_4 flux. The NEE was modelled using collar specific empirical models fit to field data, and water table had a minor impact on the overall modelled results. Thus, the changes in hourly water table help explain the variability in NEE but do not strongly control the modelled annual NEE. I argue that these are independent variables and the trends in these plots are useful results for comparing with other studies.

Manuscript changes: The plots in figure 10 were changed to include different symbols for the five ecotypes (as per comment by Reviewer 1), which improves the value of this figure in the manuscript.

L436 Consider Nugent et al (2018) Global Change Biology, https://doi.org/10.1111/gcb.14449

Response: This study was not published at the time of initial submission, but is very relevant.

Manuscript changes: This suggested publication has been included and cited in section 4.1.

L477 1960s

Response: OK

Manuscript changes: “1960’s” changes to “1960s” as per previous comment

L484/485 join the sentences

Response: Yes, this should be one sentence.

Manuscript changes: Line 484/485 have been joined as one sentence.

L490 five decades
Response: OK

Manuscript changes: “5 decades” changed to “five decades”

Section 4.2 I am not sure of the value of this section. The manuscript is already quite long and this seems superfluous (especially given the extensive data set in the Supplementary). If it really must be kept, then it should be moved to the Results section and then discussed here.

Response: After re-reading the manuscript, I agree that much of this discussion is unnecessary and a little off topic for the main findings of the paper. However, the literature comparisons in fig 11 and 12 are valuable as are the extensive data sets behind them included in the supplementary section. This information puts the study in a broader context.

Manuscript changes: Figure 11 and Figure 12 have been moved to the results section, and the discussion in section 4.2 has been substantially shortened.

L515 Natural or semi-natural = intact?
Response: See response to comment on Line 31, above.

Manuscript changes: As per above comment.

L539 What does “Restoration of high quality peatland ecology” mean?
Response: I can see how this is a bit confusing.

Manuscript changes: This “high quality” has been changed to “Sphagnum dominated.” Though, much of this section has been re-written.

L576 Not so: In Saarnio (2007) Boreal Environment Research. 12, 101-113, 15% of growing season flux is emitted in the non-growing season. This approach was also used by IPCC Wetlands Supplement (2014)

Response: That is a good point.

Manuscript changes: The results reported in figure 11 and 12 remain the same, but a cautionary note has been included on the comparison between growing season and year round data, including reference to Saarnio (2007).

L577 What is “inter flux”?
Response: A typo: winter flux

Manuscript changes: This has been changed in the manuscript.

L608/609 “The impact of these things..” is very vague.

Response: Yes, this line is “vague” and can be clarified.

Manuscript changes: This line has been changed to “the impact of these actions on C balance, CH_4 flux , and GWP must be considered”

L628 and also due the pulse effect.
Response: This comment does not seem match the text in this line.

Manuscript changes: No changes.

L630 Why not quote Frolking directly?
Response: Yes, that is a good point. I like how it is phrased by Evans et al.

Manuscript changes: The quote from Evans et al., is left in the text but this line has been shortened to exclude 'to quote from Evans et al. (2016), "as noted by Frolking et al. (2006),"' The quotation marks remain to indicate a direct quote and both citations are listed as references.

Conclusion This reads as a summary not as a conclusion; what does your study mean for land managers, policy makers etc?

Response: That is good advice.

Manuscript changes: The conclusion has been re-written to focus less on summary and more on important findings form this work.

L668 "best models" = the ones you used?
Response: Yes.

Manuscript changes: The wording "best models" has been changed in this line to "the models used."

Supplementary: Check spellings throughout

Response: OK

Manuscript changes: Section S1 has been re-worked and edited in response to both Reviewers' comments as there seems to be some confusion from both Reviewers. The supplemental section previously read as a prosaic exposition of the various models tested as part of this work. It has been changed to simply give detailed information on the models used, and other models tested are listed in a table.

Tables S1 and S2 Please provide the standard error (SE) associated with each parameter estimate. Given the large number of parameters in the models, I would suspect that the SE has been very high and would invalidate your approach.

Response: Including the SE of the model parameters was also suggested by Reviewer 1. That has been included in these tables.

Yes, there are a large number of fitting parameters. The same GPP and ER models were used for all 29 collars, but the model fit parameters were determined empirically for each of the collars individually. For the GPP modeling, there was sufficient field data to justify a model with 5 empirical fitting parameters. For the majority of the collars, all of the GPP model fit parameters are significant to 95% confidence. This model was designed in such a way that the effect of modelled parameters reduces to zero as the explanatory value of the additional variables decreases such that insignificant model parameters have a minor impact on the modelled results. For the ER modeling, the sample size is smaller and the point that Reviewer 2 is making is quite valid. There had been some debate among the authors as to which of two models to use for ER, so much so, that information was included on both of these models in the supplemental section in the original manuscript draft. Thus, the simpler ER model (with 3 fitting parameters compared to 5 fitting parameters) has been used to calculate ER in the updated manuscript.

Manuscript changes: Additional statistical information has been included in the table S1 and S2 of the model fit parameters. The ER has been calculated by a different and simpler model in the revised manuscript, which had been previously described in the supplemental section but not used in the manuscript and was taken directly from Wilson et al., 2016. Also, the text of this supplemental section has been substantially revised to clarify confusion expressed by both Reviewers.

List of Major Changes to Manuscript:

1. The ER was modelled using a simpler model with fewer fitting parameters based on the suggestion of Reviewer 2. This resulted in minor changes in the reported NEE. However, the major conclusions of the paper remained unchanged. All NEE, C balance, and GWP data was updated based on this different modelling approach.
2. The process for modelling for NEE and CH4 flux was clarified in the main body of the text and in Supplemental Section 1, based on the Reviewers comments. Further statistical information was included in the Supplemental material for the models used.
3. Cautionary notes were included for CH_4 data in 2016, which was estimated rather than measured because of equipment issues, based on suggestions from Reviewer 1.
4. The site description including site history and ecotype description was clarified in the manuscript based on comments from both Reviewers.
5. Although the main points in the discussion section remain largely unchanged, the discussion section was re-written to be much more concise and clear based on comments from both Reviewers.
6. The abstract and conclusion sections were overhauled based on comments from both Reviewers.

Revised Manuscript with track changes

Title Page

Title: Carbon balance of a restored and cutover raised bog: Implications for restoration and comparison~~Comparison~~ to global trends

Running Head: C BALANCE Of A RESTORED AND CUTOVER BOG

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Key Words: carbon dioxide, peatland restoration, methane, global warming potential, bogs, DIC, DOC, carbon balance

Paper Type: Primary Research

Abstract

The net ecosystem exchange (NEE) and methane (CH_4) flux were measured by chamber measurements for five distinct ecotypes (areas with unique eco-hydrological characteristics) at Abbeyleix Bog in the Irish midlands over a two year period. The ecotypes ranged from those with high quality peat forming vegetation to communities indicative of degraded, drained conditions. Three of these ecotypes were located in an area where peat was extracted by hand and then abandoned and left to revegetate naturally at least 50 years prior to the start of the study. Two of the ecotypes were located on an adjacent raised bog, which although never mined for peat, was impacted by shallow drainage and then restored (by drain blocking) 6 years prior to the start of the study. Other~~All~~ major aspects of the carbon (C) balance, including ~~— net ecosystem exchange (NEE),~~ ~~CH_4 flux, losses of~~ dissolved organic carbon (DOC), ~~) and~~ dissolved inorganic carbon (DIC), and open water CO_2 evasion, ~~—~~ were quantified~~measured~~ for ~~several distinct ecotypes in~~ a catchment area at the study site~~restored unharvested raised bog and an adjacent historically abandoned cutover bog~~ over the same~~a~~ two year period. The ecotype average annual ecotype C~~carbon~~ balance ranged from a net C~~at the Sub-Central ecotype, with eco-hydrological characteristics most similar to a high quality raised bog, was the largest net carbon~~ sink of -~~32~~ 58 ±60~~65~~ g C m^{-2} yr^{-1}, comparable to studies of intact peatlands, to ~~-while the Calluna Cutover ecotype, with the characteristics of~~ a substantial C~~well-drained peatland site was the largest net carbon~~ source of ~~+239~~ 205 ±80~~3~~ g C m^{-2} yr^{-1}, with NEE being the most variable component of the C~~. The annual carbon~~ balance between the five ecotypes. Ecotype annual CH_4 flux was ranged from 2.7 ±1.4 g C-CH_4 m^{-2} yr^{-1} to 14.2 ±4.8 g C-CH_4 m^{-2} yr^{-1}. Average annual aquatic C losses were 14.4 g C m^{-2} yr^{-1} with DOC , DIC, and CO_2 evasion of 10.4 g C m^{-2} yr^{-1}, 1.3 g C m^{-2} yr^{-1}, and 2.7 g C m^{-2} yr^{-1}, respectively. A statistically significant negative correlation~~from all ecotype study locations~~ was found between the ~~to be controlled by~~ mean annual

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water table (MAWT) and the plot scale NEE but not the global warming potential (GWP). However, a)~~. Also,~~ significant negative correlation was observed between the plot scale ~~global warming potential and~~ percent *Sphagnum* moss cover and the GWP, highlighting the importance of regenerating this keystone genus as a climate change mitigation strategy in peatland restoration. The data from this study was then compared to the rapidly growing number of peatland C~~carbon~~ balance studies across boreal~~Boreal~~ and temperate~~Temperate~~ regions. The trend in NEE and CH_4 flux with respect to MAWT was compared for the five ecotypes in this study ~~was~~ and literature data from degraded/restored/recovering peatlands, intact peatlands, and bare peat sites.

1. Introduction

Peatlands are important to the global carbon cycle as they act as ~~significant~~ important stores of carbon (C) and sources or sinks of carbon dioxide (CO_2) and methane (CH_4) (Gorham 1991). Despite covering only ~3% of the earth's terrestrial surface, it is estimated that between 500 and 700 billion tonnes of C are stored as organic soil within the global peatland expanse (Leifeld and Menichetti, 2018; Paige and Baird, 2016; Yu et al., 2010~~; Paige and Baird, 2016; Leifeld and Menichetti. 2018~~). However, at present, human activity is either draining or mining ~10% of global peatlands, transforming them from long-term C sinks into sources (Joosten, 2010; Leifeld and Menichetti~~.~~, 2018). In Europe, a high percentage (~46%) of the remaining peatlands are degraded to the point whereby peat is no longer actively being formed (Tanneberger et ~~al.~~ al., 2017), and in Ireland whilst ~20% of the land area is peatland, over 95% of ~~it~~ raised bogs has been degraded through anthropogenic activities such as drainage for agriculture, forestry and peat extraction (Connolly and Holden, ~~2009~~2017; Connolly and Holden, ~~2017~~2009).

The C~~carbon~~ cycle and greenhouse gas (GHG) dynamics of degraded peatlands are~~is~~ often substantially different compared to intact~~pristine~~ peatlands (Baird et al., 2009; Blodau, 2002~~; Baird et al., 2009~~) making them significant with respect to national and global GHG budgets and emission reporting (Billet et al., 2010; Wilson et~~ al.~~ al., 2013~~; Billet et al. 2010~~). Moreover, degraded peatlands can continue to emit C for decades to centuries following drainage, and current estimates are that degraded peatlands store globally ~80.8 Gt soil C and emit ~1.91 (0.31–3.38) Gt CO_2-eq. yr^{-1} (Leifeld and Menichetti~~.~~, 2018). Soil C~~carbon~~ sequestration through peatland restoration is increasingly recognized as an important strategy to tackle climate change (Dise, 2009; Leifeld and Menichetti,~~.~~ 2018), and in recent years there has been a substantial increase in money being invested in peatland projects across the world (Anderson et al., 2017). With the increase in global active peatland management, there is a need for more studies examining how drainage and restoration alters the eco-hydrology of degraded peatlands systems and their C~~carbon~~ balances (Baird et al., 2009; Young et al., 2017).

The land atmosphere CO_2 flux, or net ecosystem exchange (NEE) in peatlands is related to water table level, as inundation creates anaerobic conditions which suppresses the decomposition of soil organic matter (Lain et al., 1996). ~~This~~ High water table can result in a net CO_2 sink (negative NEE) whereas a low water table can result in a net CO_2 source (positive NEE). Thus, water table has been correlated to spatial (~~(Strack et al., 2014;~~ Junkurst and Fielder, 2007; Silvola et al., 1996; Strack et al., 2014) and temporal (Helftler et al., 2015; Lund et al., 2012; McVeigh et~~ al.~~ al., 2014; Peichl et al., 2014; ~~Lund et al., 2012;~~ Strachan et al., 2016~~; Helftler et al., 2015~~) variation in the NEE of both intact and degraded peatlands. However, anaerobic conditions due to a high water table can also increase the land atmosphere CH_4 flux (Frenzel and Karofeld, 2000). Both NEE and CH_4 flux are also

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affected by plant ecology, as the extent of aerenchymatous vegetation cover such as *Eriophorum spp.* is correlated with increased CH_4 flux (Cooper et~~ al.~~ al., 2014; Frenzel and Karofeld, 2000~~,~~; Gray et al., 2013; McNamera et al., 2008; Waddington and Day, 2007~~, McNamera et al. 2008, Gray et al. 2013~~), although this effect can possibly be reversed if aerenchymatous vegetation aerates the saturated soil (Fritz et al., 2011). *Sphagnum spp.*, however, often exhibit lower CH_4 fluxes (Frenzel and Rudolph et~~ al.~~ al., 1998) due to a symbiotic relationship with methanotrophic bacteria (Raghoebarsing et~~ al.~~ al., 2005). Also, *Sphagnum spp.* coverage may correspond to an increase in the CO_2 sink function of "natural" sites (Strack et~~ al.~~ al., 2016) as much of the peat in northern peatlands is derived from this genus (Bacon et al., 2017; Vitt et al., 2000~~, Bacon et al., 2017~~). Furthermore, the extent of vegetation cover is an important factor affecting the NEE (Strack et al., 2016; Tuitili et al., 1999; Waddington and Day, 2010~~; Tuitili et al., 1999, Strack et al., 2016~~). This is relevant to degraded and restored peatlands because mined~~harvested~~ peatlands can have large areas of bare peat (Wilson et al., 2015).

Climatic variables such as the frequency of cloudiness, temperature, and length of growing season have also been found to be important controlling factors of NEE (Charman et al., 2013; ; Helftler et al., 2015; McVeigh et al., 2014; Zhaojun et al., 2011~~; McVeigh et al., 2014; Helftler et al., 2015~~). However, climate variables cannot be controlled at a specific site, and therefore, may not be as relevant when considering climate change mitigation actions.

Although N_2O emissions can be an important aspect of the GHG emissions from organic soils (Pärn et~~ al.~~ al., 2018), this study focuses only on aspects of the C~~carbon~~ balance. In low nutrient, non-agricultural,~~semi-natural~~ sites like in this study, N_2O emissions are typically low (Haddaway et al.,

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2014) but can be higher for deeply drained (Vanselow-Algan et al., 2015) or high nutrient sites (Danevčič et al., 2010). The radiative impact of different GHGs can be normalized by converting them into a CO_2 equivalents in terms of the 100-year global warming potential (GWP) in tonnes CO_2-eq ha^{-1} yr^{-1}: over a hundred year horizon, CO_2 = 1, CH_4 = 34, and N_2O = 298, ~~(~~after ~~Wilson et al., 2016b from~~ IPCC 2013 recommendations (Myhre and Shindell, 2013~~2014~~).

Intact peatlands are a net CO_2 sink [typical annual average NEE range -31.9 to -66 g C-CO_2 m^{-2} yr^{-1}, from literature data compiled by Helftler et ~~al., (~~al. (2015)] and a CH_4 source. ~~[average of 9.2 g C-CH_4 m^{-2} yr^{-1}, (95% CI 0.3 to 44.5 g C-CH_4 m^{-2} yr^{-1}) for low nutrient temperate peatlands from Wilson et al., (2016a)].~~ By contrast, drained peatlands are a CO_2 source [the average annual NEE of +81 to +151 g C-CO_2 m^{-2} yr^{-1} reported in Renou-Wilson et ~~al., (~~al. (2018a) is typical] with very low CH_4 emissions (Baird et al., 2009). However, it should be noted that this can be offset by high CH_4~~methane~~ emissions from active drains of ~60 g CH_4 m^{-2} yr^{-1} (Evans et al., 2016). Degraded/drained peatlands typically have a larger GWP compared to intact~~natural~~ sites or rewetted sites because a large positive NEE outweighs the reduced CH_4 emissions (~~Renau~~Renou-Wilson et al., 2018a). The NEE and CH_4 fluxes from restored peatlands can be similar to intact~~pristine~~ peatlands, but exhibit greater variability (Strack et al., 2016; Wilson et al., 2016a~~; Strack et al., 2016~~).

Several studies have suggested the hypothesis that time since restoration is an important factor in the GWP of peatlands (Augustin & Joosten, 2007; Bain et al., 2011; Waddington and Day 2007). In particular, the restored sites may go through an initial period of high CH_4~~methane~~ production and high GWP because restored peatlands are often rapidly colonized by aerenchymatous vegetation, such as *Eriophorum spp.* (Cooper et al., 2014; Waddington and Day, 2007~~, Cooper et al. 2014~~). This is followed by a period of decreasing GWP as mosses and other peatland species become established (Augustin & Joosten, 2007; Bain et al., 2011). To test this hypothesis, more data is needed for peatlands "restored more than 10 years previously" (Bacon et al., 2017). Also, it is valuable to have studies which directly compare adjacent ~~raised bog and cutover bog~~sites with contrasting ~~different~~ site histories.

Aquatic losses of C~~carbon~~ include dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) in runoff as well as CO_2 evasion from open water. These have not been measured as frequently as NEE and CH_4 flux (Dinsmore et al., 2010), but can represent a key component of the net ecosystem C~~carbon~~ budget (NECB) (Barry et al., 2016; Kindler et al., 2011)~~).~~ Ignoring the aquatic C~~carbon~~ losses would result in an overestimate of the C~~carbon~~ sink function of peatlands (Billet et~~ al.~~ al., 2010). ~~The DOC losses from temperate peatlands range from 5-36 g C m^{-2} yr^{-1} and are lower for boreal peatlands (Range: 4-13 g C m^{-2} yr^{-1}) (Evans et al., 2016).~~ Few studies have ~~simultaneously~~ concurrently measured a complete NECB for a peatland including the DIC flux (Nilsson et~~ al.~~ al., 2008) and CO_2 evasion from open water (Dinsmore et~~ al.~~ al., 2010), even though CO_2 evasion has been found to be important to the overall C~~carbon~~ balance~~, with a reported 2-year average of 12.8 g C m^{-2} yr^{-1} for an intact peatland in Scotland~~ (Dinsmore et~~ al.~~ al., 2010). Further, these studies have focused on intact rather than degraded or restored ~~or recovering~~ peatlands.

~~Despite the considerable amount of recent scientific work on the greenhouse emissions from peatlands, few previous studies have quantified the carbon balance of old abandoned cutover peatlands (Bacon et al., 2017). Many studies have focused on more recently abandoned/restored degraded bogs. This may be because of the recent change in attitudes towards peatland conservation and restoration (Holden et al., 2004), which means that many bog restoration projects~~

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~~are relatively recent. The focus on the cutover ecotypes investigated in this study is therefore valuable because it the potential future climate impact of abandoned cutover bogs under the "do-nothing" restoration approach (Holden et al., 2004). This is especially true in Ireland because substantial areas of the Irish midland bogs are currently used in industrial peat harvesting, which is scheduled to cease in the coming decades (Bord na Móna website).~~

The growing body of scientific research on the GHG and C~~carbon~~ balance of peatlands and the importance to global climate change means that it is increasingly important to consider new data in the context of global studies ~~, Often, boreal and temperate peatlands have similar conditions: hydrological (consistently high water table), chemical (high carbon, often acidic peat soils), ecological (often ground cover of *Sphagnum* mosses, with low nutrient sedges and ericaceous shrubs). As similar factors (i.e. water table, plant ecology, growing season length, soil temperature, etc.) are often cited as controlling factors for greenhouse gas fluxes, it may be possible to identify global trends across boreal and temperate peatlands~~ (e.g. Junkurst and Fieldler 2007).

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The goal of this work is to quantify all of the major aspects of the C~~carbon~~ balance (NEE, CH_4 flux, and aquatic losses as DOC, DIC, and CO_2 evasion) over a two year period for five distinct peatland ecotypes, which are located in two adjacent areas with contrasting site histories: a~~, for a historically (ca. 1960) abandoned~~ peat extraction ~~cutover~~ bog, which was abandoned ca. 1960 ~~compared to~~and an ombrotrophic ~~an adjacent more recently restored (2009)~~ raised bog, which was previously impacted by drainage but not peat extraction, and then recently restored (in 2009). This study also presents the measurements in the context of global studies on boreal and temperate peatlands with

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the aim of identifying trends in NEE and CH_4 flux based on land condition (drained, restored, intact~~pristine~~), mean annual water table, and vegetation cover (presence/lack of vegetation).

