We sincerely thank the reviewer for the comments, which helped us to substantially improve our manuscript. Please find the comments (black) and our reply (green) below.

The paper describes measurements of NEE, and the two respiratory fluxes on polygon tundra in the Siberian Arctic. They authors show that flux differences persist at the micro scale between the rim and the centre of the polygon. Although the work is generally okay, I think that there is somewhat of a missed opportunity here to use the eddy covariance data that are available for this site. As the authors say, the observations are well within the footprint of the EC system, so I am left wondering why these are not used to compare chamber NEE, or split to obtain EC GPP and Reco (line 116-119). Can the authors explain why they do not use this data? Was it not available, or did it give different results (then it should certainly be used!).

By the time the manuscript was submitted, the EC dataset was not available. In the meantime the EC data were published (Holl et al., 2018) and are compared to the chamber data in the revised manuscript.

Other comments

L 33. Please be a little more precise. The Hugelius paper mentions 1300 Pg with an uncertainty range of 1100 to 1500 Pg.

Since we only refer to the organic carbon content in the uppermost three meters of permafrost affected soils (not the total organic carbon in the permafrost region) the number given by Hugelius et al. (2014) is 1035 ± 150 Pg. We slightly modified the beginning of the sentence to 'About 1,000 Pg, which considers the uncertainty range.'

L38. A more up to date reference about Arctic Amplification would be good. SWIPA 2017 would be appropriate.

We fully agree and added the suggested as well as another reference (Taylor et al., 2013).

L43. It would be appropriate to cite here Parmentier, et al., (2011). Also because it is a site in the Siberian Arctic, as discussed below in I 44-55.

We have added this reference here.

L 66. It may be better to refer to different sensitivity, rather than to "react", which is a result of the sensitivity.

We substantially revised the introduction and the mentioned sentence was re-written. Furthermore, we now use "respond" instead of "react" throughout the manuscript.

L242. Fixing the Q10 is not necessarily the correct approach here. While it is difficult to estimate Rbase separately, just fixing it does not solve. It is important here to introduce the sensitivity to the definition of the Q10 as well as resulting uncertainty.

We have tried intensely to run the respiration models with a variable Q_{10} value. However, we decided to proceed with a fixed Q_{10} value because parameter estimation during fitting in MatLab did not converge to reasonable values for Q_{10} (around 1.5). We attribute this result to the relatively low number of samples available for fitting (about 150 samples per fitting) and to a tendency of the algorithm to overfit. The range of typical Q_{10} values of (soil) respiration has been shown to be rather narrow across different biomes with 1.4 ± 0.1 (Mahecha et al., 2010). Moreover, following Runkle et al., (2013), for our site, Q_{10} has been estimated to lie within this range with 1.5 ± 0.3 by Runkle et al. (2013) using eddy covariance data. We saw the availability of a site-specific Q_{10} as an opportunity to proceed with a less complex model. In an effort to avoid overfitting and emphasize parsimony we used prior process knowledge to reduce model complexity.

L275. This is really where I would have expected the use of the eddy covariance data.

We have now compared the modelled NEE chamber data with the eddy covariance data and the comparison showed good correlation. However, the modelled chamber NEE tended to underestimate the highest and lowest NEE in comparison to modelled EC NEE. Possible reasons for this bias is part of the discussion section.

L350 and Fig 6. I am not particularly impressed by the model-data comparison. It looks as if the fluxes are severely overestimated. Can the authors not provide a simple 1:1 scatterplot to show how well the model does?

We replaced figures 6 and 7 with 1:1 scatterplots.

L 280 and further. This section is very descriptive and basically repeats the graphics. It may be useful to see if and how far this can be reduced and made more concise. It does not really read nicely.

This comment is similar to those from the other two reviews. Therefore, we substantially revised the results section focusing on the most important results.

Table 2 could include the Parmentier paper mentioned earlier.

We have changed this table and put a focus solely on CO₂ fluxes from either polygon rim or center microsites. Therefore, we have decided to not include the CO₂ fluxes reported from Parmentier et al. (2011) as it presents CO₂ fluxes of the polygonal tundra but not individual fluxes of rims and centres.

Cited literature:

- Holl, D., Wille, C., Sachs, T., Schreiber, P., Runkle, B. R. K., Beckebanze, L., Langer, M., Boike, J., Pfeiffer, E. M., Fedorova, I., Bolshiyanov, D., Grigoriev, M., and Kutzbach, L.: A long-term (2002 to 2017) record of closed-path and open-path eddy covariance CO2 net ecosystem exchange fluxes from the Siberian Arctic. 2018.
- Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E. A. G., Ping, C. L., Schirrmeister, L., Grosse, G., Michaelson, G. J., Koven, C. D., O'Donnell, J. A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J., and Kuhry, P.: Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps, Biogeosciences, 11, 6573-6593, 2014.
- Mahecha, M. D., Reichstein, M., Carvalhais, N., Lasslop, G., Lange, H., Seneviratne, S. I., Vargas, R., Ammann, C., Arain, M. A., Cescatti, A., Janssens, I. A., Migliavacca, M., Montagnani, L., and Richardson, A. D.: Global Convergence in the Temperature Sensitivity of Respiration at Ecosystem Level, Science, 329, 838-840, 2010.
- Parmentier, F., Van Der Molen, M., Van Huissteden, J., Karsanaev, S., Kononov, A., Suzdalov, D., Maximov, T., and Dolman, A.: Longer growing seasons do not increase net carbon uptake in the northeastern Siberian tundra, Journal of Geophysical Research: Biogeosciences, 116, 2011.

- Runkle, B. R. K., Sachs, T., Wille, C., Pfeiffer, E. M., and Kutzbach, L.: Bulk partitioning the growing season net ecosystem exchange of CO2 in Siberian tundra reveals the seasonality of its carbon sequestration strength, Biogeosciences, 10, 1337-1349, 2013.
- Taylor, P. C., Cai, M., Hu, A., Meehl, J., Washington, W., and Zhang, G. J.: A decomposition of feedback contributions to polar warming amplification, Journal of Climate, 26, 7023-7043, 2013.

We sincerely thank the reviewer for the comments, which helped us to substantially improve our manuscript. Please find the comments (black) and our reply (green) below.

General

This manuscript investigates effects of small-scale polygon heterogeneity on autotrophic and heterotrophic CO2 fluxes. The primary finding is that NEE spatial heterogeneity was very large, with four times more net CO2 uptake at polygon rims compared to centers. The CO2 flux rates varied with hydrology of the two rim locations, in part because GPP was higher and Rh lower in polygon centers compared to rims. The amount of information presented in the manuscript is impressive and the full partitioning of net CO2 fluxes into autotrophic and heterotrophic components provides insight to mechanisms of spatial CO2 flux variation. The manuscript is based on an impressive dataset and would be improved by streamlining the results and crafting a stronger narrative to highlight the implications of these results for understanding Arctic C fluxes. The results should be shortened, and repetition removed. A number of environmental details could be condensed, for example by showing daily averages that are more relevant to the scale of sampling and highlighting only the model output that adds understanding to the measured data, like relevant physiological parameters or cumulative flux estimates. The discussion should consider the implications of these small-scale dynamics for understanding Arctic CO2 fluxes. Table 2 is an attempt to provide this context however the comparison to other sites across the Arctic seems anecdotal and raises more questions than it answers. Instead, the authors might consider relating the small-scale heterogeneity to net CO2 flux dynamics measured at the scale of flux towers, commenting on the relative balance of wet/dry sites across the island, and expected future trajectories for the island/region. It might also be interesting to discuss the role of water table versus plant biomass or other physiological drivers of C balance. Figure 8 is a nice summary and could make an even greater statement about the ecosystem C balance by incorporating the soil C estimates and literature-based plant biomass. More details are provided below.

Thank you for this general comment. We have substantially shortened the results section and removed repetitions to highlight the general differences of individual CO₂ between rim and center. The section presenting environmental details was shortened and revised accordingly. We furthermore added a comparison between the measured chamber data and EC data from the same study site (Holl et al., 2018). The comparison of CO₂ fluxes from this study with other chamber studies (Table 2) was substantially revised by focusing on chamber CO₂ fluxes from polygonal tundra. Furthermore, Figure 8 was improved by adding estimates of soil C and scaling the size of the arrows based on the CO₂ fluxes. Throughout the figures the colors of the single fluxes were synchronized.