2. Materials and Methods

2.1 Site Description

Abbeyleix Bog (N 52.89714, W 7.35022, elevation approx. 90 m) is a ~~natural~~ peatland and natural area in Co. Laois, Ireland. This site is located in a temperate, oceanic climate with a 30 year (1981–2010) mean annual rainfall of ~~844~~923 mm and a mean annual temperature of 9.~~9~~5° C (Walsh, 2012). ~~Acidic, low nutrient, histosol, peat soils remain throughout the raised and cutover bog with 5.0-8.5 m depth on the raised bog and 1-3 m depth on the cutover bog.~~

Abbeyleix Bog ~~containing~~ contains ~~both~~areas that were historically mined for peat (referred to here as cutover bog) as well as ~~un-harvested~~ raised ombrotrophic bog ~~and~~, which was never mined for peat ~~historically harvested cutover bog~~ (Fig. 1). ~~This site is located in a temperate, oceanic climate with a mean annual rainfall of 844 mm and a mean annual temperature of 9.9° C. Acidic, low nutrient, histosol, peat soils remain throughout the raised and cutover bog with 5.0-8.5 m depth on the raised bog and 1-3 m depth on the cutover bog.~~ The areas of cutover bog were domestically mined for peat by hand cutting between the 1870s and 1960s, and then abandoned (i.e. no restoration or management works have occurred in this area post-extraction) (Ryle, 2013). Peat extraction never occurred on the remaining areas of raised bog; however, these areas ~~The areas of raised bog~~ were impacted by a surface drainage network installed in the 1980s~~1980's~~ in preparation for industrial extraction although the plans for industrial extraction of the peat were later abandoned due to resistance from the local community. Throughout the raised bog, ~~S~~surface drains were installed at 15 m spacing to a depth of 1 m, and connected with ~~older,~~older and deeper drains along a historic railway track and the margins of the ~~cutover~~ bog. ~~The plans for industrial extraction of the peat were abandoned due to resistance from the local community, and t~~ The surface drains were later blocked as part of a restoration effort in 2009, ~~7~~ six years before the start of this study. Acidic, low nutrient, histosol, peat soils remain throughout the raised and cutover bog, with 5.0–8.5 m depth on the raised bog and 1–3 m depth on the cutover bog. ~~The raised bog is mostly surrounded by cutover bog, which was domestically harvested for peat between the 1870's and 1960's, and then abandoned (Ryle, 2013).~~

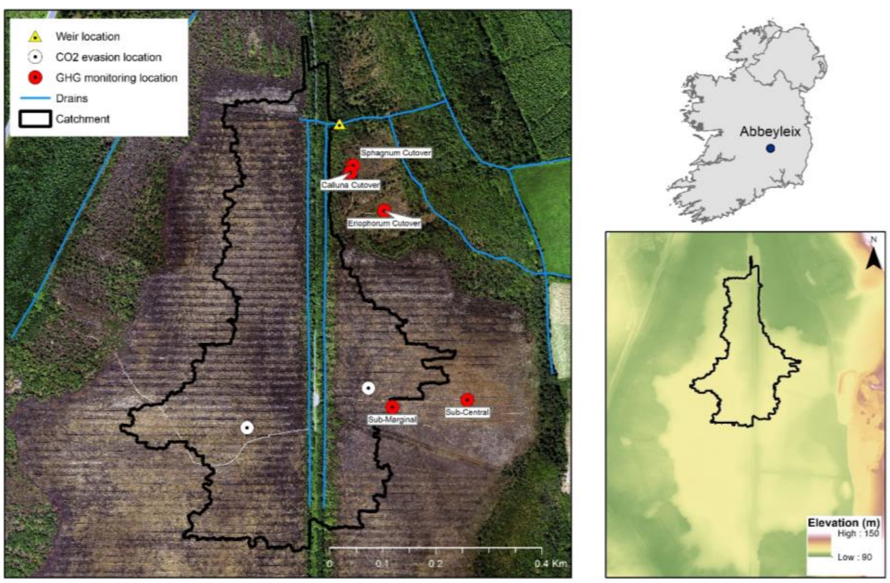

Figure 1. Location of the study site in Ireland; elevation map of Abbeyleix Bog (bottom right) showing the uncut raised bog surrounded by lower cutover bog and the higher esker complex to the east; an aerial photograph of the study site showing the weir catchment area, major drains, and sampling locations. In the aerial photograph the blocked surface drainage network on the raised bog can be seen as a set of horizontal lines and the historic railroad track can be seen as a vertical line through the middle of the photograph. White circles represent the open water CO_2 evasion locations referred to as west high bog (WHB) and east high bog (EHB).

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2.2 Sampling Locations

Five sampling locations were chosen to quantify GHG emissions, two on the uncut raised bog and three on the cutover bog. These locations were chosen to represent 5 ecotypes, where the ecotype refers to a distinct set of hydro-physical and ecological conditions. These 5 areas were chosen to represent common ecotypes on raised and cutover bogs in Ireland with the help of ecologists from the Irish National Parks and Wildlife Service (NPWS).

On the raised bog, one study location was chosen in a Sub-Central ecotype, which is defined as having a continuous *Sphagnum spp.* cover and continuously high water table but lacking the micro-topography of hummocks and hollows. The Sub-Central ecotype is the highest quality bog conditions found at this site. Another study location was chosen in a Sub-Marginal ecotype, which is defined as having a discontinuous *Sphagnum spp.* moss cover and a mixed presence of both relatively wet and dry bog vegetation (Table 1). Further description of raised bog ecotypes can be found in Schouten et ~~al.~~ ~~(~~al. (2002).

On the cutover bog, three sampling locations were chosen based on distinctions in the plant ecology. The Sphagnum Cutover ecotype contains a continuous *Sphagnum spp.* cover (primarily as hummocks of *Sphagnum capilifolium* with some *Sphagnum subnitens* and *Sphagnum magellanicum*) and a mixture of plant species similar to the Sub-Central ecotype. The Calluna Cutover ecotype contains a low diversity of plant species characteristic of a well-drained peat soil, dominated by heather (*Calluna vulgaris*), bare peat, and lichens (mostly *Cladonia portenosa*) similar to a facebank ecotype on a raised bog. The Eriophorum Cutover ecotype is dominated by *Eriophorum angustifolium*, and contains a moderate percent (21-54% in this study) cover of *Sphagnum spp.*

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(Table 1). All sampling locations were chosen in open areas, excluding any ~~large~~ trees, shrubs or other vegetation that could not fit under the gas sampling chambers (see Section 2.3). Six collars were installed for each ecotype except for the Calluna Cutover ecotype where 5 collars were installed. Collar locations were chosen to represent ecological variability within each ecotype. Plant ecology was characterized for all collars in June 2016 and again in June 2017 with the help of ecologists from the NPWS. The plant ecology was determined in terms of the percent cover of every species present, averaged over the two years.

Table 1. Summary of the plant ecology for each ecotype in this study. Data is reported as the mean (range) of the 5 or 6 collars within each ecotype.

Ecotype	Percent *Sphagnum*~~*Spahgnum*~~ *spp.* cover	Percent *Eriophorum*~~*Eriophorum*~~ *spp.* cover	Percent *Calluna vulgaris* cover	Percent Total Plant Cover
Sphagnum Cutover	94 (78 to 100)	8 (3 to 23)	16 (5 to 30)	119 (103 to 134)
Calluna Cutover	0	2 (0 to 3)	35 (8 to 50)	51 (18 to 68)
Eriophorum~~Eriophorium~~ Cutover	35 (21 to 54)	51 (21 to 80)	6 (2 to 15)	103 (77 to 140)
Sub-Marginal	57 (15 to 89)	13 (4 to 37)	9 (2 to 15)	100 (69 to 114)
Sub-Central	98 (93 to 100)	8 (1 to 39)	2 (0 to 8)	124 (107 to 151)

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2.3 Meteorological Field Data

On site, hourly measurements of air temperature and humidity (CS215 probe, Campbell Scientific, Loughborough, UK), rainfall (ARG100 Tipping Bucket Raingauge, Campbell Scientific), barometric pressure (PTB110 Barometer, Vaisala, Oyj, Finland), and soil temperature at 5 and 10 cm (PT100 temperature probes, Campbell Scientific) were recorded by a CR1000 Data logger (Campbell Scientific). Soil temperature was also recorded at ecotypes by two LogBoxAA data loggers (Novus, Miami, USA). Hourly phreatic water table was recorded in 5 cm diameter stilling wells located at each of the five ecotypes by an Orphius Mini Level Logger (vented transducer, 0.1% error, OTT Hydromet, Kempten, Germany). The ground elevation at the center of each collar was surveyed and compared to the stilling well using an RTK GPS with ± 2mm accuracy (TDL 450L, Trimble, Sunnyvale, CA), and the hourly water table at each collar was offset by this difference in elevation. All collars were located within 8 m of the ecotype water table logger.

The hourly light intensity was measured in the field in units of W/m^2 using an LP02 Pyranometer (Hukseflux Thermal Sensors, Delft, Netherlands). This sensor was calibrated to the photosynthetically active radiation (PPFD) sensor (TPR-2, PP Systems), which recorded~~)~~ in units of (µmol m^{-2} s^{-1}),~~)~~ used during the field ~~chamber~~ measurements, located inside the chamber~~.~~ A linear calibration between these two sensors was found for both sunny and overcast days (n=27, r^2=0.82), which was used to convert hourly light intensity to hourly PPFD.

2.4 CO_2 and CH_4~~Greenhouse Gas~~ Flux Measurements

The closed static chamber method was used to measure ~~greenhouse~~CO_2 and CH_4 gas fluxes from all plots, comparable to methods used in a large number of other studies, particularly on peatlands in Ireland (e.g. Wilson et~~al.~~ al., 2016b). Stainless~~A stainless~~ steel collars were~~collar was~~ permanently installed 20 cm into the ground at least two weeks before the start of sampling. This collar had a water trough along the top edge to ensure a suitable seal with the chamber. The chambers were constructed in-house of clear polycarbonate for CO_2 measurements and opaque polystone^tm for CH_4 and were equipped with a fan. Chambers were ~~(~~ of size 60 x 60 x 30 cm or 54 l total with a measurement area of 0.36 m^2. ~~equipped with a fan) were constructed in house of clear polycarbonate for CO_2 measurements and opaque polystone^tm for CH_4.~~ A system of wooden

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platforms was constructed 6-7 weeks before the start of sampling so that each collar could be accessed without putting pressure on the ground surface adjacent to it. Platforms were placed on piles to the base of the peat in the Sub-Central ecotype to prevent sinking into the bog. For CO_2 flux measurements, chambers were gently set on the collar and any pressure differential between the chamber headspace and the ambient atmosphere was vented using a 5 cm^2 hole set in the side of the chamber. The chamber was then sealed and the CO_2 concentration was recorded in the field every 15 seconds for a period of 105 seconds using an EGM-4 infra-red gas analyser (PP Systems, Amesbury, USA). CO_2 flux was calculated from the slope of the linear increase in CO_2 ~~flux~~ concentration over time. In order to maintain a constant temperature over the chamber closure time, particularly under high irradiance, a cooling system was installed in the~~this~~ chamber, which pumped water from an ice bath through a small radiator located behind the fan to keep the variance of the chamber temperature to within 1°C during the measurement. The CO_2 flux measurement was repeated under a range of light levels by artificially shading the chamber, generally under full ambient light, 1-2 light other partial shading light levels, and a completely shaded measurement.~~.~~ Ecosystem respiration is assumed to be the CO_2 flux ~~where~~ when the light transmitted into the chamber was zero. For this study, a positive sign convention is indicates a net loss of C from the peatland. CO_2 flux measurements were conducted over 63 field days between January 2016 and August 2017. Over 29 collar locations, a~~A~~ total of 3358 ~~quality checked~~ chamber measurements for CO_2 flux were ~~conducted~~ kept for modelling after quality checking to ensure that the change in CO_2 concentration over the chamber closure was monotonic and that the PPFD did not change by more than 50 μmol m^{-2} s^{-1} over the chamber closure. ~~over 29 collar locations.~~

For CH_4 flux measurements, gas samples of 20 mL each were extracted from the chamber every 10 minutes beginning 5 minutes after the chamber had been placed on the collar and sealed. These samples were later analyzed in the lab on an Agilent Gas Chromatograph instrument with a flame ionization detector and a 30 m long Elite-plot Q GC column. Samples were collected over 17 field days between April 2017 and January 2018.

Additionally, the soil temperature at 5 and 10 cm depth, water table adjacent to the collar, air temperature, and light level inside the chamber (for CO_2 flux measurements) were recorded for each chamber closure at the time of sampling.

2.5 NEE Modelling

The NEE was modelled on an hourly basis to account for the expected diurnal variations, which is driven by diurnal variations in ~~PPFD and temperature for the daytime uptake and night time release, respectively~~light intensity and soil temperature. Field measurements of CO_2 flux were used to build collar specific empirical models of gross primary production (GPP) and ecosystem respiration (ER). Hourly measurements of field variables were input into these empirical models to calculate hourly GPP and ER, which were then summed to calculate NEE.

Several different empirical models of GPP and ER were tested ~~to~~based on the fit the field data (see Supplemental Section 1), which~~). These models~~ were judged based on the sum of the squares of the residuals and r^2 values. Models were also checked to ensure that there was no bias or trend in the residuals with respect to independent variables. Of the models tested, t~~T~~he GPP model in Eq. (1) and ER model in Eq. (2) (from Wilson et al., 2016b) ~~was~~were found to best explain the variance in the field data for all of the 29 collars.

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$$GPP = -(a + c * \sin((JDAY + 215)/365 * 2\pi)) * \frac{PAR}{PAR+b} * exp(T_{5cm} * d) * (1 + WT * e) \qquad (1)$$

where ***a***, ***b***, ***c***, ***d***, and ***e*** are collar specific empirical fitted model parameters and JDAY is the Julian day of the year, PPFD is the light level in (μmol m^{-2} s^{-1}), T_{5cm} is the soil temperature at 5 cm, and WT is the water level in cm below ground surface at the collar. The r^2 value of the modelled versus measured data using Eq. (1) ranged between 0.77 and 0.94 for each of the 29 collars (Table S3). ~~(Table S3).~~

~~For ER, the model in Eq. (2) was found to best explain the variance in the field data for all of the 29 collars. For this ER model, the r^2 values ranged from 0.74 to 0.94 for each of the collars.~~

$$ER = (a + b * WT) * \exp\left(c * \left(\frac{1}{(283.15 - 227.13)} - \frac{1}{(TK5cm - 227.13)}\right)\right) \cancel{ER}$$

$$\cancel{= \left(a + d * \sin\left(\frac{JDAY + 215}{182.5} * 2\pi\right) + e * WT\right)}$$

$$\cancel{* \exp\left(c * \left(\frac{1}{(283.15 - 227.13)} - \frac{1}{(TK5cm - 227.13)}\right)\right) + b * WT} \qquad (2)$$

where ***a***, ***b***, ~~*c*, *d*,~~ and ~~*e*~~*c* are collar specific emperical fitting parameters, and other variables are as above. For this ER model, the r^2 values ranged from 0.63 to 0.92 for each of the 29 collars (Table S4). (Other metrics on model fitting for Eq. (1) and Eq. (2) including the standard error of the model fitting parameters and n values are shown in Table S3 and Table S4). ~~F~~Fitting parameters and more information on the GPP and ER models tested can be found in Supplemental Section 1.

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Hourly water level, T_{5cm}, PAR, and Julian day data were input into Eq. (1) and Eq. (2) (with the collar specific fitting parameters) to calculate hourly GPP and ER at each collar over a two year period.

2.6 CH_4~~Methane~~ Modelling

The annual ~~In contrast to CO_2 flux,~~ CH_4 fluxes for 2017 were ~~are expected to be much more constant throughout the day (Pypker et al. 2013) with apparently random variation. Therefore, CH_4 fluxes from each collar could be~~ calculated from the average measured flux at each collar ~~over a given time period~~ (as in Strack et ~~al.~~ al., 2014) over the year.~~).~~ However, in this case, the data collection was bias toward the warmer part of the year, with no ~~methane flux~~ measurements collected during January–March~~were not conducted over the entire 2 year time period~~ because of equipment issues. To account for this bias in sampling period, the collar average CH_4 flux was scaled by a factor of 0.80. This factor was in turn derived from an empirical ~~Thus, a~~ model fit to ~~was constructed for the purpose of extrapolating~~ the field data, which modelled the ~~to the entire study period. The field data of CH_4 flux from all collars were normalized by the collar average CH_4 flux and lumped together to model the average~~ temporal variation in CH_4 flux as a function~~. The variations in CH_4 flux was modelled according to the Julian day~~ of ~~year and~~ soil temperature and day of the year (Eq. S3). The modelling process is described more fully in the Section S1. Throughout all of 2016, equipment issues prevented the collection of CH_4 flux measurements. ~~S11),~~ Due to this~~limited~~ data limitation, the GWP and C balance for 2016 was calculated using the 2017 values of CH_4 flux. ~~, methane flux variations were assumed to follow the same temporal trend across all ecotypes.~~ The reported GWP and to a lesser extent C balance for 2016 should thus be interpreted with some caution.~~overall average temporal variation was then multiplied by the average measured methane flux at a given collar,~~ The assumption~~model gave little difference between 2016 and 2017, and as~~

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~~field data was only collected in 2017, it was assumed~~ that CH_4 fluxes were similar in 2016 and 2017 is partially justified by ~~the methane flux from both years was the same for~~ the fact that the empirical model of CH_4 flux gave very similar results for 2016 and 2017 (<3% difference).~~purposes of calculating annual carbon balance and GWP.~~

2.7 Aquatic C~~Carbon~~ Losses

A thin plate V-notch weir was installed to measure hourly discharge from a 249,000 m^2 catchment area on-site (as shown in Fig. 1). The weir catchment area was delineated in ARC-GIS using a digital terrain map based on LiDAR survey data from 2013. The majority of this catchment area was composed of marginal and sub-marginal uncut raised bog (>90%) as well as lightly forested drains along a bog road (<10%). Aquatic C~~carbon~~ losses as DOC and DIC were quantified at this location only, and assumed to be the same for all ecotypes (even those adjacent to but outside of this catchment area), ~~given~~due to the difficulty in resolving the relative contributions of each ecotype to the total DOC flux. The DOC concentration was measured weekly in 2016 and every 12 hours (with a few gaps) from January through November 2017. DOC samples were filtered in the field using a 0.45 µm cellulose syringe filter after rinsing the syringe and filter with 20 mL of sample. Samples were then acidified to pH 2 using 10% HCl to preserve them and stored under refrigeration at 4° C and analysed within two months. The DOC concentration was measured by UV absorbance as in other studies (e.g. Jager et ~~al.~~ al., 2008;~~,~~ Koehler et al., 2009) at wavelength 254 nm. A site specific calibration curve was determined between 254 nm UV absorbance and DOC concentration measured using a Vario Total Organic Carbon (TOC) Select Analyzer (Elementar, Langenselbold, Germany). This was undertaken on samples collected from January 2016 to April 2016, July 2016, and July 2017 (r^2 =0.997, n=76). The error of this method was ± 1.1 mg C~~/~~ L^{-1} based on the standard deviation of the residuals. The hourly discharge at the weir was multiplied by the most recent DOC

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concentration measurement to calculate a C~~carbon~~ flux as DOC from the catchment. This value was then divided by the catchment area to calculate the aquatic C~~carbon~~ loss as DOC per m^2.

The DIC concentration at the weir was calculated from the aqueous partial pressure of CO_2 as well as the pH and temperature using equations from Gelbrecht et~~ al.~~ al. (1998) as in Nillson et~~ al.~~ al. (2008) where dissolved CO_2 was included as part of DIC. Partial pressure of CO_2, was measured on-site in triplicate by filling, then sealing a 250 mL bottle with 200 mL of water sample. Circulated air was bubbled through the sample and the change in CO_2 concentration in the headspace was measured over time using an EGM-4 infra-red gas analyser (PP Systems, Amesbury, USA) until the concentration was constant (10-12 minutes). The initial partial pressure of dissolved CO_2 in the sample was then back calculated from the total change in CO_2 concentration in the headspace. A total of 7 DIC measurements were taken at the weir between November 2016 and October 2017. The average DIC concentration was multiplied by the hourly discharge and divided by the catchment area to calculate the aquatic C~~carbon~~ loss as DIC per m^2.

CO_2 evasion occurred from the open water areas of blocked drains on the raised bog and from the functioning drain network upstream of the weir. CO_2 evasion was measured in triplicate with a CPY-4 (PP systems, Amesbury, USA) chamber fitted to a small floating raft and EGM-4 gas analyser. A total of 15 measurements of CO_2 evasion were conducted between two locations of blocked drains on the raised bog (Fig. 1), and 8 measurements were conducted just upstream of the weir from November 2016 to July 2017.

For the calculation of the global warming potential, 90% of the DOC loss is assumed to be converted to CO_2 and 10% to longer term storage (after Evans et ~~al.~~ al., 2016), while 100% of the DOC flux is included in the calculation of the C~~carbon~~ balance for the system. All of the DIC loss is assumed to be converted to atmospheric CO_2 as DIC is almost entirely composed of dissolved supersaturated CO_2.