Abstract

Line 21-22: 'Fluxes measured at the microscale were used to model NEE, GPP, Reco, RH, RA and NPP over the growing season.' Modeled at what scale? It's a little unclear whether the fluxes were scaled up to a larger area or to get cumulative growing season estimates.

We have revised this sentence to "The measured fluxes on the microscale (1 m - 10 m) were used to model the NEE, GPP, R_{eco} , R_{H} , R_{A} and net ecosystem production (NPP) to determine cumulative growing season fluxes".

Line 22: 'For the first time' – first time ever in all permafrost systems? Or for the Lena River Delta?

To the best of our knowledge this is the first time that the differing response of R_A and $R_H CO_2$ fluxes to hydrological conditions have been examined in permafrost systems. We have revised this sentence accordingly.

Line 31: 'lad' should be led

Changed accordingly.

Line 31: It would be helpful to conclude the abstract with a few words on the implications of the work.

We concluded the abstract with a summary of the implications of the current study.

Introduction

Since this manuscript focuses on wet vs dry microsites the introduction should guide the reader toward moisture effects on CO2 flux, and interactions between moisture and warming. As it stands, the introduction focuses overwhelmingly on warming responses, partly because there is more literature on warming effects which is in itself a useful thing to highlight.

The introduction was substantially revised to consider to a greater extend changes in soil moisture in permafrost regions after warming and its effects on CO_2 fluxes in arctic ecosystems.

Line 43: There may be more appropriate citations here that specifically address plant and nutrient responses. For example: (Elmendorf et al. 2012, Salmon et al. 2016)

The respective literature is cited here.

Line 46: It would be useful to be a little more specific with this statement. There are a number of studies that suggest the annual CO2 budget of arctic tundra is a weak sink to source (Oechel et al. 2014, Celis et al. 2017, Euskirchen et al. 2017) but that there's substantial spatial variation that we don't fully understand (Belshe et al. 2013, Ueyama et al. 2013). The effects of shifting hydrology are also not well understood.

Thank you for this important comment. In this part of the introduction we wanted to address the imbalance between the number of studies on CO_2 fluxes from Russian and Alaskan tundra ecosystems. However, this part of the introduction was deleted. The introduction now focus on partitioning CO_2 fluxes and the impact of environmental parameter on the individual fluxes rather than on CO_2 budgets.

Line 47: see also (McGuire et al. 2018)

Since we made substantial changes within this paragraph the suggested reference does not fit anymore.

Line 59: The discussion of variation in total flux magnitude could be condensed in this paragraph. The uncertainty related to hydrologic changes should be discussed.

Thank you for this suggestion. We have made changes in the two sections between lines 44-67 focusing now on moisture effects on CO_2 fluxes. This includes a substantial reduction of the discussion on the total flux magnitude.

Line 64: specify: 'inorganic fluxes are minor in highly organic soils'

We have revised the wording in the paragraph. Furthermore, we added values of total inorganic C (TIC) content in the last paragraph of section 4.1 as these values (just 0.2% TIC in all depths at rim and center) show the minor importance of TIC here.

Line 66-67: state briefly why it's important that the component fluxes react differently to changing conditions

A sentence on the importance of flux partitioning was added and embedded into the section about temperature and moisture impacts on CO_2 fluxes.

Line 85-87: This sentence is very dense and so specific that it doesn't sufficiently highlight the uncertainties. The phrasing is also a little confusing because an increase in Ra would lead to a relative decrease in Rh but not necessarily an absolute decrease in Rh. And that detail isn't necessarily essential to the introduction. It would be helpful to discuss a little more generally how warming and moisture interact and highlight some of the competing CO2 flux processes. For example: warming stimulates plant productivity and CO2 uptake while increasing moisture has been found to suppress or stimulate both GPP and Reco (Chivers et al. 2009, Zona et al. 2012, Mauritz et al. 2017). Drainage and warmer surface soils could reduce microbial biomass (Frey et al. 2008) however the effects could vary throughout the soil profile with drainage potentially stimulating decomposition of deeper soil C (Natali et al. 2015).

Thank you for this helpful comment. Substantial changes were made in this part of the introduction to point out the importance of warming and changes of soil moisture on the individual CO₂ fluxes. Here we have added the suggested research (Chivers et al. 2009, Zona et al. 2012, Natali et al. 2015, Mauritz et al. 2017)

Line 86-87: (Segal and Sullivan 2014) might be a helpful citation regarding the contributions of root/shoot respiration and Rh to Reco.

In the discussion section root/shoot respiration and R_h to R_{eco} is considered and the respective citation is now also considered in this part of the introduction.

Study Site

Line 101: delete 'of' in 'depths of down to 300 to 500m'

Deleted.

Methods

Line 185: Heterotrophic respiration section: The discussion of trenching and isotope methods producing relatively similar estimates of Rh might be better placed here than in the introduction. The introduction can then instead focus more on the big picture and include less methodological detail. This is a useful approach for fitting and evaluating NEE and Reco chamber measurements.

The discussion about methods to partition R_{eco} is included now into the method section 3.4 as suggested.

Line 193-196: what exactly does this 2014-2015 trenching comparison test?

The clipping and trenching method is related to considerable disturbances to the ecosystem. It was shown for other ecosystems that the additional decomposition of dead roots after clipping and trenching, can lead to an overestimation of R_H (Subke et al., 2006). Therefore, we compared CO_2 fluxes from measurement plots that were trenched in 2014 with those that were trenched in 2015 to see if differences in R_H fluxes could be measured. We assumed that an additional decomposition of residual roots from plots trenched in 2014 would have ceased in 2015, one year after the treatment (following Diaz-Pines et al., 2010). The results have shown no significant differences between the plots that were trenched and clipped in different years. We have revised the respective section for clarity.

Line 216: what is meant by 'the flux curve was re-inspected to see if irregularities could be removed by adjusting the time series'? What gets adjusted?

The start time of the measurement was in some cases manually adjusted to remove irregularities of the flux curve. The start and end times were written down manually and were therefore partwise not identical to the real start of the flux measurement. We have revised this sentence and substituted 'adjusting the time series' with 'adjusting the flux calculation window'.

Line 240-245: Does this mean the only flexible and estimable parameter was Rbase?

Yes.

Results

Throughout, specify figure panels, eg: line 280 soil temperature (figure 2a).

The figure panels were specified accordingly.

Line 278 – 279: This sentence is out of place since it's a rim/center comparison and the following descriptions are all seasonal. The logical flow would be nicer with a general seasonal description followed by a microsite comparison.

To clearly distinguish between general seasonal descriptions and microsite comparison, we have placed the description of the soil temperature at the rim and center at the beginning of the next paragraph.

Line 286: how does total precip compare to longer-term means?

We have added a comparison with precipitation data between 2003 and 2010.

Line 293-296: Is this level of detail on PAR necessary? It is impossible to see this detail in the figure, and the measurements were taken every few days so the detailed diurnal variation is less important. The occurrence of polar day/night is important and was already mentioned in the methods. A figure of daily PAR might be more useful since it would presumably show the declining light conditions toward the end of the season. This high-resolution figure could go in the supplement, if it's necessary to refer to it at some point.

The complete figure was revised (see response below) and smaller adjustments were made to the text.

Line 299-306: This information is given in the site description, and it is unclear whether it's considered a result from the study or whether this data was collected simply for greater site characterization. Collecting this information is a lot of work and the details could be retained and moved to a supplement, perhaps with depth-resolved figures or tables which provide added value to the data from this paper but are not central to the results.

We have shortened this paragraph and removed parts of the results as they are not central to the chamber flux results.

Line 300: a reduction in %C with depth at both the center and rim? Is the reduction in depth similar or do they reduce by different amounts?

We have revised this sentence as the wording was not sufficient. The reduction of the total soil C content with depth was observed at both the center and rim, but more pronounced at the rim. Here the soil C content was half as much compared to the surface after 5 cm soil depth, while the C content at the center halved after 20 cm.

Line 308: Start with the larger picture to put the fluxes in context. It's much more interesting and easier to read a description of the magnitudes and patterns of NEE, GPP, Reco, Ra, Rh and differences between microsites. Which microsite has higher sink strength? How do seasonal NEE patterns differ between center and rim? How do the magnitudes of Reco and GPP compare between center and rim? Does one site have more seasonal variation than the other? The specific max or min values or periods only need to be highlighted if it serves to illustrate something important or remarkable.

We have revised the description of chamber flux results substantially and removed specific values. Instead, we put a focus on the description of the differences between the microsites and the seasonality of the single fluxes.