2.8 Statistical Analysis

The standard error and statistical significance of model fit parameters in Table S5 and Table S6 was determined using Minitab© 2018 Statistical Software with the non-linear regression function. The differences between ecotypes for C balance, CH_4 flux, and GWP was determined using 1-way anova with the annual results from the 29 collars grouped by ecotype, which was coupled with Bonferroni honestly significant difference for multiple pair-wise comparisons. The statistical significance of ecotype annual C sinks/sources was determined using a student's t-test of the five or six collars in the ecotype. The significance of linear trends was determined using Microsoft Excell© data analysis package. ~~The ecotype variance in the NEE can be calculated as the sum of the within collar variance and the between collar variance. The within collar variance was calculated from the sum of model error and the error of input field variables. The annual model error was calculated from the standard deviation of the residuals for GPP and ER models for each collar on an hourly time step and propagated for the entire year. Similarly, the field inputs into the NEE models were assumed to have a hourly random variation of ± 1°C, ±1 cm WT, and ± 5% PAR. The effect of which on the NEE, was calculated from sensitivity analysis, which was run for all models and propagated for the entire year. The variance in the ecotype CH_4 flux was also calculated from the sum of the within collar variance and the between collar variance. The annual within collar standard deviation of CH_4 flux~~

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~~was assumed to be ± 30% of the collar average annual CH_4 flux, or 2.8 g C-CH_4 m^{-2} yr^{-1}, which was applied to all collars. For the carbon balance and GWP, the variance in NEE and CH_4 flux was summed with the variance due to measurement error in the DOC flux, DIC flux, and CO_2 evasion. Significant differences between ecotype annual carbon balance, and GWP was determined using 1-way ANOVA and Bonferroni confidence intervals. The significance of the linear regressions was determined with Minitab 18 Statistical Software.~~

Commented [M1]: This section has changed substantially from the first draft. This is partially because of confusion expressed by one of the reviewers at the wording and partially because much of the statistical analysis was redone in a simpler and more straightforward way with the change in model results.

4.2 Comparisons with Global Studies of Boreal and Temperate Peatlands

The annual NEE, CH_4 flux, and water table data from the ecotypes in this study were compared to global studies of boreal and temperate peatlands. The data from global studies was divided into three generic categories as follows: *Intact peatlands* - those peatlands that have not been mined, undergone intensive agriculture or forestry, and are not heavily impacted by drainage or other disturbance; *Bare peat sites* - previous peat extraction sites where there is an absence of vegetation cover; *Degraded/Restored/Recovering peatlands*: - peatlands that have (at some point in time) been substantially altered by previous/current land use, drainage, or peat extraction, where recovering is defined here as the "spontaneous revegetation of mined peatlands" (Poulin et al., 2005), which have had no definite action taken to rehabilitate them. This compilation of data focuses on low nutrient (if specified, pH<6) semi-natural sites, i.e. excludes sites that are actively used for intensive agriculture, forestry, or other uses.

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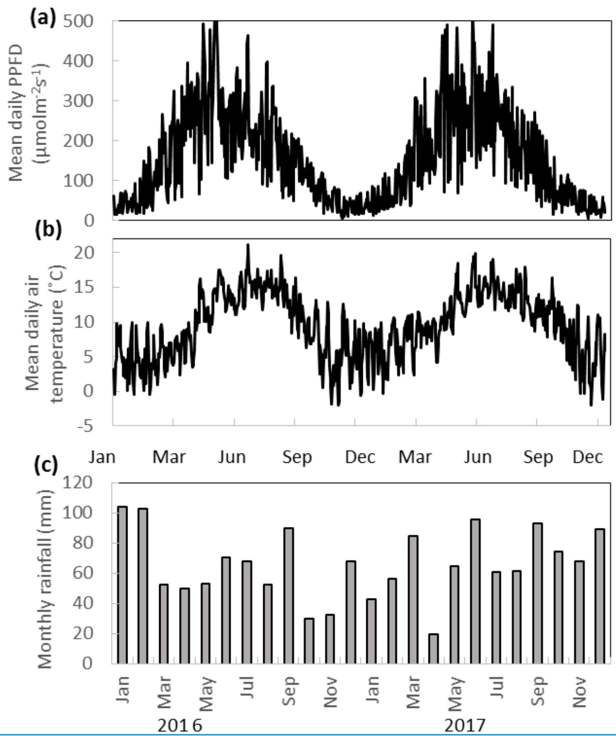
3. Results

_*3.1 Environmental Monitoring*

The annual rainfall measured at Abbeyleix Bog was 746 mm in 2016 and 840 mm in 2017, compared to the 2001-~~2016~~2017 (the period of record) annual average of ~~838~~ 862 ± 134 mm at the Ballyroan (Oatlands) daily rainfall station, located approximately 5 km NE of the site. The mean annual temperature at Abbeyleix bog was 9.6˚ C and 9.7˚ C in 2016 and 2017, similar to the ~~(1978-2007)~~30 year average (1981-2010) ~~average~~ of 9.5~~9~~˚ C based on a gridded interpolation of Irish climate (Walsh, 2012). Mean daily PPFD, air temperature, and monthly rainfall are shown in Figure 2 over the study period. The mean annual water table (MAWT) was within 2 cm ~~at all ecotypes~~ between the two years for all ecotypes. The winter (Oct-Mar) water table was higher than summer (Apr-Sep) water table, as expected (Fig. 3). The average soil pore water pH was 4.7 (range: 4.4-5.1) for all ecotypes.


(a)
Mean daily PPFD (μmolm-2s-1)
500
400
300
200
100
0
(b)
Mean daily air temperature (°C)
20
15
10
5
0
-5
Jan
Mar
Jun
Sep
Dec
Mar
Jun
Sep
Dec
(c)
Monthly rainfall (mm)
120
100
80
60
40
20
0
Jan
Mar
May
Jul
Sep
Nov
Jan
Mar
May
Jul
Sep
Nov
2016
2017

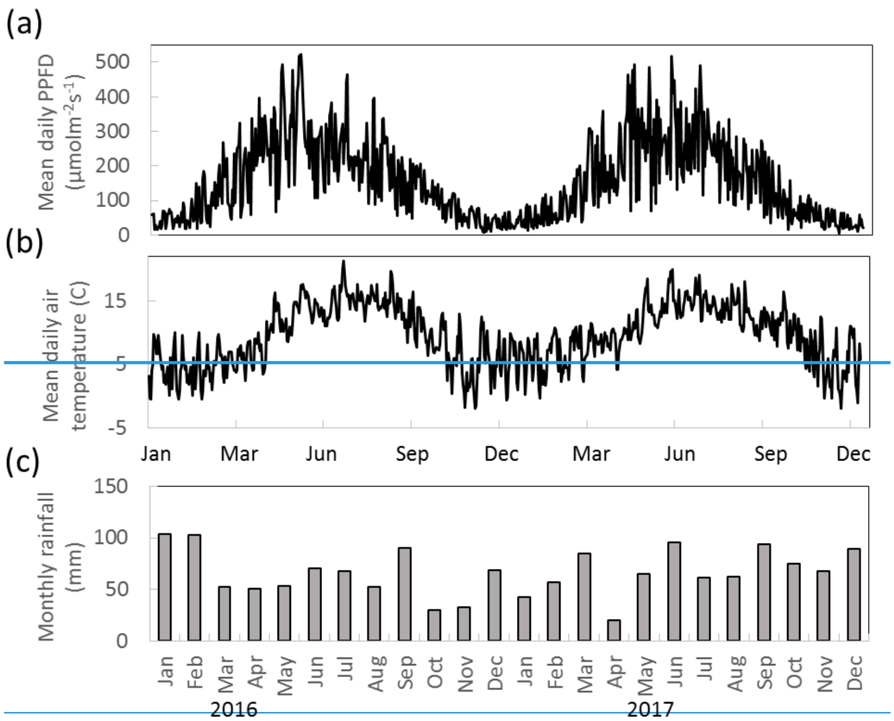


Figure 2. (a) Mean daily PPFD, (b) mean daily temperature, and (c) monthly rainfall at Abbeyleix Bog in 2016 and 2017.

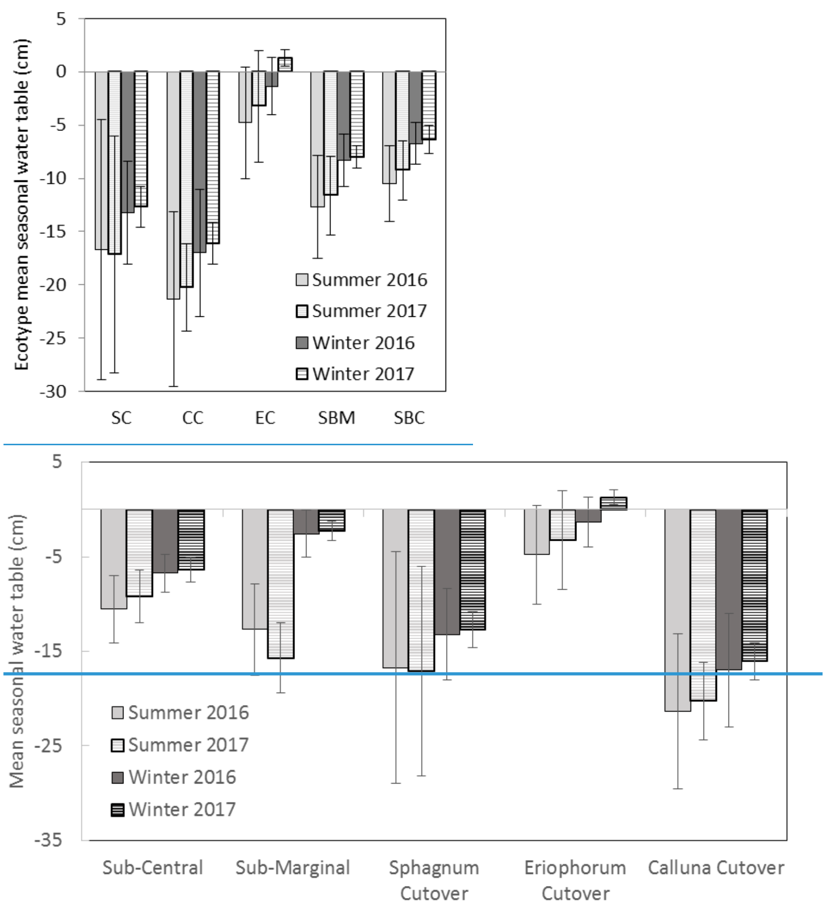


Figure 3. Mean seasonal water table for each of the ecotypes for summer (Apr-Sep) and winter (Oct-Mar), where the mean annual water table is measured with respect to the springtime peat surface or sphagnum surface (if present). The ecotypes are abbreviated as SC = Sphagnum Cutover, CC = Calluna Cutover, EC = Eriophorum Cutover, SBM = Sub-Marginal, and SBC = Sub-Central.

3.2 CO_2 and CH_4 Gas Fluxes

The modeled annual GPP, ER, and NEE for each collar is shown in (Table ~~S5~~S8). The ecotype CO_2 fluxes were calculated as the average of all collars in each ecotype. The seasonal trend in modeled monthly GPP and ER were similar among all ecotypes increasing in magnitude during the summer

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and decreasing during~~in~~ the winter (Fig. 4a & 4b). The Sphagnum Cutover ecotype had the largest monthly GPP from January to June both years. The monthly ER was highest at the Calluna Cutover ecotype, especially during the summer months. The ecotypes show different seasonal trends in cumulative NEE (Fig. 4c). The Sphagnum Cutover and the Sub-Central ecotypes were net CO_2 sinks (negative slope) from March (March 27 for Sub-central and March 4 for Sphagnum Cutover) to October 24, 2016 and April 24 to October 7, 2017 and CO_2 sources the rest of the year, showing an overall similar pattern to other studies of intact peatlands (e.g. Gažovič et ~~al.~~ al., 2013). ~~By contrast, the Calluna Cutover ecotype was the strongest CO_2 source during the summer months.~~ The Sub-Marginal ecotype is an overall moderate CO_2 source both years with a minor net CO_2 uptake occurring during summer of 2017. The Eriophorum Cutover ecotypes is approximately CO_2 neutral for much of the year with short periods of CO_2 uptake during the summer months. Some caution should be applied to interpreting the 2017 NEE data because the field measurements of NEE were conducted for 8 months of 2017 (Jan–Aug), although the field measurements in 2017 did encompass the warmest months of the year when the largest variation in NEE occured.

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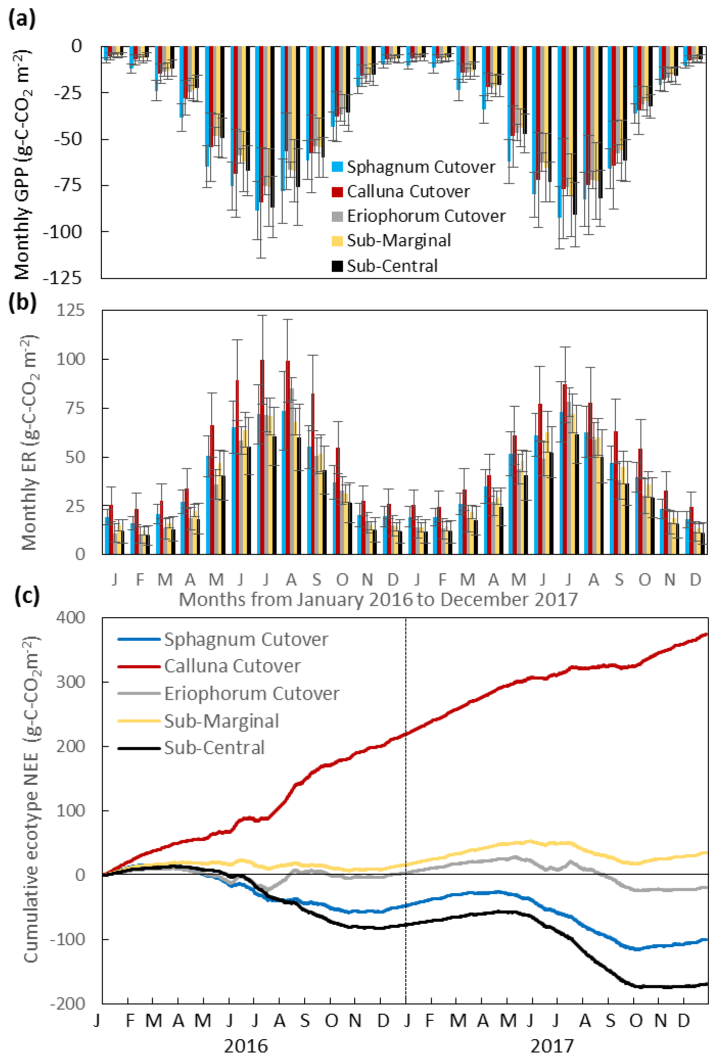
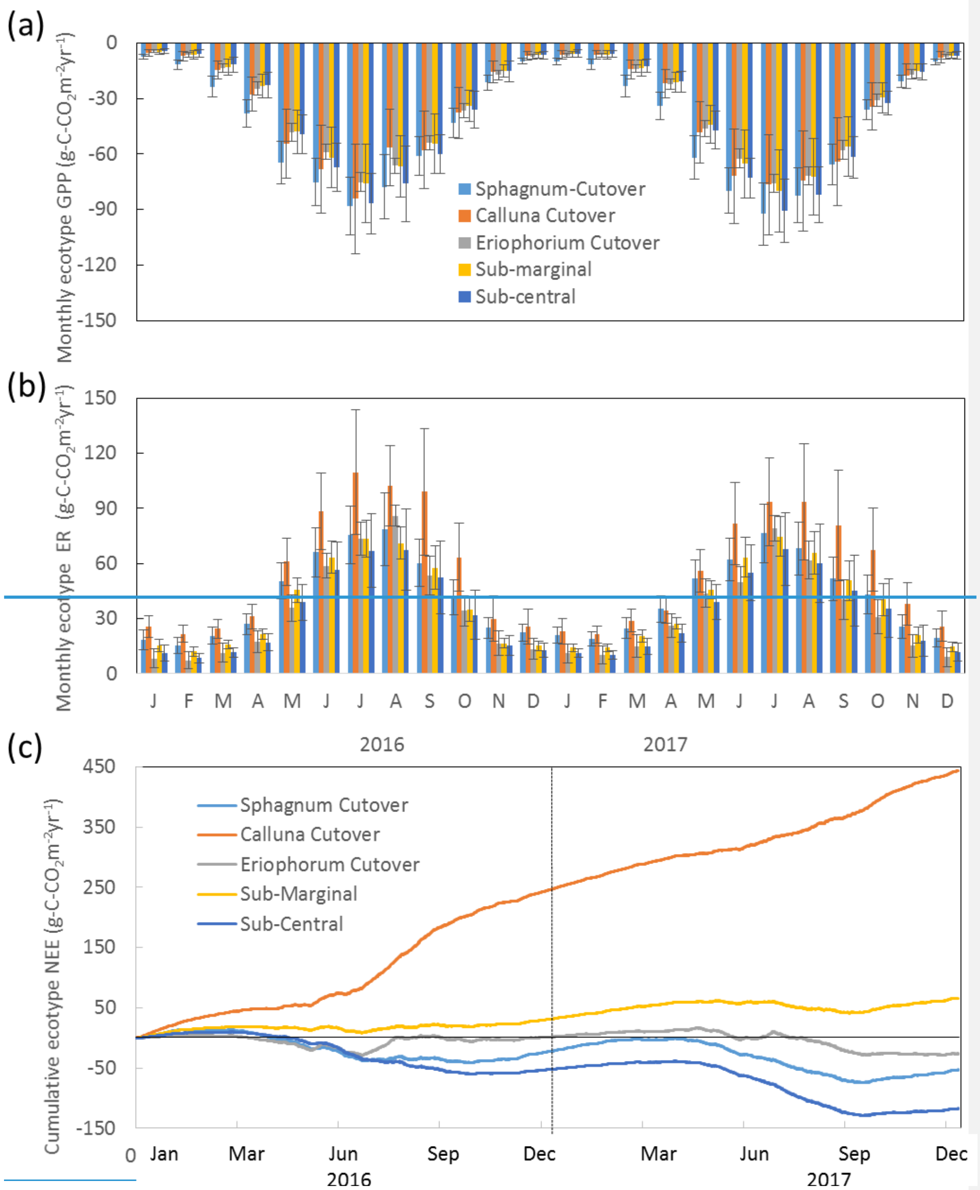
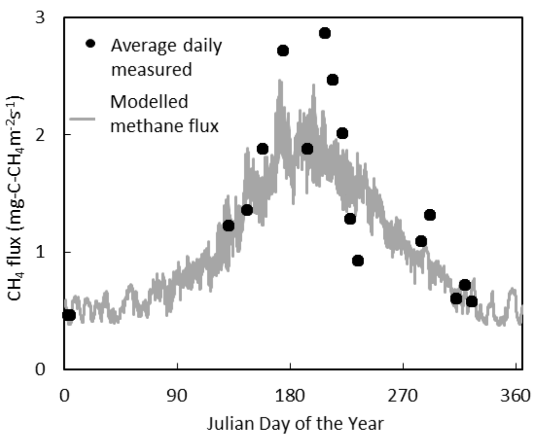
The temporal variation in measured CH_4~~methane~~ flux followed a seasonal trend becoming larger and more variable during the summer months, which was captured reasonably well ~~(r^2 =0.61)~~ by the model (Fig. 5, Fig. S2). ~~The methane data was extrapolated to an annual period using this model.~~ Annual CH_4~~methane~~ fluxes by ecotype are shown in Figure 6~~, and annual methane emissions~~ and for each collar ~~are shown~~ in Table S8~~5~~. The annual CH_4~~methane~~ emissions are highest for the Eriophorum Cutover (14.2 ±4.8 g C-CH_4 m^{-2} yr^{-1}) and Sub-Central ecotypes (12.6 ±7.9 g C-CH_4 m^{-2} yr^{-1}), which have the highest mean annual water table (MAWT). The annual CH_4 flux at the Sub-Central ecotype is highly variable with a range of 1.2 to 19.3 g C-CH_4 m^{-2} yr^{-1} between collars. The annual CH_4~~methane~~ flux is lowest for the Calluna Cutover ecotype (2.7 ±1.4 g C-CH_4 m^{-2} yr^{-1}).


(a)
Monthly GPP (g-C-CO2 m-2)
0
-25
-50
-75
-100
-125
Sphagnum Cutover
Calluna Cutover
Eriophorum Cutover
Sub-Marginal
Sub-Central
(b)
Monthly ER (g-C-CO2 m-2)
125
100
75
50
25
0
J F M A M J J A S O N D J F M A M J J A S O N D
Months from January 2016 to December 2017
(c)
Cumulative ecotype NEE (g-C-CO2m-2)
400
300
200
100
0
-100
-200
Sphagnum Cutover
Calluna Cutover
Eriophorum Cutover
Sub-Marginal
Sub-Central
J F M A M J J A S O N D J F M A M J J A S O N D
2016
2017



(a)
Monthly ecotype GPP (g-C-CO2m-2yr-1)
Sphagnum-Cutover
Calluna Cutover
Eriophorum Cutover
Sub-marginal
Sub-central
(b)
Monthly ecotype ER (g-C-CO2m-2yr-1)
J F M A M J J A S O N D J F M A M J J A S O N D
2016
2017
(c)
Cumulative ecotype NEE (g-C-CO2m-2yr-1)
Sphagnum Cutover
Calluna Cutover
Eriophorum Cutover
Sub-Marginal
Sub-Central
Jan Mar Jun Sep Dec Mar Jun Sep Dec
2016
2017

Figure 4. Monthly (a) GPP and (b) ER, and (c) cumulative NEE for each ecotype for 2016 and 2017, where the ecotype values are the average of all collars in the ecotype.