Line 346: The water analysis deserves its own section. What about correlations between VWC and R fluxes on the rim?

This is definitely one of the questions arising from the correlation of respiration fluxes with the water table at the polygon center. However, we haven't found a correlation between soil moisture and respiration fluxes at the polygon rim. Due to its elevation and the fast run-off of melt and precipitation water, the moisture regime at the polygon rim is completely different compared to the center. For instance, we discussed a 'recycling' of respired CO₂ due to its slow diffusion through the moss layer (caused by a submersion of mosses), as possible reason for a correlation between R_A fluxes and water table fluctuations at the polygon center. However, the moss layer at the polygon rim is not water-saturated and therefore respired CO₂ can diffuse much faster through the moss layer than at the center. Furthermore, the moisture differences at the polygon rim are rather small, with a range between 28 and 34 % VWC, which might be not enough to cause differences in respiration fluxes. We added this to the discussion section 5.3.

Line 351: Remind the reader what the parameters represent or refer back to the equations.

We have added references to the equations in brackets.

Line 354: This sentence says that Pmax showed strong temporal variation at the polygon center (mean 250.7 +/- 101.9) what does the +/- represent? Spatial variation around the mean? Or temporal variation? Is it a range, standard error, standard deviation, confidence interval?

It is a standard deviation of the daily averaged means and displays the temporal variation of the fitting parameter. We have revised the wording to clarify it.

Line 355: This might not be the most informative comparison given the very different temporal patterns in Pmax. In Figure 5b it looks like the patterns differ between Rim and Center until mid-August and then converge. That matches the GPP pattern between the two sites, and interestingly it does not coincide with marked changes in temperature or moisture. Perhaps it does coincide with the onset of nights?

Thank you for this comment. Although P_{max} is strongly reduced at the onset of polar night the steep decrease in P_{max} at the polygon center is likely caused by plant senescence. Runkle et al. (2013) related the decrease of P_{max} at the end of August to plant senescence and we think that this factor leads to the convergence of the patterns between the two microsites. As discussed in section 5.2, the P_{max} at the polygon rim seems to be less affected by plant senescence, most probably due to the resilience of mosses, which are dominant at this site.

Line 364: Hm, it's interesting that center is fit better with surface temperatures. Could this be related to the low fluctuation in soil temperature and the fact that surface temperature captures some of the variation in Reco that is related to Ra?

Yes, we agree with the reviewer's interpretation. The higher sensitivity of R_{eco} fluxes at the polygon center to air/surface temperature is likely due to the sensitivity of R_A to changes in these temperature rather than changes in soil temperatures. At the polygon rim it is the other way round (the soil temperature describes the R_{eco} fluxes better than the surface temperature). This makes sense if the different contributions of R_H on R_{eco} fluxes are considered with contributions of >50% at the rim and <50% at the center. Giving this contribution, the R_{eco} fluxes at the center are stronger affected by surface/air temperature as the fluxes are mainly driven by R_{A_r} while at the rim the fluxes are mainly driven by R_H and are therefore stronger affected by soil temperature. However, this holds not true for the modelled R_H fluxes as the R_H fluxes from the polygon center are better described by air than by soil temperature. Therefore, we cannot fully explain why the respiration fluxes are best described by air/surface temperatures at the polygon center. Both the soil temperature at polygon center and rim were measured at an adjacent polygon rim and center. The water table at the adjacent polygon center was permanently above the soil surface, while this was not the case at the polygon center where the flux measurements were conducted (see Fig 2). Therefore, there are most likely differences in soil temperatures in the upper soil layers between the polygon centers, which could lead to an attenuated fitting of the soil temperature with R_H fluxes at the center.

Line 368: averaged or cumulative? Why compare means instead of cumulatives?

We do both a comparison of means and, later in the manuscript (section 4.4), a comparison of cumulative fluxes.

Line 368 -397: This section is confusing, it repeats many of the flux results described above. It is unclear what additional information is gained from this detailed description of modeled fluxes. What

do we learn from the means of the modeled fluxes? Isn't the main purpose of modeling to calculate seasonal cumulative fluxes?

We have streamlined this section and put a focus on seasonal cumulative fluxes (section 4.4 and Fig. 8). However, in Table 1 we still show the mean values and ranges of the modelled fluxes as we think that especially the ranges are in particular cases of interest to the reader.