Average daily measured
Modelled methane flux
CH4 flux (mg-C-CH4 m-2 s-1)
Julian Day of the Year
0
90
180
270
360
0
1
2
3

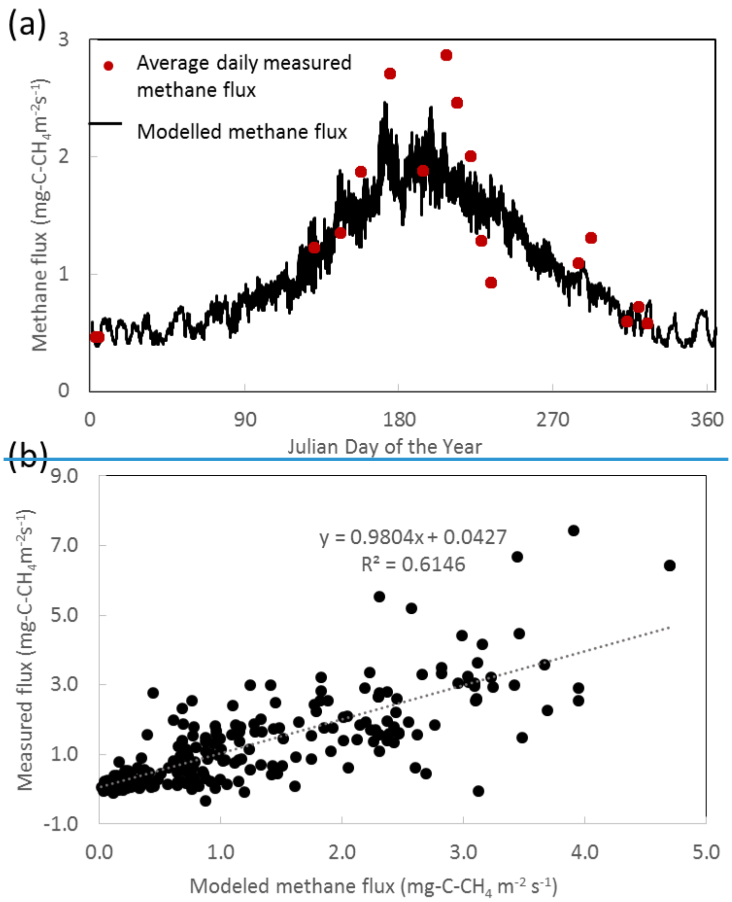
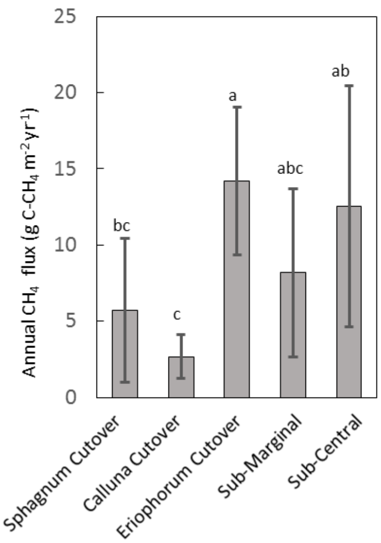


Figure 5. ~~(a)~~ The average daily CH_4~~methane~~ flux measured in the field compared to the modelled temporal fluctuations in CH_4~~methane~~ flux for 2017.~~, and (b) the modelled vs. measured methane flux when the temporal variation in multiplied by the collar average flux.~~



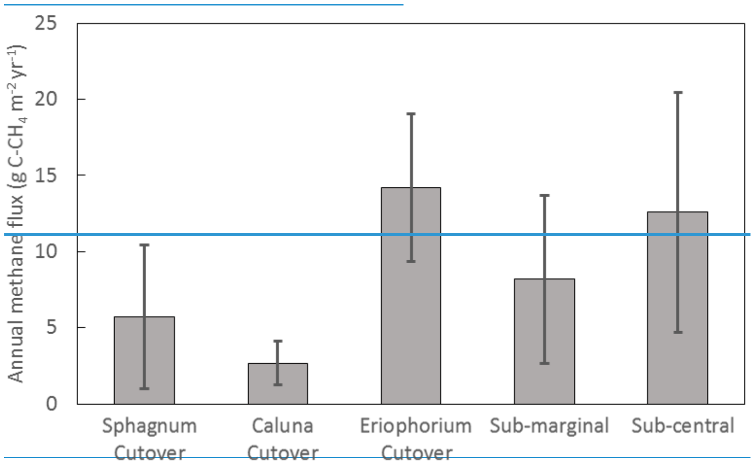


Figure 6. Annual CH_4~~methane~~ flux for each ecotype averaged over all collars in the ecotype. Shared letters represent no statistically significant difference between ecotypes based on one-way ANOVA with Bonforroni honestly significant difference for pairwise comparisons.

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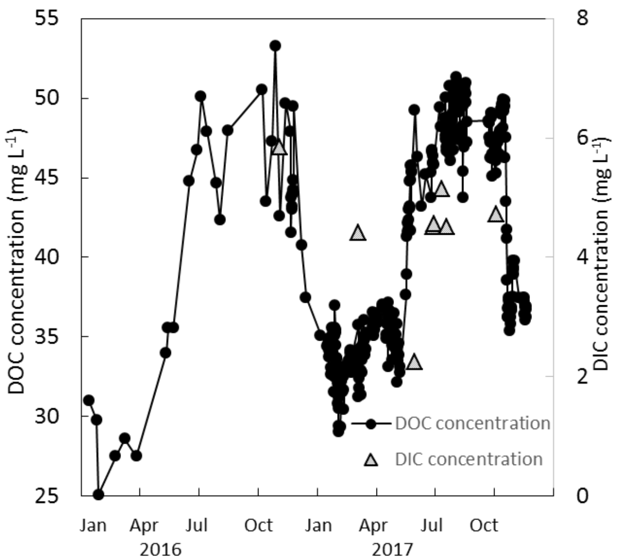
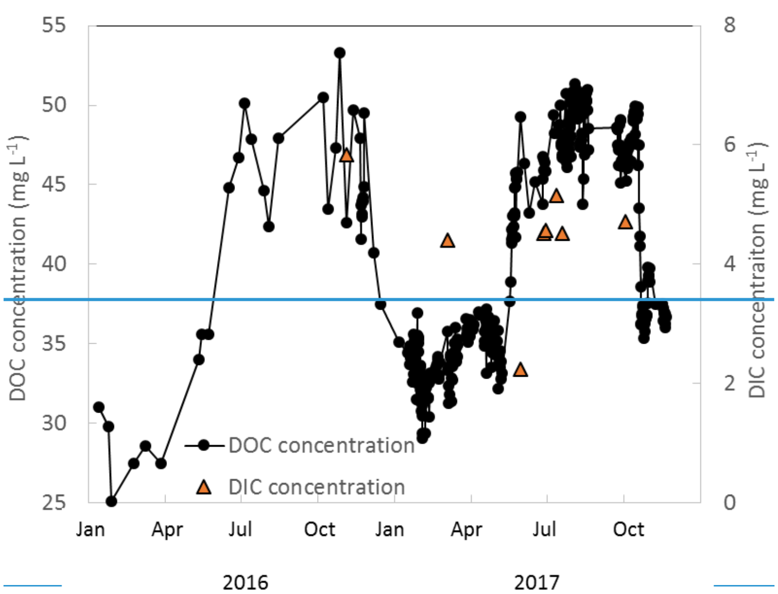
3.3 Aquatic C~~Carbon~~ Losses

The DOC concentrations showed a seasonal trend for both years - higher between approx. June and November (46.0 ±3.0 mg L^{-1}) and lower between December and May (34.5 ±2.3 mg L^{-1}) (Fig. 7).



55
50
45
40
35
30
25
8
6
4
2
0
DOC concentration (mg L-1)
DIC concentration (mg L-1)
DOC concentration
DIC concentration
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
2016
2017



55
50
45
40
35
30
25
8
6
4
2
0
DOC concentration (mg L-1)
DIC concentraiton (mg L-1)
DOC concentration
DIC concentration
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
2016
2017

Figure 7. Measured DOC and DIC concentrations (mg L^{-1}) over a two year period (2016 and 2017) at the weir.

No trend in DOC concentration was observed with respect to discharge. The discharge at the weir site was much higher in the winter months, with a resulting higher total DOC flux over those months. Annual losses of DOC were 8.0 ±1.6 and 12.8 ±2.5 g C m^{-2} yr^{-1} for 2016 and 2017, respectively. Seven DIC measurements were conducted at the weir site between November 2016 and October 2017. The average DIC concentration at the weir was 4.6 ±1.1 mg L^{-1}, excluding 1 low outlier (2.2 mg L^{-1}) on June 2, 2017 (Fig. 7). Based on this limited amount of data there is no significant trend in DIC concentration with respect to season, temperature, or discharge, so it was assumed constant throughout the 2 year study period. Annual C~~carbon~~ losses as DIC were 1.1 ±0.2 and 1.5 ±0.3 g C m^{-2} yr^{-1}. These values of annual aquatic C~~carbon~~ loss for DOC and DIC were applied to each of the ecotypes equally when calculating the C~~carbon~~ balance and GWP. Open water CO_2 evasion was measured for two blocked drains on the raised bog and just upstream of the weir. The average CO_2 evasion rate from the two blocked drains on the western and eastern portion of the raised bog (WHB and EHB, respectively) (n=15) was 5.1 x 10^{-3} ±2.9 x 10^{-3} mg C-CO_2 m^{-2} s^{-1} and was somewhat higher at the weir (n=8) as 9.2 x 10^{-3} ±3.2 x 10^{-3} mg C-CO_2 m^{-2} s^{-1} (Fig. 8).

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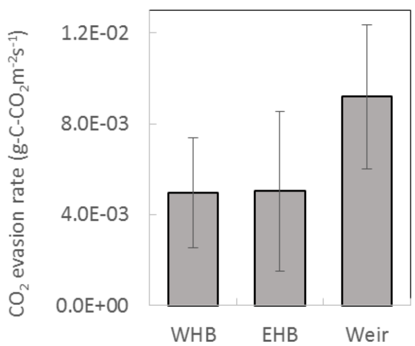

Figure 8. CO_2 evasion rate measured at two blocked drains on the high bog (WHB and EHB) and just upstream of the weir. Locations of WHB and EHB are shown as white dots in Fig 1 as is the Weir location. Data was collected between March and July 2017 at the WHB location (n=7), November 2016 and July 2017 at the EHB location (n=8), and December 2016 and July 2017 at the weir location (n=8).

Based on this limited data set, there was no significant trend in evasion rate with respect to season, temperature, or (at the weir site) discharge. CO_2 evasion rate was thus assumed constant and extrapolated to give an annual C~~carbon~~ loss as CO_2 evasion of 162 ±91 g C-CO_2 m^{-2} yr^{-1} and 290 ±100 g C-CO_2 m^{-2} yr^{-1} for open water blocked ditches and active drain network of the weir, respectively. The open water areas in the drain network contributing to the weir were ~0.9% of the total catchment area to give a C~~carbon~~ loss of 2.7 ±0.9 g C-CO_2 m^{-2} yr^{-1} for the weir catchment area as a whole. As above, this was applied equally all ecotypes. Open water areas of blocked drains only occurred near one of the ecotypes (Sub-Marginal), where they were estimated to be 2.8% of the total surface area. This gives an additional C~~carbon~~ loss in the Sub-Marginal ecotype of 4.5 ±2.6 g C-CO_2 m^{-2} yr^{-1}.

3.4 Carbon Balance and GWP by Ecotype

The NEE, CH_4 fluxes, and the aquatic losses of C~~carbon~~ were compiled to calculate the C~~carbon~~ balance and GWP ~~and GWP~~ for each ecotype ~~(Fig. 9~~(Fig. 9)~~.~~, with collar specific data shown in Table

S8. Two of the ecotypes were on average C sinks both years: the Sphagnum Cutover (-29.8 ± 42 g-C m^{-2} yr^{-1} for 2016 and -30.0 ± 40 g-C m^{-2} yr^{-1} for 2017) and the Sub-Central ecotypes (-53.0 ± 37 g-C m^{-2} yr^{-1} for 2016 and -62.4 ± 46 g-C m^{-2} yr^{-1} for 2017), but only the Sub-Central ecotype was a statistically significant carbon sink based on a student's t-test (p= 0.018 in 2016 and p=0.021 in 2017, n=6). The Calluna Cutover ecotype was a substantial C~~carbon~~ source of ~~260~~ 234 ± 52~~70~~ g C-CO_2 m^{-2} yr^{-1} and 175~~218~~ ±61~~78~~ g C-CO_2 m^{-2} yr^{-1} for 2016 and 2017, respectively. This ecotype was significantly higher than all the other ecotypes in 2016 ($p < 0.001$) and 2017 (p=0.~~011~~017) (Fig. 9a). The Sub-Marginal, Eriophorum Cutover, and Sphagnum Cutover ecotypes showed no statistically significant different from C neutral both years. However, the Sub-Marginal ecotype had one collar, which was a low outlier (Table S8); this collar is much more similar ecologically and hydrologically to the Sub-Central ecotype (Table S7). If this low outlier is removed, then the Sub-Marginal ecotype is a significant C source both years (p=0.003 for 2016 and p=0.003 for 2017, n=5), based on a student's t-test. Removing this outlier, the Sub-Marginal ecotype is a significantly higher C source than the Sub-Central (p= 0.007) and Sphagnum Cutover (p=0.046) ecotype in 2016, and higher than the Sphagnum Cutover ecotype to marginal significance (p=0.057) in 2017. ~~**The** annual carbon balance for the other ecotypes was not significantly different from carbon neutral. However, four of the six collars at the Sub-Central ecotype were significant carbon sinks both of the years (range **-25 to -97 g C-CO_2 m^{-2} yr^{-1}).** One collar in the Sub-Central ecotype was found to be a significant carbon source both of the measured **years (51 and 62 g C-C02 m^{-2} yr^{-1}).**~~ There is substantial variation between collars within each ecotype for NEE and CH_4 flux, which is the largest source of error in ecotype C~~carbon~~ balance and GWP.

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Commented [M2]: These and other values in this section have been changed from the first draft because a different model was used to calculate ER.

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All ecotypes had an average positive GWP~~GPW~~ both years, with the lowest average GWP of ~~2.1~~1.2 ± ~~2.4~~2.6 tonnes~~tons~~ CO_2-eq m^{-2} yr^{-1} at the Sphagnum Cutover ecotype and the highest average GWP occurring at the Calluna Cutover ecotype of ~~9.8~~8.6 ± 3.~~3~~5 tonnes~~tons~~ CO_2-eq m^{-2} yr^{-1} (Fig. 9b). The *Sphagnum* dominated ecotypes, Sphagnum Cutover and Sub-Central, were on average the lowest GWP sources, with the Sphagnum Cutover ecotype lower than the Calluna Cutover ecotype to a high degree of significance ($p<0.001$) and significantly lower ($p= 0.001$ for 2016 and $p=0.010$ for 2017) than the Eriophorum Cutover ecotype both years. The Sub-Central ecotype significantly lower ($p<0.001$ for 2016 and $p=0.020$ for 2017) than the Calluna Cutover ecotype. ~~GWP at the Calluna Cutover ecotype was significantly higher than the Sphagnum Cutover (p = 0.002) and Sub-Central ecotype (p = 0.028) in 2016 and only the Sphagnum Cutover ecotype in 2017 (p = 0.018) (Fig. 9b).~~ CH_4~~Methane~~ emissions account for ~~12~~13% and ~~14~~16% of the GWP at the Calluna Cutover ecotype in 2016 and 2017, respectively. CH_4~~Methane~~ emissions account for the majority of the total GWP in all other ecotypes (~~65~~72-~~146~~210%). Thus, the differences between ecotype GWP should be interpreted with some caution for 2016, with CH_4 flux assumed to be the same as 2017.

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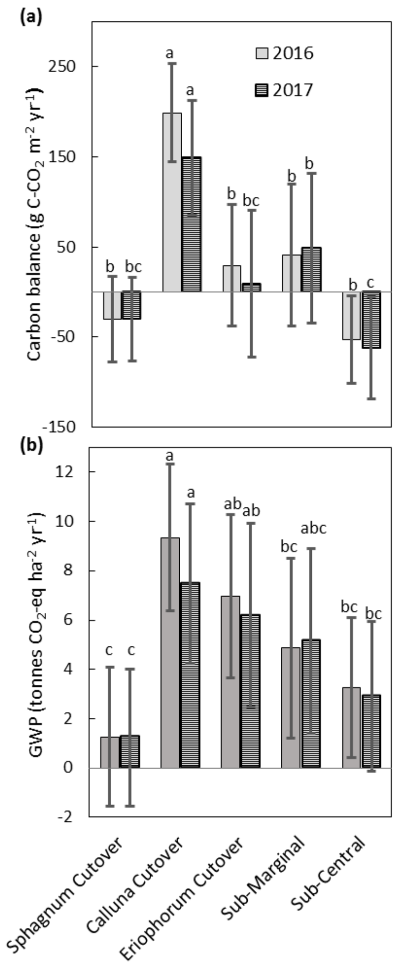
(a)
2016
2017
Carbon balance (g C-CO_2 m^{-2} yr^{-1})
250
150
50
-50
-150
a
a
b
bc
b
bc
b
b
b
c
(b)
GWP (tonnes CO_2-eq ha^{-2} yr^{-1})
12
10
8
6
4
2
0
-2
a
a
ab
ab
bc
abc
bc
bc
c
c
Sphagnum Cutover
Calluna Cutover
Eriophorum Cutover
Sub-Marginal
Sub-Central

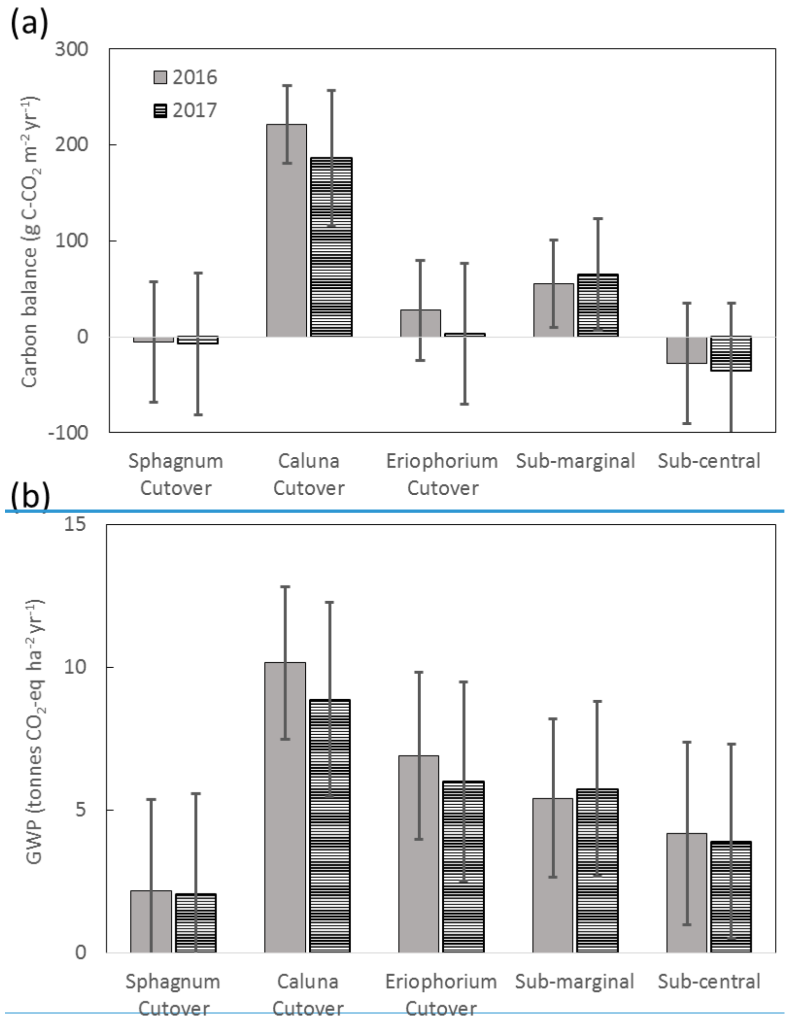

Figure 9. (a) Annual C~~Carbon~~ balance for each ecotype including NEE, CH4 flux, aquatic losses as DOC and DIC, and open water CO_2 evasion averaged over all collars in each ecotype. (b) ~~G~~Annual global warming potential for each ecotype. Shared letters represent no statistically significant difference between ecotypes based on one-way ANOVA with Bonforroni honestly significant difference for pairwise comparisons. Letters apply for each year separately.

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3.5 Drivers of NEE and GWP

Environmental drivers of the annual NEE~~carbon balance~~, CH_4 flux, and GWP were analyzed by comparing the data from each of the 29 collars. There is a significant (slope = -5.8 ± 2.6, p=0.015, n=29) but weak (r^2 = 0.~~20~~16) negative linear correlation between the two year average annual NEE~~carbon balance~~ and the ~~average~~ MAWT (Fig. 10a). This particular data set is skewed by the Sphagnum Cutover ecotype, where there is a relatively low water table and a moderate CO_2 sink~~n overall neutral carbon balance~~ due to the presence of *Sphagnum spp.* hummocks. If the Sphagnum Cutover ecotype is excluded, the linear regression between average annual NEE~~carbon balance~~ and MAWT is more highly significant (slope = -9.2 ± 2.8, p = ~~<~~0.003, n=29~~1~~) with a stronger correlation (r^2 = 0.~~41~~35). The annual CH_4 flux has a significant (slope = 0.57 ± 0.11, p < 0.001, n=29) positive linear correlation (r^2=0.51) with the average MAWT (Fig. 10b). The trends in CH_4 flux and NEE~~carbon balance~~ with respect to MAWT offset each other such that there is no trend (slope = 0.04 ± 0.09, p = 0.~~91~~61, n= 29, r^2 < 0.01) in GWP with respect to mean annual water table (Fig. 10c).

The collar annual average GWP has a highly significant (slope = -0.067 ± 0.010, p < 0.001, n=1) negative linear correlation (r^2 = 0.~~58~~63) with the percent *Sphagnum spp.* cover in the collar (Fig. 10f). The percentage *Sphagnum spp.* cover and *Eriophorum spp.* cover in the collar seem to be correlated in a non-linear fashion with the average annual NEE ~~carbon balance~~ and the annual CH_4 flux, respectively (Fig. 10 d,e). In particular, the annual CH_4 flux is greater than ~9 g C-CH_4 m^{-2} yr^{-1} for all collars where the percentage *Eriophorum spp.* cover is higher than 10%.

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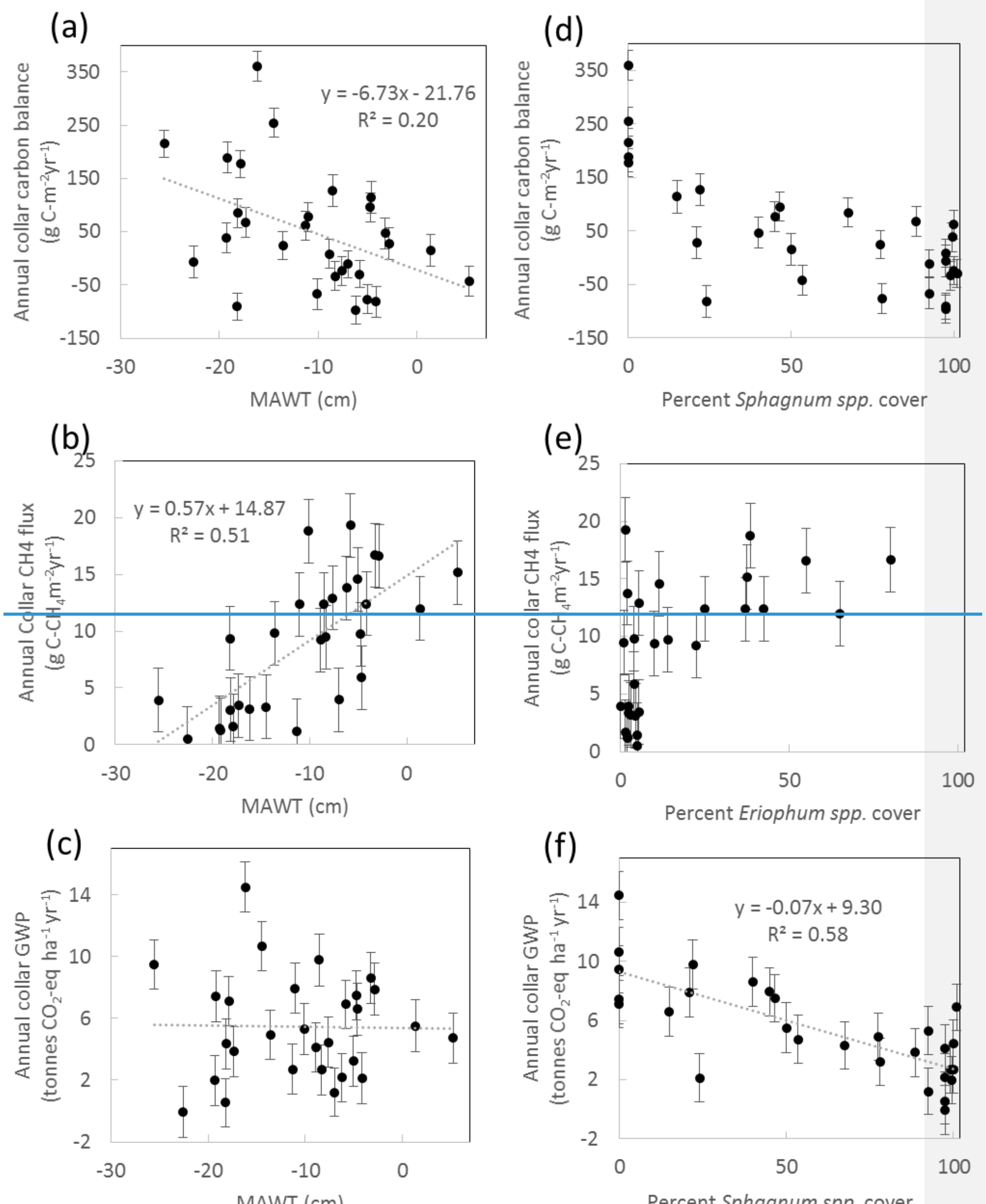
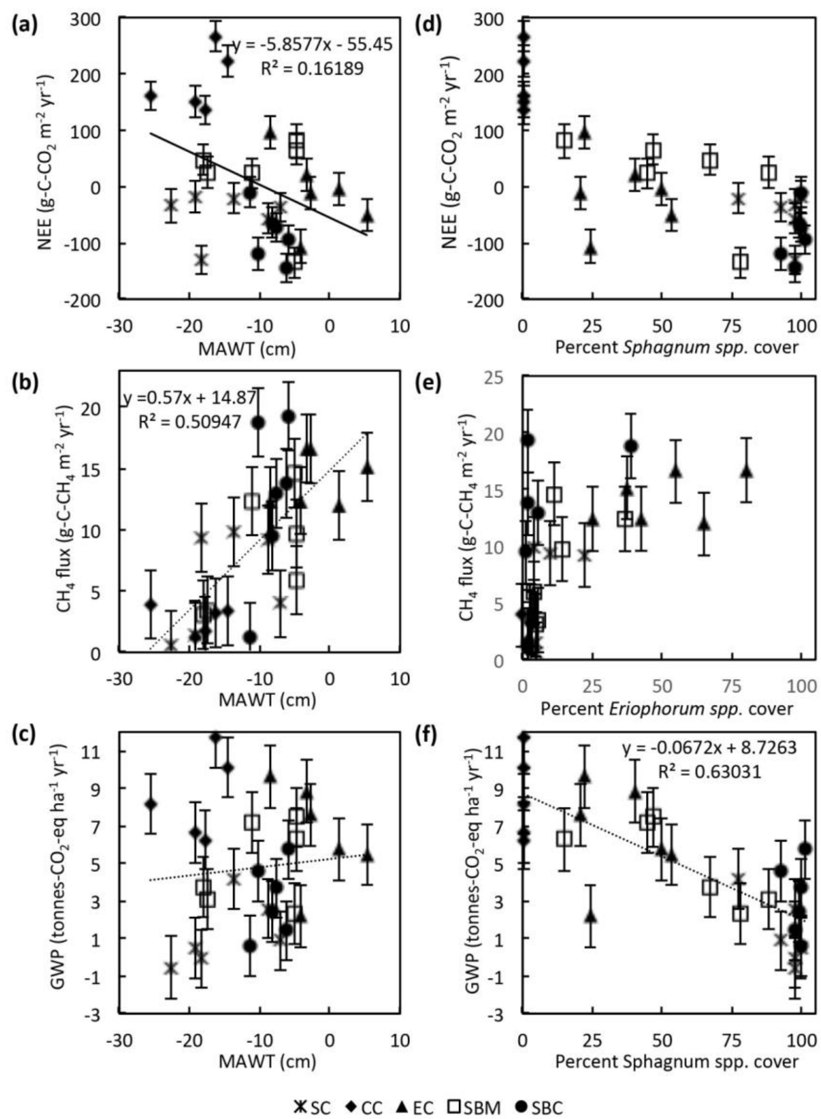

(a)
y = -6.73x - 21.76
R² = 0.20
Annual collar carbon balance (g C-m-2yr-1)
MAWT (cm)
(d)
Percent Sphagnum spp. cover
(b)
y = 0.57x + 14.87
R² = 0.51
Annual Collar CH4 flux (g C-CH4m-2yr-1)
MAWT (cm)
(e)
Percent Eriophum spp. cover
(c)
Annual collar GWP (tonnes CO2-eq ha-1yr-1)
MAWT (cm)
(f)
y = -0.07x + 9.30
R² = 0.58
Percent Sphagnum spp. cover



(a)
y = -5.8577x - 55.45
R² = 0.16189
NEE (g-C-CO2 m-2 yr-1)
MAWT (cm)
(d)
NEE (g-C-CO2 m-2 yr-1)
Percent Sphagnum spp. cover
(b)
y =0.57x + 14.87
R² = 0.50947
CH4 flux (g-C-CH4 m-2 yr-1)
MAWT (cm)
(e)
CH4 flux (g-C-CH4 m-2 yr-1)
Percent Eriophorum spp. cover
(c)
GWP (tonnes-CO2-eq ha-1 yr-1)
MAWT (cm)
(f)
y = -0.0672x + 8.7263
R² = 0.63031
GWP (tonnes-CO2-eq ha-1 yr-1)
Percent Sphagnum spp. cover
SC CC EC SBM SBC

Figure 10. Trends in collar annual C~~carbon~~ balance, CH_4 flux, and GWP plotted against mean annual water table (MAWT) (a-c) and percent genus cover (d-f). Data is displayed by ecotype with abbreviations in legend as in Fig 2. ~~Data is averaged over the two year period.~~

3.6 Comparison with Global Studies

The annual NEE and CH_4 flux from this study were compared to a compilation of literature data from global studies of boreal and temperate peatlands. This comparison is shown graphically in Fig. 11 and Fig. 12 and in tabular form in Table S9.

For both vegetated and bare peat sites, there is a negative correlation between MAWT and NEE (Fig. 11). ~~Both intact peatlands and variously degraded/recovering peatlands fall on the same trend line, agreeing with Wilson et al. (2016a).~~ Annual NEE for vegetated sites followed a linear trend with respect to MAWT with slope of -4.5 g C-CO_2 m^{-2} yr^{-1} per cm rise in MAWT and an intercept of -92 g C-CO_2m^{-1}yr^{-1}.

The *Sphagnum* dominated ecotypes in this study (Sphagnum Cutover and Sub-Central) were just below the overall trend line for vegetated sites in Fig. 11. The Sub-Central ecotype in this study has continuous *Sphagnum spp.* lawns similar to an intact peatland. This ecotype has a mean annual NEE of -85 ± 67~~57~~ g C-CO_2 m^{-2} yr^{-1} and a mean annual water table of -8.2 cm. This is close to the overall average NEE (-60 g C-CO_2 m^{-2} yr^{-1}) and mean annual water table (-9 cm) for intact peatlands shown in this figure. The other ecotypes in this study were higher than the overall trend line for vegetated sites in Fig. 11. ~~This comparison is valuable for validating the data for the other ecotypes because the C balance of intact bogs is comparatively better characterized than degraded systems and the potential for systematic bias in chamber measurements.~~ The Calluna Cutover ecotype from this

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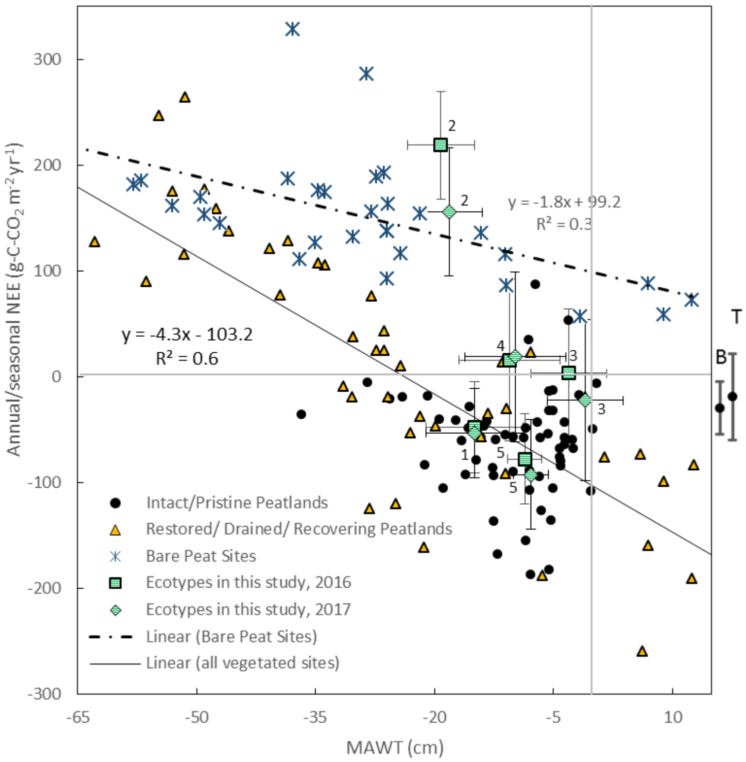
study had an exceptionally high NEE (188 ± 79 g C-CO_2 m^{-2} yr^{-1}) for the given MAWT (-18.6 cm) compared to the NEE (-5 g C-CO_2 m^{-2} yr^{-1}) predicted from the best fit trend line of vegetated sites.



~~The slope is similar to that reported from a review of studies of peatlands with MAWT higher than -30 cm (Wilson et al. 2016a) of -2.0 ±1.0 and -5.0 ±2.0 g C-CO_2 m^{-2} yr^{-1} per cm rise in MAWT for boreal and temperate peatlands, respectively. However, the trend in NEE with respect to MAWT should be interpreted with some caution because of the difficulty of generalizing across sites based on simple water table proxies (Wilson et al. 2016a). For example, there was a "highly peatland-specific dependency (i.e., with different offsets and slopes) of the CO_2 response to water table depth" for grassland peatlands in Germany (Tiemeyer et al. 2017), although, that study looked at grasslands, which may have much more variability in soil type, land management, nutrient status, etc. than the natural and semi-natural low nutrient sites shown in Figure 11. This trend may also break down as MAWT becomes too low (e.g. Tiemeyer et al. 2017) because soil respiration can be limited if the soil is too dry (Briones et al., 2014). Thus, climate patterns could be an important factor in CO_2 response to water table (Tiemeyer et al., 2017).~~

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~~Based on the data collected in Figure 11, intact peatlands occur at a narrower range of mean annual water table and NEE. This is expected because degraded peatlands can have a wider range of site histories and eco-hydrological conditions (Wilson et al. 2016a). This agrees with Strack et al. (2016) who reported greater variation in CO_2 and CH_4 fluxes at restored plots when compared to either unrestored or intact plots. As with data from this study, this may suggest that restoration of *Sphagnum* dominated peatland ecology has an additional NEE benefit beyond raising the water table.~~

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~~The Sub-Central ecotype in this study has continuous *Sphagnum spp.* lawns similar to an intact peatland. This ecotype has a mean annual NEE of -57 g C-CO_2 m^{-2} yr^{-1} and a mean annual water table of -8.2 cm. This is close to the overall average NEE (-60 g C-CO_2 m^{-2} yr^{-1}) and mean annual water table (-9 cm) for intact peatlands in this figure. This comparison is valuable for validating the data for the other ecotypes because the C balance of intact bogs is comparatively better characterized than degraded systems and the potential for systematic bias in chamber measurements. The Calluna Cutover ecotype from this study has an **exceptionally high NEE (222 g C-CO_2 m^{-2} yr^{-1}) for the mean annual water table (-18.6 cm) compared to the NEE (-5 g C-CO_2 m^{-2} yr^{-1}) predicted** from the best fit trend line of vegetated sites.~~

~~Also, as shown in Figure 11, bare peat sites have a higher NEE than vegetated sites at a given MAWT, and these trend lines diverge at higher MAWT. As it can take decades for vegetation to be established in industrially mined peatlands (Wilson et al., 2015), this data would suggest that restoration to encourage plant colonization could reduce the short term CO_2 emissions even if no other restoration works are undertaken. This data set could be used to predict the CO_2 reduction from raising the water table as well as establishing vegetation on bare peat sites. Further, peatlands may be large C sinks in the years immediately post restoration as vegetation recovers due to the rapid, subsequent increase in vegetation biomass. For example, an annual NEE of -473 g C-CO_2 m^{-2} yr^{-1} was reported by Waddington et al. (2010) one year post restoration for sites where herbaceous vegetation increased dramatically. This may explain some of the low outliers in Figure 11 for restored/recovering sites. Three of the low outliers in Figure 11 are from Strack et al. (2014), which is 4 years post restoration with a growing season NEE of -162, -121 and -126 g C-CO_2 m^{-2} for mean seasonal water tables of -21.3, -24.9 and -28.2 cm, respectively.~~

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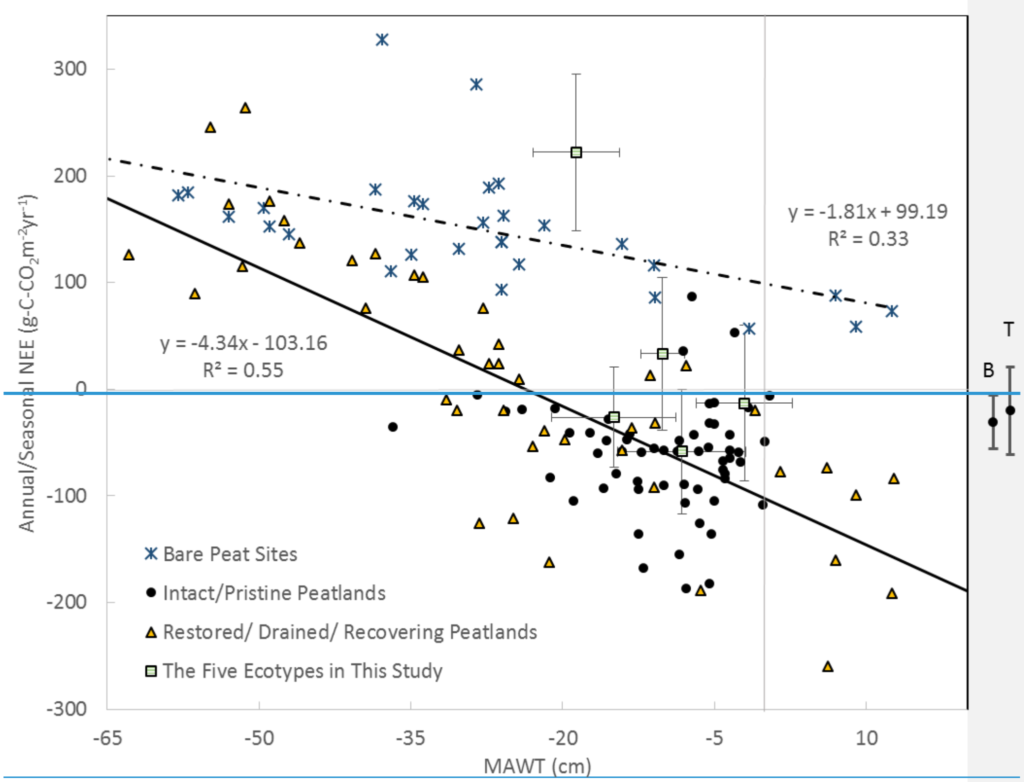

Figure 11. Mean annual water table vs. the annual NEE for the 5 ecotypes in this study (error bars are standard deviation) compared to global studies from boreal and temperate peatlands. ~~The solid line shows the best fit linear trend line from all vegetated sites and the dashed line shows the best fit trend line for bare peat sites.~~ (Data from: Wilson et al., 2015; Wilson et al., 2016; Vanslow-Algan et al., 2015; Tuittili et al., 1999; Waddington et al., 2010; Strack et al., 2014; Nilsson et al., 2008; Dinsmore et al., 2010; Koehler et al., 2011; Chimner et al., 2017; Gazovic et al., 2013; Lund et al., 2012; Levy and Grey et al., 2015; McVeigh et al., 2014; Helftler et al., 2015; Piechl et al., 2014; Stranchen et al., 2016; Roulet et al., 2007; Waddington and Roulet, 2000; for more details and additional studies see ~~Supplemental~~ Table ~~S6~~ S9 in Supplemental Section 3). Also, shown to the right of the figure is the mean and 95% CI NEE from nutrient poor, wet (MAWT >-30 cm) boreal (B) and temperate (T) peatlands (from the review paper, Wilson et ~~al.~~ al., 2016a). Numbers indicate the ecotype with Sphagnum Cutover = 1, Calluna Cutover = 2, Eriophorum Cutover = 3, Sub-Marginal = 4, and Sub-Central = 5.