Line 399: The previous section can be reduced, with far less detailed description of the modeled flux fluctuations. That space can be used to expand upon this section because it's very interesting. Address each flux component in turn, and how they compare between the two sites, and what that means for the NEE of each site.

We have reduced the section 4.3 and adjusted 4.4 to show the differences of each flux component and their impact on differences in NEE fluxes between the microsites. As we discuss the impact of the single flux components on the net CO_2 fluxes and their drivers intensely in the next section, we haven't expanded the mentioned section here.

Discussion

Line 406: This is a nice study with results that are a valuable contribution in their own right. Saying 'this is the first' doesn't necessarily elevate the results. Instead the value of the results might be better emphasized by highlighting the general differences in environmental conditions and fluxes between center and rim, and the most interesting elements of the results (like the different GPP:Reco ratios).

We revised this paragraph by highlighting the general differences between polygon rim and center.

Line 412-414: That is interesting. That should definitely be more visible in the presentation of the results.

We have added an additional sentence to highlight the differences in R_{eco} fluxes at the two sites in the results section 4.2.

Line 421: starting the sentence with something other than 'Solely' would be better.

This paragraph was revised substantially. We now focus on the comparison of CO_2 fluxes from this study with other studies considering polygon rim and center microsites.

Line 421-423: Out of how many studies compared? Are these all the known studies from Polygonal tundra? Based on (Virkkala et al. 2017)? And 3/8 studies agreeing means that about half the sites show comparable Reco.

We have changed the comparison of CO_2 fluxes from this study with other studies substantially. All the known chamber flux studies from polygon rims and centers are included (based on Virkkala et al., 2018).

Line 430: this section is misnamed since the majority of the writing is not about environmental controls. Environmental controls are typically abiotic factors and a lot of what is discussed here are vegetation factors.

We have changed the title of this section to 'Factors controlling CO₂ fluxes'

Line 454-455: lead this paragraph with Reco or Rh since they are directly related to SOM decomposition.

Changed accordingly.

Line 467-468: remain consistent in terminology rather than switching between NEE and net CO2 uptake.

We have harmonized the terminology throughout the complete manuscript and only use NEE.

Line 466-469: These trends are not terribly convincing. It is possible that the eye sees declining NEE in the center because of the steep slope from June to September and a smaller decline on the rim because NEE is overall lower through the season. What is the main argument here?

We agree, that these trends are not convincing when considering the complete measurement period. However, by zooming into the fluxes during September, the trends are much clearer with a significant increase of NEE at the polygon rim and a slight decline of NEE at the polygon center. We discuss in section 5.2 that this increase might be assigned to the dense moss cover at the polygon rim, which might show low photosynthesis rates due to light stress during times of high PAR and desiccation (Murray et al., 1993, Zona et al., 2011). This interpretation is in accordance with the observation of rising NEE at the polygon rim when the drier period ended and PAR values were decreasing towards the end of the season (see Fig. 2).

Line 481: What about (Dorrepaal et al. 2009, Schuur et al. 2009, Nowinski et al. 2010, Hicks Pries et al. 2013)?

We didn't discuss the mentioned studies since they haven't estimated R_H fluxes over the growing season under in situ conditions. However, the wording was misleading and was revised to '(...) a few studies have estimated R_H fluxes from arctic tundra ecosystems over a growing season under in situ conditions'.

Line 481: Unclear what 'these estimates of Rh' refers to. The previously cited studies? The results of this study?

We have revised the wording to '(...) differences in R_H fluxes between these estimates and those presented in this study (...)'.

Line 515: what is meant by recycled? The CO2 is taken up from the water column by plants before it can escape into the atmosphere? Is the argument here that declining Ra and Reco with rising water table is actually the result of CO2 uptake from the water column and thus a lower flux of CO2 to the atmosphere?

Yes, an uptake of CO₂ from the water column by plants could serve as an explanation for the relationship between water table fluctuations and R_A fluxes. The diffusion velocity through watersaturated soils is distinctly slower compared to well-aerated soils (Frank et al., 1996). Therefore, it seems plausible that a 'recycle' process as described by Liebner et al. (2011) gains more importance and lead to lower release of CO₂ by R_A. This process would affect R_{eco}, not only R_A fluxes. However, the relationship between R_H fluxes and water table fluctuations might be missed due to the absence of photosynthetic active biomass in the measurement plots. We have revised this paragraph in section 5.3 substantially to clearly explain this effect on respiration fluxes. Line 528 – 532: This would be a useful statement in the introduction too.