~~There are a few cautionary notes that should accompany this plot. First, some of this data was collected using the closed chamber method and some collected using eddy covariance methods.~~

~~Although both methods measure the same metric (NEE), closed chamber methods are inherently micro-scale while eddy-covariance methods are inherently landscape scale, as are the water table measurements accompanying them. Eddy-covariance measurements spatially integrate the micro-variations within the landscape compared to closed chamber measurements, and much of the NEE data reported in Figure 11 for intact peatlands is from eddy-covariance flux towers while there are very few studies that have used this technique on degraded or recovering peatlands. This may cause apparently higher variation in NEE for restored/recovering peatlands. Second, many of the studies on boreal peatlands report only growing season NEE and water table because of frozen winter conditions. Seasonal values from these studies are assumed to approximately represent annual values because winter fluxes at boreal sites are probably of minor importance to the annual fluxes. Third, this figure contains data points from different locations as well as the same location over multiple years where data is available.~~

Similarly, annual/seasonal CH_4 emissions are plotted against MAWT (Fig. 12). Reported CH_4 emissions from drained peatlands are quite low and typically do not exceed 0.6 g C-CH_4 m^{-2} yr^{-1} when the mean annual water table is below -30 cm. There is a high degree of variability in CH_4 emissions in sites where the MAWT is higher than -20 cm. This figure excludes infilled ditches, which can be hotspots for CH_4 emissions (Waddington and Day, 2000). For example, Cooper et al. (2014) reports 53.9 g C-CH_4 m^{-2} yr^{-1} for infilled ditches (Cooper et al., 2014). There are few studies that have reported CH_4 emissions from bare peat sites, and the results are generally low (mean of -0.03 g C-CH_4 m^{-2} yr^{-1}) even at high water table. The data from the ecotypes in this study fall well within the range of the CH_4 flux values in Fig. 12 for given MAWTs~~this compilation of data.~~ ~~.~~

~~Reported CH_4 emissions from drained peatlands are quite low and typically do not exceed 0.6 g C-CH_4 m^{-2} yr^{-1} when the mean annual water table is below -30 cm.~~

~~There is a high degree of variability in CH_4 emissions in sites where the MAWT is higher than -20 cm. Thus, a high MAWT seems to be a prerequisite for high CH_4 emissions but does not necessarily result in a high CH_4 emissions, which agrees with Tiemeyer et al. (2017). As in Wilson et al. (2016a), there does not seem to be a difference between restored and intact peatlands for the CH_4 flux data presented in Figure 12, excluding infilled ditches, which can be hotspots for CH_4 emissions (Waddington and Day, 2000). For example, Cooper et al., (2014) reports 53.9 g C-CH_4 m^{-2} yr^{-1} for infilled ditches (Cooper et al. 2014). There are few studies that have reported CH_4 emissions from bare peat sites, and the results are generally low (mean of -0.03 g C-CH_4 m^{-2} yr^{-1}) even at high water table. The low CH_4 emissions from rewetted bare peat soils suggests that the methanogenesis is limited by substrate availability in cutover peatlands (Tuittila et al. 2000; Tuittila et al. 1999).~~

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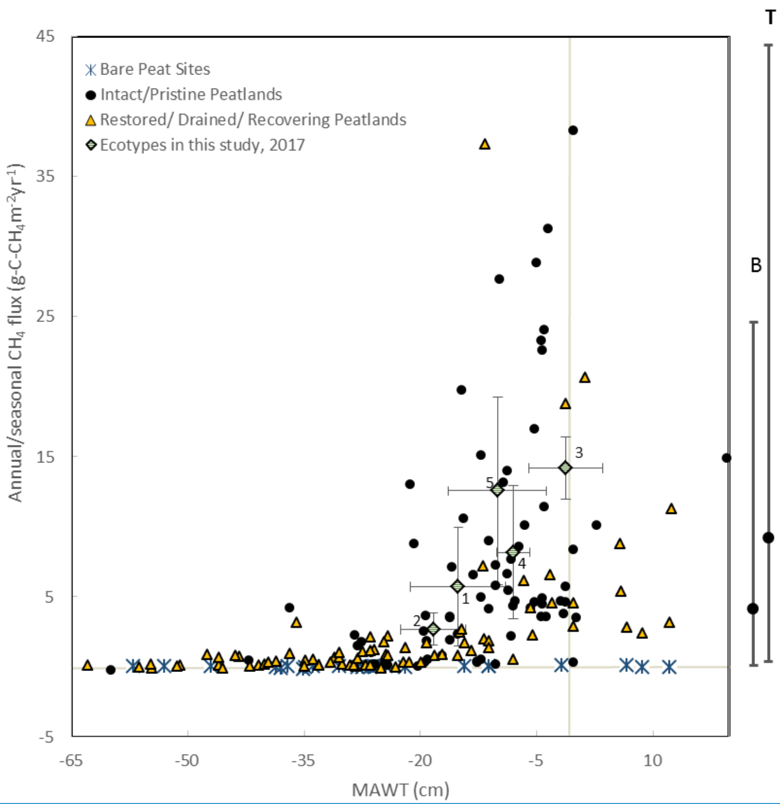

Bare Peat Sites
Intact/Pristine Peatlands
Restored/ Drained/ Recovering Peatlands
Ecotypes in this study, 2017
Annual/seasonal CH_4 flux (g-C-CH_4 $m^{-2}yr^{-1}$)
MAWT (cm)
45
35
25
15
5
-5
-65
-50
-35
-20
-5
10
1
2
3
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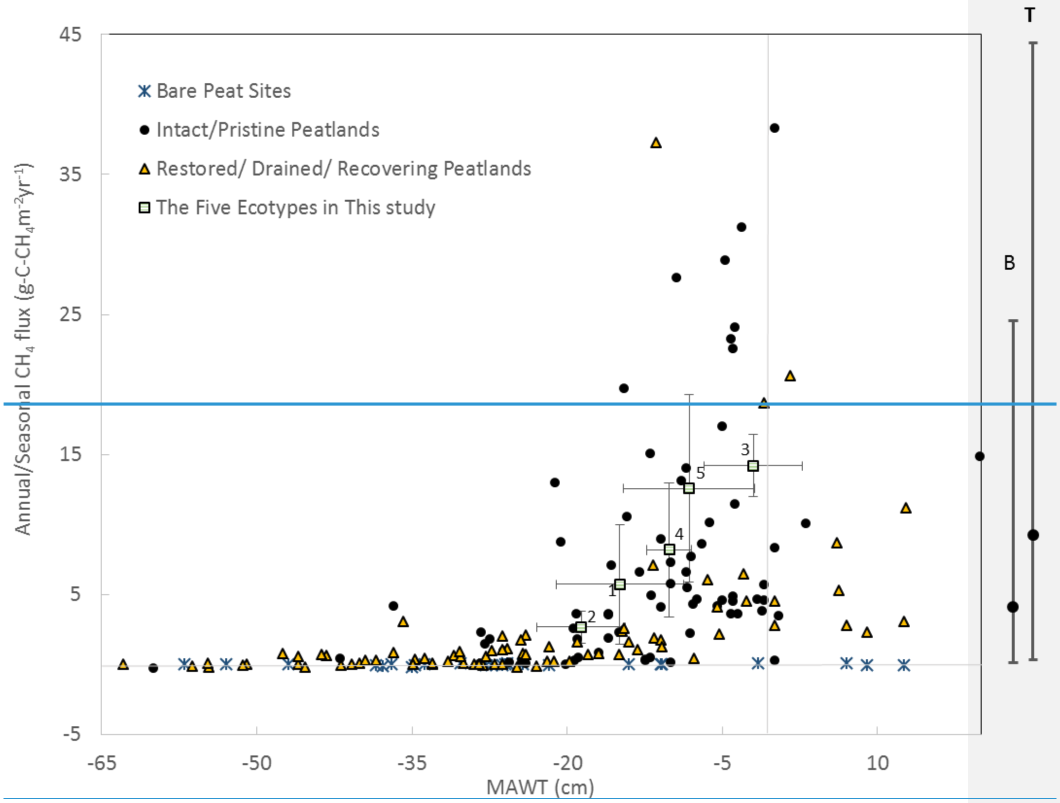

Fig. 12. This figure shows the mean annual water table plotted against the measured 2017 annual CH_4 emissions for each ecotype ~~for each ecotype~~ in this study (error bars are standard deviations) and from global studies of temperate and boreal peatlands (Sources: Flessa et ~~al.~~ al., 1998, Fieldler et ~~al.~~ al., 1998, Wilson et ~~al.~~ al., 2016; Tuitili et al., 1999; Wilson et al., 2018; Danevic et al., 2010; Von Arnold et al., 2005; Laine et al., 1996; Yamulki et al., 2012; Nykanen et al., 1998; Fieldler et al., 2007; Cooper et al., 2014; Waddington and Day, 2007; Chimner et al., 2017; Waddington and Roulet 2000; for more details see Table ~~S6~~ S9 in Supplemental Section 3. Also, shown to the right of the figure is the mean and 95% CI of CH_4 emissions from nutrient poor, wet (MAWT >-30 cm) boreal (B) and temperate (T) peatlands (from the review paper, Wilson et ~~al.~~ al., 2016a). Numbering of ecotypes is the same as in Fig. 11.

~~As with the NEE data in Figure 11, this figure contains both annual and seasonal fluxes, where seasonal fluxes are more often reported for boreal sites. This figure excludes CH_4 emissions from infilled ditches.~~ ~~There are few studies that have reported CH_4 emissions from bare peat sites, and~~

~~the results are generally low (mean of -0.03 g C-CH_4 m^{-2} yr^{-1}) even at high water table.~~ There are a few cautionary notes that should accompany these plots. First, some of this data was collected using the closed chamber method and some collected using eddy covariance methods. Although both methods measure the same metric (NEE), closed chamber methods are inherently micro-scale while eddy-covariance methods are inherently landscape scale, as are the water table measurements accompanying them. Eddy-covariance measurements spatially integrate the micro-variations within the landscape compared to closed chamber measurements. Much of the NEE data reported in Figure 11 for intact peatlands are from eddy-covariance flux towers while there are very few studies that have used this technique on degraded/restored/recovering peatlands. This may cause apparently higher variation in NEE for degraded/restored/recovering peatlands. Second, many of the studies on boreal peatlands report only growing season NEE and water table because of frozen winter conditions. Data collected from literature included in Fig 11 and Fig 12 are reported as is without attempting to account for the differences in growing season vs. annual values. Though, non-growing season gas fluxes can account for ~15% of annual fluxes for boreal peatlands (Saarnio et al., 2007). Third, this figure contains data points from different locations as well as the same location over multiple years where data is available. The data used to compile Figs. 11 and 12 and additional studies can be found in Supplemental Section 3, Table ~~S6~~S9.

4. Discussion

4.1 Comparison between ecotype NEE and CH_4 flux

~~1. Ecotype differences and ecotype trends~~

~~a. How are these ecotypes different and why.~~

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~~b. Age since restoration. Ecological trajectory. Actually a divergent trend possible. Thus, the importance of restoration early.~~

~~i. It is interesting the differences between ecotypes in both GWP,C balance, and CH4 with the same site history. i.e. the compatisions of Sub-Cent and Sub-Marginal and cutover ecotypes.~~

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~~c. How are these ecotypes different and why. Brief.~~

~~d. Aquatic losses [can be] proportionally more important for degraded peatlands.~~

~~e. Age since restoration. Ecological trajectory~~

~~Misc Pieces from thesis:~~

- ~~*This is in agreement with others studies, which have found that even relatively high quality restored bogs tend have positive overall GWP (Renou-Wilson et al., 2018).*~~
- ~~The *Sphagnum spp.* dominated ecotypes (Sphagnum Cutover and Sub-Central) were the lowest GWP sources. Additionally, *Sphagnum spp.* cover was negatively correlated to the GWP at the collar scale. In terms of restoration, this suggests that there is GHG benefit for both raising the water table as well as establishing high quality bog vegetation such as *Sphagnum spp.*~~
- ~~This may be related to the postharvest time; it has been observed that CO_2 flux in harvested peatlands can increase with postharvest time (Waddington et al., 2002). The cutover areas at Abbeyleix Bog have a longer postharvest (> 5 decades) time than many previous studies on cutover peatlands.~~

~~The Calluna Cutover ecotype was not only a larger CO_2 source than the other ecotypes in this study, but also much higher than values reported in the literature for degraded bogs at a comparable MAWT (as in Fig. 11). This may be due to the longer time post-abandonment because the CO_2 emissions can possibly increase with postharvest time (Waddington et al., 2002).~~

All of the ecotypes in this study were on average GWP sources both years, which was statistically significant for all but the Sphagnum Cutover ecotype both years. This is in agreement with others studies, which have found that even relatively high quality restored bogs tend to have positive overall GWP (Renou-Wilson et al., 2018b). The *Sphagnum spp.* dominated ecotypes (Sphagnum Cutover and Sub-Central) were on average the lowest GWP sources, and plot scale *Sphagnum spp.* cover had a statistically significant negative correlation to the GWP. In terms of restoration, this suggests that there is a direct GHG benefit for establishing high quality bog vegetation such as *Sphagnum spp.*

There is some debate about the use of GWP as a metric for peatlands because this metric focuses on a 100-year time window, which may not be appropriate. For example, "the long-term sequestration of CO_2 into stable organic matter gradually outweighs the warming effect of CH_4, due to the shorter atmospheric lifetime of the latter, so that natural peatlands exert a net cooling impact on the atmosphere over longer periods" i.e. the Holocene (Evans et al., 2016; Frolking et al., 2006). This means that peatland *preservation* is beneficial (in terms of warming impact) despite CH_4 emissions. However, peatland *restoration* may impact the eco-hydrological trajectory on a shorter time scale (i.e. decadal as opposed to millennial) in which case, the increased CH_4 emissions resulting from restoration works (such as raising the water table) may be proportionally more important to

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consider for the overall greenhouse gas effect. This would mean that 100-year GWP may be a more appropriate metric for restored peatlands than intact peatlands.

It is interesting to observe that ecotypes with identical site history, close physical proximity, similar soils, and only subtle differences in hydrology can have substantial differences in the NEE, CH_4 flux, and resulting GWP. In the cutover areas of Abbeyleix Bog, a mosaic of ecotypes has naturally developed in the time since abandonment. The resulting ~~carbon balance~~ C cycling is highly spatially variable throughout the cutover bog: the Calluna Cutover ecotype is a considerable carbon source; the Eriophorum Cutover ecotype is approximately carbon neutral; and the Sphagnum Cutover ecotype is on average a moderate carbon sink. Also, the Eriophorum Cutover ecotype was found to produce much higher CH_4 emissions than the other two cutover ecotypes. The Sphagnum Cutover ecotype in this study was a statistically significant lower GWP source than the other ecotypes on the cutover bog and a substantially lower CO_2 source than the Calluna Cutover Ecotype, ~~on average a lower CO_2 source and GWP source than the other ecotypes on the cutover bog~~ although the Sphagnum Cutover ecotype was located within 30 m of the Calluna Cutover ecotype.

The Calluna Cutover ecotype was not only a larger CO_2 source than the other ecotypes in this study, but also much higher than values reported in the literature for degraded/restored/recovering bogs at a comparable MAWT (as in Fig. 11). This may be due to the longer time post-abandonment than many other studies because the CO_2 emissions from peat soils can possibly increase with postharvest time (Rankin et al., 2018; Waddington et al., 2002). If this is true, differences in eco-hydrological trajectory (e.g. between the Sphagnum Cutover and Calluna Cutover ecotypes) may

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even result in a divergent trend in the global warming impact over time, which would underscore the important of restoration as soon as possible postharvest.

Similarly, the two ecotypes on the restored raised bog share a similar site history, i.e. both were restored by drain blocking 6 years prior to the start of the study. The Sub-Central ecotype was on average a C sink while the lower quality Sub-Marginal area was on average a moderate carbon source in 2016 and 2017 despite only minor differences in hydrology (Fig. 3). This is an example where the successful restoration of a continuous *Sphagnum* moss layer has resulted in an improved C sink. The Sub-Central ecotype had an average annual NEE that was similar to other studies on intact bog locations (as in Fig. 11, & Helftler et al., 2015; McVeigh et al., 2014; Nugent et al., 2018, etc.). This demonstrates that restored bogs can be returned to a similar CO_2 sink as intact bogs agreeing with Nugent et al. (2018), depending on the initial level of disturbance (Renou-Wilson et al., 2018a).

The eco-hydrological conditions seem to be what determines GHG emissions, rather than time since restoration/abandonment.

~~The Calluna Cutover ecotype was found to be a substantial carbon source and this is likely due to a lower water table and a plant ecology reflective of a degraded peatland. The Calluna Cutover ecotype was not only a larger~~ $\cancel{CO_2}$ ~~source than the other ecotypes in this study, but also much higher than values reported in the literature for degraded bogs at a comparable MAWT (as in Fig. 11). This may be due to an increase in~~ $\cancel{CO_2}$ ~~emissions with postharvest as hypothesized by Waddington et al. (2002) because the time since abandonment of cutover areas of Abbeyleix Bog is relatively long (>~~

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~~5 decades). This may even result in a divergent trend in the global warming impact over time, which would underscore the important of restoration as soon as possible postharvest. The Eriophorum Cutover ecotype has the highest mean annual water table and the highest *Eriophorum spp.* cover; both of which are related to an increase in the observed methane flux. Even with the increased methane flux at the Eriophorum Cutover ecotype, the GWP at this ecotype was not higher than the Calluna Cutover ecotype. This agrees with Wilson et al. (2016b), where a rewetted bog in Ireland was found to have a lower GWP than a well-drained site even where *Eriophorum angustifolium* developed. The *Sphagnum spp.* dominated ecotypes (Sphagnum Cutover and Sub-Central) were on average the lowest GWP sources, and plot scale *Sphagnum spp.* cover was negatively correlated to the GWP. In terms of restoration, this suggests that there is GHG benefit establishing high quality bog vegetation such as *Sphagnum spp.*~~

~~similar soils,~~

~~The eco-hydrological conditions seem to be what determines GHG emissions, rather than time since restoration.~~ The data here do not support the hypothesis that time since restoration/abandonment~~abondonment~~ *per se* is an important factor in the GHG emissions (once vegetation is established as discussed below). This is evidenced by the fact that ecotypes with the same site history (e.g. the cutover ecotypes or the raised bog ecotypes) can have very different C cycling. Also, locations with very different site history (e.g. the Sphagnum Cutover and Sub-Central ecotypes) can have similarities in plant ecology, C balance, and GWP. ~~For example, all three of the cutover sites were presumably abandoned at the same time (circa 1960's). However, these three~~

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~~sites have very different CO_2 and CH_4 emissions despite their close physical proximity (within 200 m), similarities in soil, and a shared site history. Similarly, the raised bog ecotypes (Sub-Central and Sub-marginal) were restored more recently by drain blocking in 2009. The average carbon balance and GWP of the Sub-Marginal ecotype falls within the range of the much older cutover ecotypes, and the Sub-Central ecotype has a similar average GWP to the Sphagnum Cutover ecotype. This hypothesis would only be true if is there is an eco-hydrological trajectory in the years post restoration/abandonment where *Eriophorum spp.* cover decreases or *Sphagnum spp.* cover increases, for example. Further, although the Calluna Cutover location is much higher carbon source than the Sub-Marginal or Sub-Central locations. This area is similar ecologically (and presumably in terms of hydrologic conditions) to the large areas of the uncut raised bog, which are heavily degraded. This type of habitat seems to be the most common habitat in the cutover areas in Abbeyleix bog, and is probably similar to much of the degraded bog areas in Ireland. In the absence of restoration works, this ecotype remains a large carbon source more than 5 decades after abandonment.~~

~~There is a need for simple methodologies to predict greenhouse emissions from peatlands for policy and management, particularly from data that are available at the regional or national scale. Water table, vegetation cover, and soil temperature have been previously suggested as potential predictive metrics of GHG fluxes from peatlands (Strack et al. 2016). Hence, a simple linear regression based on MAWT (in cm below ground level) and percent genus cover was fit to the data from the 29 collars in this study to predict the annual carbon balance **(Eq. (3), r^2 = 0.71) and CH_4 flux (Eq. (4), r^2 = 0.56).**~~

~~**Annual** carbon **balance = 117.9 - 6.23*(MAWT) - 2.1*(Percent *Sphagnum spp.*) (3)**~~

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~~**Annual CH_4 Flux = 12.23 + 0.440*(MAWT) + 0.0754*(Percent *Eriophorum spp.*)**~~

~~In the cutover areas of Abbeyleix Bog, a mosaic of ecotypes have naturally developed in the time since abandonment. The resulting carbon balance is highly spatially variable throughout the cutover bog: the Calluna Cutover ecotype a considerable carbon source; the Eriophorum Cutover ecotype approximately carbon neutral; and the Sphagnum Cutover ecotype on average a moderate carbon sink. Also, the Eriophorum Cutover ecotype was found to produce much higher methane emissions than the other two cutover ecotypes.~~

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~~The Sphagnum Cutover ecotype in this study was on average a lower CO_2 source and GWP source than the other ecotypes on the cutover bog although the location of this ecotype was within 30 m of the Calluna Cutover ecotype. The Calluna Cutover ecotype was not only a larger CO_2 source than the other ecotypes in this study, but also much higher than values reported in the literature for degraded bogs at a comparable MAWT (as in Fig. 11.4). This may be due to the longer time post-abandonment because the CO_2 emissions can possibly increase with postharvest time (Waddington et al., 2002). For these two ecotypes, this may even result in a divergent trend in the global warming impact over time, which would underscore the important of restoration as soon as possible postharvest. All of the ecotypes on the cutover bog have similar soils, site history, climate, etc. which means that subtle difference in the micro-scale hydrology has resulted in very different eco-hydrological trajectories and global warming impact.~~

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~~On the restored raised bog, the Sub-Central ecotype was on average a carbon sink while the lower quality Sub-Marginal area was on average a moderate carbon source over 2016 and 2017 despite similarities in hydrology (e.g. Fig. 7.2). This shows an example where areas with a successful restoration of bog habitat result in an improved global warming impact. The Sub-Central ecotype had an average annual NEE that was similar other studies on high quality bog locations. This demonstrates that restored bogs can be returned to a similar CO_2 sink as pristine raised bogs, at least when the initial disturbance is minimal.~~

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4.2. Aquatic carbon losses

~~1. Comparison to other studies in *other* aspects of the C balance~~
    ~~a. le format. Even though other aspects of the carbon balance are Aquatic losses [can be] proportionally more important for degraded peatlands.~~

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Only a handful of previous studies have concurrently quantified annual fluxes of all major aspects of the C balance for a peatland site (Table 2). Of these, only one study, to the authors' knowledge, (Nugent et al., 2018) has concurrently measured annual NEE, CH_4 flux, and DOC flux for a restored peatland site.

Table 2. This table shows the average annual C balance from various studies which have measured multiple aspects of the C balance. All units are in g-C m^{-1} yr^{-1}, with a negative sign convention indicating C uptake to the bog. Where two or three years of data were available the range is given (min to max), where more years of data were available ±SD is included.

		Restored 14 years previously	Intact peatlands		
Reference	This study	Nugent et al., 2018	Nillson et al., 2008	Dinsmore et al., 2010	Nugent et al., 2018
Location	Abbeyleix Bog, Ireland	Bois-des-Bel peatland in Quebec, Canada	Degerö Stormyr, Northern Sweden	Auchencorth Moss, Scotland	Mer Bleue peatland, Ontario Canada
Study Period	2016–2017	2014–2016	2004–2005	2007–2008	1998–2014
NEE	(-92 to +219)†	-90 (-105 to -70)	-50 (-55 to -44)	-115 (-136 to -93.5)	-73 ± 40
CH_4 flux	(2.7 to 14.2)†	4.4 (4.2 to 4.5)	11.5 (9 to 14)	0.32 (0.29 to 0.35)	6.0 ± 4.0
DOC	10.4 (8.0 to 12.8)	6.9 (4.8 to 9.2)	13.0 (11.9 to 14.0)	25.4 (18.6 to 32.2)	17 ± 3.0
DIC‡	1.3 (1.1 to 1.5)	--	4.6 (3.1 to 6.0)	2.0 (2.0 to 2.1)	--
CO_2 evasion	2.7§	--	--	12.7 (11.5 to 13.9)	--
Other C losses/ gains	--	--	-1.1 (-1.3 to -0.8)	2.3 (0.51 to 4.03)	--
Carbon Balance	--	-78 (-94 to -61)	-23.5 (-27 to -20)	-70 (-101 to -38.2)	-50 ± 40

†Range for various ecotypes
‡Including super saturated CO_2 as DIC
§In the vicinity of the Sub-Marginal ecotype, this value was found to be 7.2 g-C-CO_2 m^{-1} yr^{-1} because of more open water surface area from blocked ditches.

The annual C export as DOC measured in this study was lower than the value reported in Dinsmore et al. (2010) from Auchencorth Moss, Scotland, which is similarly located in a temperate oceanic climate. The annual DOC export measured at Abbeyleix Bog was also on the lower end of the range (5–36 g C m^{-2} yr^{-1}) reported for temperate peatlands in the review by Evans et al. (2016). ~~The total~~

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~~NECB was also measured for a Boreal oligotrophic mire in northern Sweden (Nilsson et al. 2008) and Auchencorth Moss, a lowland bog in Scotland (Dinsmore et al. 2010). The average annual DOC losses found in this study (10.4 g C m^{-2} yr^{-1}) are comparable to the average annual losses reported in Nillson et al. (2008) of 13.0 g C m^{-2} yr^{-1} and lower than those reported Dinsmore et al. (2010) of 25.4 g C m^{-2} yr^{-1}.~~ The DIC losses in this study (1.3 g C m^{-2} yr^{-1}, including super-saturated CO_2 as DIC) are lower than the values reported in Nilsson et~~ al.~~ (al. (2008) and Dinsmore et~~ al.~~ (al. (2010) of 2.0 and 4.6 g C m^{-2} yr^{-1}, respectively. This is partially because the average DIC concentration measured in this study (4.6 ±1.1 mg C ~~/~~L~~L~~$^{-1}$) is somewhat lower than that reported in Nillson et~~ al.~~ (al. (2008) of 9.6 mg C~~/~~ L~~L~~$^{-1}$ and at Auchencorth Moss (Dinsmore et~~ al.~~ al., 2013) of 8.65 mg C~~/~~ L~~L~~$^{-1}$. The annual open water CO_2 evasion found in this study (2.7 or 7.2 g C m^{-2} yr^{-1}) is lower than what was reported in Dinsmore et~~ al.~~ (al. (2010) (12.7 g C m^{-2} yr^{-1}), but this is dependent on the geometry of the system as water surface area is a factor in the calculation. Also, the floating chamber method used in this study may have underestimated total CO_2 evasion (Dinsmore et~~ al.~~ al., 2010).

~~The overall two year average aquatic carbon loss found in this study (14.4 g C m^{-2} yr^{-1}) is comparable to Nilsson et al. (2008) (17.8 g C m^{-2} yr^{-1}) and lower than Dinsmore et al. (2010) (43.8 g C m^{-2} yr^{-1}).~~

~~For the first time, all of the major aspects of the carbon balance were measured simultaneously in a recovering peatland. Also, the carbon balance of ecotypes with different degradation histories was compared for a naturally recovering old cutover bog and a restored unharvested raised bog.~~ Although the NEE is the most variable component of the C~~carbon~~ balance ~~and~~ and often drives the

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~~4.2~~4.3 *Implications for Peatland Management and Restoration*

~~2. Implications for management:~~

~~a. Management can impact hydrology and ecology. Figs can be used to compare the impact of vegetation of bare peatlands and raising water levels.~~

~~b. GWp as a peatland metric, time scale and restoration~~

~~There is some debate about the use of GWP as a metric for natural peatlands because this metric focuses on a 100-year time window, which may not be appropriate. For example, "the long-term sequestration of CO_2 into stable organic matter gradually outweighs the warming effect of CH_4, due to the shorter atmospheric lifetime of the latter, so that natural peatlands exert a net cooling impact on the atmosphere over longer periods" (Evans et AL., 2016; Frolking et al., 2006) i.e. the Holocene. This means that peatland *preservation* is beneficial (in terms of greenhouse gasses) despite CH_4 emissions. However, peatland *restoration* works may impact the eco-hydrological trajectory on a shorter time scale (i.e. decadal as opposed to millennial) in which case, the methane emissions may be proportionally more important to consider for the overall greenhouse gas budget for restoration works.~~

~~c. GWP response with respect to MAWT~~

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~~i. Generally, other studies show an improvement, but is highly variable because of variable methane emissions.~~

~~ii. Variable based on data in fig 11 and 12~~

~~iii. Sphagnum has GWp benefit from this study~~

~~d. Vegetation:~~

~~i. Bare peat~~

~~ii. Value of encouraging Sphagnum (not isolated from hydrology)~~

Peatland management and restoration is primarily able to alter 1) the hydrology, typically managing the water table through drainage or drain blocking and 2) the plant ecology, through revegetation efforts and controlling invasive species (Andersen et al., 2017). If peatland management is used as a climate change mitigation tool [as suggested in Birkin et al. (2011); Wilson et al. (2013); Leifeld and Menichetti (2018)], then, the impact of these actions on C balance, CH_4 flux, and GWP must be considered. The trends in Fig. 11 could be used to predict the NEE impact of rewetting and/or revegetating a peatland. However, the trend in NEE with respect to MAWT in Fig. 11 should be interpreted with some caution because of the difficulty of generalizing across sites based on simple water table proxies (Wilson et al., 2016a). For example, there was a “highly

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peatland-specific dependency (i.e., with different offsets and slopes) of the CO_2 response to water table depth" for grassland peatlands in Germany (Tiemeyer et al., 2017). The reader is directed toward various formal literature reviews, which have considered the impact of re-wetting or water table on peatland CO_2 and CH_4 emissions (Haddaway et al., 2014; Junkurst and Fielder, 2007; Saarnio, et al., 2007; Turetsky et al., 2014; ~~Junkurst and Fielder 2007, hadaway, 2014?~~ Wilson et al., 2016a).

Higher water table generally corresponds to increased CH_4 emissions and reduced CO_2 emissions (Wilson et al., 2016a), which was found in this study as well. For sites with a higher water table, the CO_2 uptake tends to outweigh the higher CH_4 emissions (Junkurst and Fielder, 2007) such that rewetting of a drained peatland has often been observed to result in an overall reduction in GWP (Renou-Wilson et al., 2018b; Wilson et al., 2016a; Wilson et al., 2016b). However, this is not necessarily the case because of the high degree of variability for reported methane emissions. For example, in this study, the Eriophorum Cutover ecotype (with the highest MAWT) was found to have a higher GWP than the Sphagnum Cutover ecotype (with a much lower MAWT) both years. Also, this study found that the plot scale GWP showed no trend with respect to MAWT.

~~a.~~

~~b.~~ MAWT~~Thus, a high MAWT seems to be a prerequisite for high CH_4 emissions but does not necessarily result in a high CH_4 emissions, which agrees with Tiemeyer et al. (2017).~~

~~c. Vegetation~~

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~~Establishing moss dominated vegetation important. Do you have support for this other than your study? Raising the water table of a degraded bog does not necessarily result in the development of high quality bog vegetation. Do you have support for this other than your study? For a successful ecological restoration, the complex eco-hydrological function of raised bogs has to be replicated.~~ ~~The low CH_4 emissions from rewetted bare peat soils suggests that the methanogenesis is limited by substrate availability in cutover peatlands (Tuittila et al. 2000; Tuittila et al. 1999).Also, a~~As shown in Figure 11, bare peat sites have a higher NEE than vegetated sites at a given MAWT, and these trend lines diverge at higher MAWT. As it can take decades for vegetation to be established in industrially mined peatlands (Wilson et al., 2015), th~~is~~ese data would suggest that restoration to encourage plant colonization could reduce the short term CO_2 emissions even if no other restoration works are undertaken. ~~This data set could be used to predict the CO_2 reduction from raising the water table as well as establishing vegetation on bare peat sites.~~ Further, peatlands may be large C sinks in the years immediately post restoration as vegetation recovers due to the rapid, subsequent increase in vegetation biomass. For example, an annual NEE of -473 g C-CO_2 m^{-2} yr^{-1} was reported by Waddington et ~~al. (~~al. (2010) one year post restoration for sites where herbaceous vegetation increased dramatically. This may explain some of the low outliers in Figure 11 for degraded/restored/recovering~~restored/recovering~~ sites. Three of the low outliers in Figure 11 are from Strack et ~~al. (~~al. (2014), which is 4 years post restoration with a growing season NEE of -162, -121- and -126 g C-CO_2 m^{-2} for plots with mean seasonal water tables of -21.3, -24.9 and -28.2 cm, respectively. On the other hand, the low CH_4 emissions from rewetted bare peat soils suggests that the methanogenesis is limited by substrate availability in cutover peatlands (Tuittila et al., 2000; Tuittila et al., 1999).Thus, establishing vegetation on a cutover peatland could increase methane

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emissions compared to bare peat, even so restored peatlands often have lower CH_4 flux than intact reference sites (e.g. Nugent et al., 2018).

The results from this study demonstrate the importance of establishing a *Sphagnum* moss for C sink and GWP. This is somewhat contradictory to Wilson et al. (2016b), who found that locations in a restored Irish peatland with only *Eriophorum angustifolium* had a stronger CO_2 sink and lower GWP than locations with *Eriophorum* and *Sphagnum* together. Still, the successful restoration of *Sphagnum* on a mined peatland has been found to result in a stable and strong C sink and a low CH_4 emissions (e.g. Nugent et al., 2018). Also, Strack et al. (2016) found that variation in CO_2 and CH_4 flux was lower for natural sites, with a high percent moss cover, than restored sites with a lower percent moss cover. Thus, the re-establishment of *Sphagnum* moss seems to be tied to a consistent C sink function.

~~*From Thesis Conclusion chapter may be useful.*~~

~~Despite the considerable amount of recent scientific work on the greenhouse emissions from peatlands, few previous studies have quantified the carbon balance of old abandoned cutover peatlands (Bacon et al., 2017). Many studies have focused on more recently abandoned/restored degraded bogs. This may be because of the recent change in attitudes towards peatland conservation and restoration (Holden et al., 2004), which means that many bog restoration projects are relatively recent. The focus on the cutover ecotypes investigated in this study is therefore valuable because it the potential future climate impact of abandoned cutover bogs under the "do-nothing" restoration approach (Holden et al., 2004). This is especially true in Ireland because substantial areas of the Irish midland bogs are currently used in industrial peat harvesting, which is scheduled to cease in the coming decades (Bord na Móna website).~~

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~~In the cutover areas of Abbeyleix Bog, a mosaic of ecotypes have naturally developed in the time since abandonment. The resulting carbon balance is highly spatially variable throughout the cutover bog: the Calluna Cutover ecotype a considerable carbon source; the Eriophorum Cutover ecotype approximately carbon neutral; and the Sphagnum Cutover ecotype on average a moderate carbon sink. Also, the Eriophorum Cutover ecotype was found to produce much higher methane emissions than the other two cutover ecotypes.~~

~~The Sphagnum Cutover ecotype in this study was on average a lower CO_2 source and GWP source than the other ecotypes on the cutover bog although the location of this ecotype was within 30 m of the Calluna Cutover ecotype. The Calluna Cutover ecotype was not only a larger CO_2 source than the other ecotypes in this study, but also much higher than values reported in the literature for degraded bogs at a comparable MAWT (as in Fig. 11.4). This may be due to the longer time post-abandonment because the CO_2 emissions can possibly increase with postharvest time (Waddington et al., 2002). For these two ecotypes, this may even result in a divergent trend in the global warming impact over time, which would underscore the important of restoration as soon as possible postharvest. All of the ecotypes on the cutover bog have similar soils, site history, climate, etc. which means that subtle difference in the micro-scale hydrology has resulted in very different eco-hydrological trajectories and global warming impact.~~

~~On the restored raised bog, the Sub-Central ecotype was on average a carbon sink while the lower quality Sub-Marginal area was on average a moderate carbon source over 2016 and 2017 despite similarities in hydrology (e.g. Fig. 7.2). This shows an example where areas with a successful restoration of bog habitat result in an improved global warming impact. The Sub-Central ecotype had an average annual NEE that was similar other studies on high quality bog locations. This demonstrates that restored bogs can be returned to a similar CO_2 sink as pristine raised bogs, at least when the initial disturbance is minimal.~~

~~Previous 4.1~~

~~The Calluna Cutover ecotype was found to be a substantial carbon source and this is likely due to a lower water table and a plant ecology reflective of a degraded peatland. The Eriophorum Cutover ecotype has the highest mean annual water table and the highest *Eriophorum spp.* cover; both of which are related to an increase in the observed methane flux. Even with the increased methane flux at the Eriophorum Cutover ecotype, the GWP at this ecotype was not higher than the Calluna Cutover ecotype. This agrees with Wilson et al. (2016b), where a rewetted bog in Ireland was found to have a lower GWP than a well-drained site even where *Eriophorum angustifolium* developed. The *Sphagnum spp.* dominated ecotypes (Sphagnum Cutover and Sub-Central) were the lowest average GWP sources, and *Sphagnum spp.* cover was negatively correlated to the GWP at the collar scale. In terms of restoration, this suggests that there is GHG benefit for both raising the water table as well as establishing high quality bog vegetation such as *Sphagnum spp.*~~

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~~The eco-hydrological conditions seem to be what determines GHG emissions, rather than time since restoration. The data here do not support the hypothesis that time since restoration/abondonment *per se* is an important factor in the GHG emissions (once vegetation is established as discussed below). For example, all three of the cutover sites were presumably abandoned at the same time (circa 1960's). However, these three sites have very different CO_2 and CH_4 emissions despite their close physical proximity (within 200 m), similarities in soil, and a shared site history. Similarly, the raised bog ecotypes (Sub-Central and Sub-marginal) were restored more recently by drain blocking in 2009. The average carbon balance and GWP of the Sub-Marginal ecotype falls within the range of the much older cutover ecotypes, and the Sub-Central ecotype has a similar average GWP to the Sphagnum Cutover ecotype. This hypothesis would only be true if is there is an eco-hydrological trajectory in the years post restoration/abandonment where *Eriophorum spp.* cover decreases or *Sphagnum spp.* cover increases, for example. Further, although the Calluna Cutover location is much higher carbon source than the Sub-Marginal or Sub-Central locations. This area is similar ecologically (and presumably in terms of hydrologic conditions) to the large areas of the uncut raised bog, which are heavily degraded. This type of habitat seems to be the most common habitat in the cutover areas in Abbeyleix bog, and is probably similar to much of the degraded bog areas in Ireland. In the absence of restoration works, this ecotype remains a large carbon source more than 5 decades after abandonment.~~

~~There is a need for simple methodologies to predict greenhouse emissions from peatlands for policy and management, particularly from data that are available at the regional or national scale. Water table, vegetation cover, and soil temperature have been previously suggested as potential predictive metrics of GHG fluxes from peatlands (Strack et al. 2016). Hence, a simple linear regression based on MAWT (in cm below ground level) and percent genus cover was fit to the data from the 29 collars in this study to predict the annual carbon balance (Eq. (3), $r^2 = 0.71$) and CH_4 flux (Eq. (4), $r^2 = 0.56$).~~

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~~Annual carbon balance = 117.9 - 6.23*(MAWT) - 2.1*(Percent *Sphagnum spp.*) (3)~~

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~~Annual CH_4 Flux = 12.23 + 0.440*(MAWT) + 0.0754*(Percent *Eriophorum spp.*) (4)~~

~~where annual carbon balance and annual CH_4 flux are in units of g C m^{-2} yr^{-1}. While these coefficients are site specific, these metrics may be useful for comparison to future studies.~~

~~**4.2 Comparisons with Global Studies of Boreal and Temperate Peatlands**~~

~~The annual NEE, CH_4 flux, and water table data from the ecotypes in this study were compared to global studies of boreal and temperate peatlands. The data from global studies was divided into three generic categories as follows:~~

- ~~Pristine/Intact peatlands; - those peatlands that have not been harvested, undergone intensive agriculture or forestry, and are not heavily impacted by drainage or other disturbance;~~
- ~~Bare peat sites; - previous peat extraction sites where there is an absence of vegetation cover;~~

- ~~Restored/Degraded/Recovering peatlands; - all other peatlands are grouped into this category for this comparison.~~

~~This compilation of data focuses on low nutrient (if specified, pH<6) natural and semi-natural sites and excludes sites that are actively used for intensive agriculture or forestry.~~

~~For both vegetated and bare peat sites, there is a negative correlation between MAWT and NEE (Fig. 11). Both intact peatlands and variously degraded/recovering peatlands fall on the same trend line, agreeing with Wilson et al. (2016a). Annual NEE for vegetated sites followed a linear trend with respect to MAWT with slope of -4.5 g C-CO_2 m^{-2} yr^{-1} per cm rise in MAWT and an intercept of -92 g C-CO_2 m^{-1} yr^{-1}. The slope is similar to that reported from a review of studies of peatlands with MAWT higher than -30 cm (Wilson et al. 2016a) of -2.0 ±1.0 and -5.0 ±2.0 g C-CO_2 m^{-2} yr^{-1} per cm rise in MAWT for boreal and temperate peatlands, respectively. However, the trend in NEE with respect to MAWT should be interpreted with some caution because of the difficulty of generalizing across sites based on simple water table proxies (Wilson et al. 2016a). For example, there was a "highly peatland-specific dependency (i.e., with different offsets and slopes) of the CO_2 response to water table depth" for grassland peatlands in Germany (Tiemeyer et al. 2017), although, that study looked at grasslands, which may have much more variability in soil type, land management, nutrient status, etc. than the natural and semi-natural low nutrient sites shown in Figure 11. This trend may also break down as MAWT becomes too low (e.g. Tiemeyer et al. 2017) because soil respiration can be limited if the soil is too dry (Briones et al., 2014). Thus, climate patterns could be an important factor in CO_2 response to water table (Tiemeyer et al. 2017).~~

~~Based on the data collected in Figure 11, intact peatlands occur at a narrower range of mean annual water table and NEE. This is expected because degraded peatlands can have a wider range of site histories and eco-hydrological conditions (Wilson et al. 2016a). This agrees with Strack et al. (2016) who reported greater variation in CO_2 and CH_4 fluxes at restored plots when compared to either unrestored or natural plots. As with data from this study, this may suggest that restoration of high quality peatland ecology has an additional NEE benefit beyond raising the water table.~~

~~The Sub-Central ecotype in this study has continuous *Sphagnum spp.* lawns similar to an intact peatland. This ecotype has a mean annual NEE of -57 g C-CO_2 m^{-2} yr^{-1} and a mean annual water table of -8.2 cm. This is close to the overall average NEE (-60 g C-CO_2 m^{-2} yr^{-1}) and mean annual water table (-9 cm) for intact/pristine peatlands in this figure. This comparison is valuable for validating the data for the other ecotypes because the carbon balance of natural bogs is comparatively better characterized than degraded systems and the potential for systematic bias in chamber measurements. The Calluna Cutover ecotype from this study has an exceptionally high NEE (222 g C-CO_2 m^{-2} yr^{-1}) for the mean annual water table (-18.6 cm) compared to the NEE (-5 g C-CO_2 m^{-2} yr^{-1}) predicted from the best fit trend line of vegetated sites.~~

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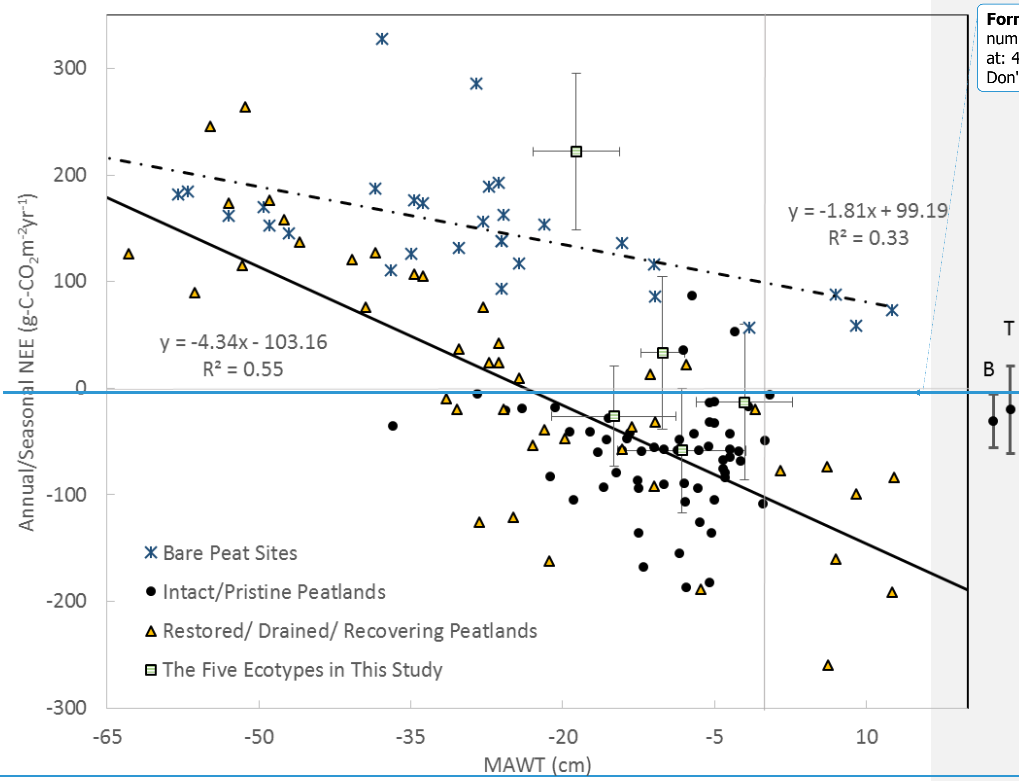
~~Also, as shown in Figure 11, bare peat sites have a higher NEE than vegetated sites at a given MAWT, and these trend lines diverge at higher MAWT. As it can take decades for vegetation to be established in industrially harvested peatlands (Wilson et al., 2015), this data would suggest that restoration to encourage plant colonization could reduce the short term CO_2 emissions even if no other restoration works are undertaken. This data set could be used to predict the CO_2 reduction from raising the water table as well as establishing vegetation on bare peat sites. Further, peatlands may be large carbon sinks in the years immediately post restoration as vegetation recovers due to the rapid, subsequent increase in vegetation biomass. For example, an annual NEE of -473 g C-CO_2 m^{-2} yr^{-1} was reported by Waddington et al. (2010) one year post restoration for sites where herbaceous vegetation increased dramatically. This may explain some of the low outliers in Figure 11 for restored/recovering sites. Three of the low outliers in Figure 11 are from Strack et al. (2014), which is 4 years post restoration with a growing season NEE of -162, -121- and -126 g C-CO_2 m^{-2} for mean seasonal water tables of -21.3, -24.9 and -28.2 cm, respectively.~~



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~~Figure 11.~~ ~~**Mean annual water table vs. the annual NEE for the 5 ecotypes in this study (error bars are standard deviation) compared to global studies from boreal and temperate peatlands. The solid line shows the best fit linear trend line from all vegetated sites and the dashed line shows the best fit trend line for bare peat sites. (Data from: Wilson et al., 2015; Wilson et al., 2016; Vanslow-Algan et al., 2015; Tuittili et al., 1999; Waddington et al., 2010; Strack et al., 2014; Nilsson et al., 2008; Dinsmore et al., 2010; Koehler et al., 2011; Chimner et al., 2017; Gazovic et al., 2013; Lund et al., 2012; Levy and Grey et al., 2015; McVeigh et al., 2014; Helftler et al., 2015; Piechl et al., 2014; Stranchen et al., 2016; Roulet et al., 2007; Waddington and Roulet, 2000; for more details and additional studies see Supplemental Table S6 in Supplemental Section 3). Also, shown to the right of the figure is the mean and 95% CI NEE from nutrient poor, wet (MAWT >-30 cm) boreal (B) and temperate (T) peatlands (from the review paper, Wilson et al. 2016a).**~~

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~~There are a few cautionary notes that should accompany this plot. First, some of this data was collected using the closed chamber method and some collected using eddy covariance methods. Although both methods measure the same metric (NEE), closed chamber methods are inherently micro-scale while eddy-covariance methods are inherently landscape scale, as are the water table measurements accompanying them. Eddy-covariance measurements spatially integrate the micro-variations within the landscape compared to closed chamber measurements, and much of the NEE data reported in Figure 11 for intact peatlands is from eddy-covariance flux towers while there are very few studies that have used this technique on degraded or recovering peatlands. This may cause apparently higher variation in NEE for restored/recovering peatlands. Second, many of the studies on boreal peatlands report only growing season NEE and water table because of frozen winter conditions. Seasonal values from these studies are assumed to approximately represent annual values because inter fluxes at boreal sites are probably of minor importance to the annual fluxes. Third, this figure contains data points from different locations as well as the same location over multiple years where data is available.~~

~~Similarly, annual/seasonal methane emissions are plotted against MAWT (Fig. 12). The data from the ecotypes in this study fall well within the range of the CH_4 flux values in this compilation of data. Reported methane emissions from drained peatlands are quite low and typically do not exceed 0.6 g C-CH_4 m^{-2} yr^{-1} when the mean annual water table is below -30 cm.~~

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~~There is a high degree of variability in methane emissions in sites where the MAWT is higher than -20 cm. Thus, a high MAWT seems to be a prerequisite for high methane emissions but does not necessarily result in a high methane emissions, which agrees with Tiemeyer et al. (2017). As in Wilson et al. (2016a), there does not seem to be a difference between restored and intact peatlands for the CH_4 flux data presented in Figure 12, excluding infilled ditches, which can be hotspots for methane emissions (Waddington and Day, 2000). For example, Cooper et al., (2014) reports 53.9 g C-CH_4 m^{-2} yr^{-1} for infilled ditches (Cooper et al. 2014). The low methane emissions from rewetted bare peat soils suggests that the methanogenesis is limited by substrate availability in cutover peatlands (Tuittila et al. 2000; Tuittila et al. 1999).~~

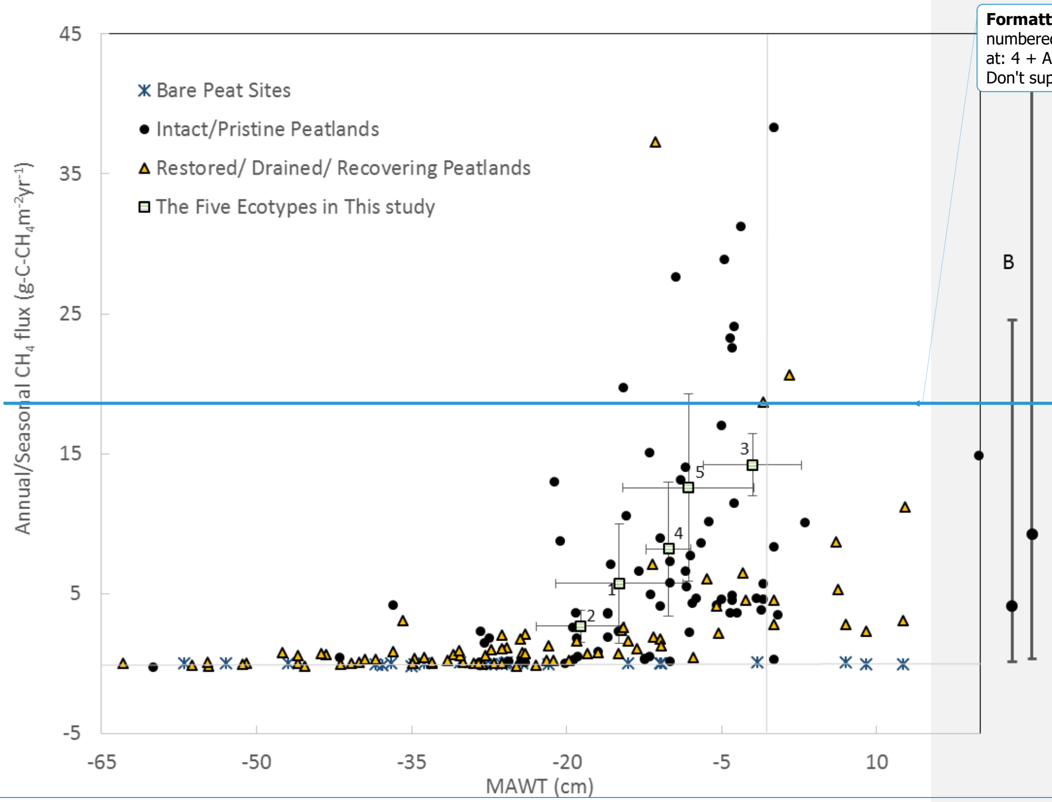

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Fig. 12. ~~This figure shows the mean annual water table plotted against the measured annual methane emissions for each ecotype for each ecotype in this study (error bars are standard deviations) and from global studies of temperate and boreal peatlands (Sources: Flessa et al. 1998, Fieldler et al. 1998, Wilson et al. 2016; Tuitili et al., 1999; Wilson et al., 2018; Danevic et al., 2010; Von Arnold et al., 2005; Laine et al., 1996; Yamulki et al., 2012; Nykanen et al., 1998; Fieldler et al., 2007; Cooper et al., 2014; Waddington and Day, 2007; Chimner et al., 2017; Waddington and Roulet 2000; for more details see Table S6 in Supplemental Section 3. Also, shown to the right of the figure is the mean and 95% CI of methane emissions from nutrient poor, wet (MAWT >-30 cm) boreal (B) and temperate (T) peatlands (from the review paper, Wilson et al. 2016a).~~

~~As with the NEE data in Figure 11, this figure contains both annual and seasonal fluxes, where seasonal fluxes are more often reported for boreal sites. This figure excludes methane emissions from infilled ditches. There are few studies that have reported methane emissions from bare peat sites, and the results are generally low (mean of -0.03 g C-CH_4 m^{-2} yr^{-1}) even at high water table. The data used to compile Figs. 11 and 12 and additional studies can be found in Supplemental Section 3, Table S6.~~

~~Previous 4.3 Implications for Peatland Management and Restoration~~

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~~Peatland management and restoration is primarily able to alter 1) the hydrology, typically managing the water table through drainage or drain blocking and 2) the plant ecology, through revegetation efforts, managing water table, and controlling invasive species (Andersen et al. 2017). If peatland management is used as a climate change mitigation tool [as suggested in Birkin et al. (2011); Wilson et al. (2013); Leifeld and Menichetti, (2018)], the impact of these things must be considered. The wide range of methane emissions reported in the literature at high water tables means that generalizations cannot be made about GWP for restored vs. pristine peatlands or GWP as a function of water table. For example, reported values of annual CH_4 fluxes in Fig. 12 from sites with a MAWT above -10 cm range from 0.3 (Nykanen et al., 1995) to 38.3 g C-CH_4 m^{-2} yr^{-1} (calculated from Junkurst and Fieldler, 2007) for intact peatlands and 0.4 (Strack et al. 2014) to 20.6 g C-CH_4 m^{-2} yr^{-1} (Renou-Wilson et al. 2018a) for restored peatlands. This corresponds to a 100-year GWP of 0.1 to 17.3 and 0.2 to 9.3 tonnes CO_2-eq ha^{-1} yr^{-1}, respectively. This range is larger than the largest reported CO_2 sink for intact peatlands of -6.9 tonnes CO_2-eq ha^{-1} yr^{-1} (calculated from Levy and Grey 2015) and far larger than the average CO_2 sink for intact peatlands of -2.2 tonnes CO_2-eq ha^{-1} yr^{-1} reported in Figure 11. Still, a GWP decrease is often observed following rewetting (Wilson et al. 2016a, Wilson et al. 2016b, Renou-Wilson et al. 2018b). Additionally, the data from this study would suggest that the presence of *Sphagnum spp.* corresponds to a decreased GWP.~~

~~Junkurst and Fielder (2007) conducted a review of CO_2 and CH_4 flux for boreal and temperate peatlands. They state that the methane fluxes in temperate peatlands are “usually found to be three orders of magnitude lower than simultaneously measured CO_2 emissions.” Thus, they conclude that the suppressed CO_2 emission from higher water table would outweigh the GWP effect of increased methane emissions. This conclusion seems unlikely to be generally true based on the data shown Figure 11 and 12.~~

~~There is some debate about the use of GWP as a metric for natural peatlands because this metric focuses on a 100-year time window, which may not be appropriate. For example, to quote from Evans et al. (2016), “as noted by Frolking et al. (2006), the long-term sequestration of CO_2 into stable organic matter gradually outweighs the warming effect of CH_4, due to the shorter atmospheric lifetime of the latter, so that natural peatlands exert a net cooling impact on the atmosphere over longer periods.” This means that the long term climate benefit of peatlands is primarily controlled by NEE. However, this logic would only apply to restoration works if these impact the eco-hydrological conditions on time scales >> 100 years.~~

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~~The ecotypes of the uncut raised bog at Abbeyleix were mapped by Bord na Móna in 2009 just after restoration works blocking surface drains and again in 2014. During this time the extent of Sub-Central area increased by approx. 2.1 ha largely at the loss of the Sub-Marginal ecotype. Assuming the values found in this study are representative of all years, the restoration works resulted in a reduction of 7.0 ± 7.7 tonnes yr^{-1} CO_2 although a smaller reduction (3.3 ± 7.6 tonnes yr^{-1}) of CO_2 equivalents. Additionally, there is a potential reduction in CO_2 emissions due to raising the water table throughout the entire 108 ha of raised bog area. The change in water table from these restoration works was not directly measured, but based on the typical depths of water in the blocked drains, there was an estimated 10–40 cm rise in water table. For the 108 ha of raised bog area, this could result in an additional reduction of 166–664 tonnes yr^{-1} of CO_2 based on the trends in Fig. 11. The impact of increased methane emissions in this case is probably minimal because the majority (67%) of the raised bog area, although with a higher water table than previously, remains as deeply drained ecotypes (Marginal or Facebank).~~

~~5.~~5 Conclusions

~~1. Opposite trends in NEE and CH4 with MAWT so no trend in GWP with MAWT. But a sig decrease in GWP with percent S cover.~~

In general, this study found large differences in carbon balance and GWP emissions of various ecotypes in a recovering cutover bog despite of the close physical proximity (within 200 m), similarities in soil, and a shared site history. This highlights the importance of microscale hydrological variations on the eco-hydrological trajectory and need for more research on the eco-hydrology of degraded bogs as well as the requirements for successful restoration. On both a

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recovering cutover bog and a drain blocked raised bog, lower GWP was observed where there had been recovery of high quality peatland vegetation such as *Sphagnum spp.*

At the plot scale, t~~T~~he trends in CH_4 flux and ~~carbon~~ C balance with respect to MAWT offset each other such that there is no trend in GWP with respect to ~~mean annual water table~~MAWT. The collar annual average GWP showed~~has~~ a highly significant negative linear correlation with the plot scale percent *Sphagnum spp.* cover. Altogether, ~~T~~this demonstrates the greenhouse gas benefit of restoring degraded bogs back to active, *Sphagnum* dominated systems.

~~In general, this study found large differences in carbon balance and GWP emissions of various ecotypes in a recovering cutover bog despite of the close physical proximity (within 200 m), similarities in soil, and a shared site history. Both a recovering cutover bog and a drain blocked raised bog can have low GWP if there is recovery of high quality peatland vegetation such as *Sphagnum spp.*~~

As degraded peatlands are major aspects of the European landscape and given their importance to global greenhouse gas emissions, it is valuable to continue building a database of greenhouse gas emissions from peatlands and the effects of peatland management and restoration. This requires three aspects of future research: 1. More field data is ~~valuable~~ needed to thoroughly characterize the wide range of peatlands and drivers of~~in~~ peatland greenhouse gas emissions; 2. The types of data collected, methods used, and ~~ways~~ format of reporting this data need to be streamlined across the scientific community; 3. The data from the growing number of studies focused on peatland

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greenhouse gas emissions needs to be compiled in accessible ways to both the scientific community and policy managers.

~~2. Sites with similar site histories have very different NEE and CH4 despite sublte differences in hydrology. Difficult to generalize carbon cycling based on generic landuse.~~

~~3. Need for more streamlined collection of data and organizied data based because of rapidly growing number of studies on peatland carbon cycling and the importance of peatlands for global atmospheric carbon.~~

~~**4. Raising water table is a necessary component of improving the ecological trajectory, but does not necessarily result in S cover. Therefore, more science is needed on how to restore S and the subtle differences in ecohydrology.**~~

~~5.~~

~~All the major components of the carbon balance were measured at several different ecotypes, on restored and cutover raised bog with different land use and degradation histories. Trends in annual NEE and~~ ~~CH_4~~ ~~fluxes were observed with respect to both ecological and hydrological conditions. In particular, higher water level and intact *Sphagnum* vegetation seem to be related to higher carbon sink and lower GWP. The data from ecotypes in this study were compared to a large number of studies on boreal and temperate peatlands with respect to MAWT. In this broader comparison, negative trends were observed in NEE with respect to MAWT for both vegetated and bare peat sites, while~~ ~~CH_4~~ ~~fluxes were more variable at high MAWT.~~

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Data availability

Much of the data on the various aspects of the annual C~~carbon~~ balance including all the data behind Fig. 6, Fig. 9, Fig. 10, Fig. 11, and Fig. 12 can be found in the supplemental material. All other data used in this study are archived by the authors and are available on request (swensonm@tcd.ie).

Supplemental Information

Section S1. A description of the NEE and CH_4 flux models tested and the thought behind these models. Also, for each of the 29 collars in this study, the empirical fitting parameters, and statistical information for the ~~the r^2, and the standard deviation of the residuals is shown for the best~~ GPP and ER models used.

Section S2. Eco-hydrological conditions and C~~carbon~~ balance terms for all collars, ~~and~~ both years of this study.

Section S3. Data collected from literature on peatland C balance and other site information. ~~: measurements aspects of peatland greenhouse gas balance.~~ This section includes the data behind Fig. 11 and Fig. 12 as well as other studies.

Author contribution

Michael Swenson collected and analyzed the majority of the field data and prepared the manuscript with contributions from other co-authors. Shane Regan attained the grant award, determined the field site location, and contributed to setting up the field equipment and measuring infrastructure. Dirk Bremmers collected CH_4~~methane~~ flux data in the field and analyzed gas samples in the lab. Jenna Lawless collected field measurements of DIC and CO_2 evasion. Shane Regan, Matt Saunders and Laurence Gill contributed technical advice and guidance throughout the project implementation and manuscript writing stages.

Competing interests

The authors declare that they have no conflict of interest.

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