Yes, while we have made substantial changes of the introduction with changing the focus from CO_2 budgets towards a focus on the impact of environmental and vegetation factors on single CO_2 fluxes, we have also added a sentence about the necessity of studying the impact of hydrological regimes on R_A fluxes.

Line 541: Except that Ra might not actually be driven by WT? Because the Ra measurement might in fact be affected by CO2 recycling? And the center vs rim comparison certainly does not suggest lower Ra in wet areas.

Yes, it might be possible that just the release of CO_2 by R_A is driven by WT and not the R_A flux itself. Therefore, we revised this sentence accordingly. However, we think that there is a lower release of CO_2 by R_A from the polygon center compared to the rim. Although the integrated fluxes are almost the same one has to consider the differences in GPP between the sites as photosynthesis is the source of R_A . The GPP: R_A ratio at the polygon center is twice as high as at rim (10.5 and 5.1, respectively), which shows that about half as much CO_2 is released by R_A at the center compared to the rim at similar GPP rates. These findings are added in section 5.3 to illustrate the difference in R_A fluxes from rim and center. Furthermore, the GPP and R_A fluxes at the rim are linearly correlated ($R^2 = 0.48$, p <0.05), with higher R_A during times of high GPP. This trend was not observed at the center ($R^2 = 0.01$, p > 0.05). This indicates that there certainly is a lower release of CO_2 by R_A in wet areas.

Figures and Tables

Table 2: This table is not particularly helpful since it is unclear whether this is an exhaustive summary of other locations, or how this site relates to these other studies.

Thank you for this comment. We have made substantial changes to the comparison between CO_2 fluxes from the current and previous studies on chamber CO_2 fluxes from polygonal tundra sites. According to Virkkala et al., (2018), CO_2 fluxes on the chamber scale (1 - 10 m) from polygonal tundra were only reported from Barrow and the Lena River Delta. We have also emphasized this fact in the introduction.

Figure 1: Turn landsat website into a citation so that the link can be removed from the caption. Just to make the caption a little cleaner.

Changed.

Figure 2: This figure is difficult to read because of so much overlapping data within single panels. It should be revised to highlight only the most important variables, group variables with more logic (for example why is soil temperature in the panel with precipitation and air temperature in a separate panel (c)? it might make more sense to pair air temperature with precipitation). Consider showing these data at a temporal frequency more relevant to the measurements. panel b, add a line at y=0 to make it easier to see the WT relative to the soil surface. panel d give y-axis a negative scale otherwise it doesn't really make sense.

We have revised the figure. We adjusted the temporal frequency to daily means instead of half-hourly means. Furthermore, we have added lines at y=0 if necessary and gave a negative scale for the panel with thaw depths. The precipitation data are now presented in an own panel.

At line 829 'rim an center' has a typo, fix to 'rim and center'

Changed.

Figure 3: Add label for Polygon Center on the top and Polygon Rim on the bottom to make the figure easier to read at a glance.

We have added the labels. Furthermore, we have changed the colors of the single fluxes to synchronize them with the colors of the single fluxes of Fig. 8.

Figure 4: panel letters are missing? Caption is incorrect in the flux sequence. For Rh and GPP, if the regressions are non-significant then there shouldn't be a line. Add a vertical line at 0cm to make it easier to see water table above and below the surface. Was this analysis done as a mixed effects model? Including a plot random effect might strengthen some of the relationships because it would control for plot-level variation (eg: biomass differences). Is this analysis picking up seasonal fluctuation in temperature (and light?) that coincides with rainfall and higher water tables. Even if the analysis is picking up seasonal variation in light and temperature RA and GPP would be expected to behave similarly. This is interesting to discuss.

Thank you for this comment. We have removed the regression line for insignificant fluxes and added a vertical line at 0 cm. Unfortunately, we were not able to control for plot-level variation as the R_A fluxes were calculated from fluxes from different measurement plots and not measured directly. Furthermore, there are no estimates of biomass for each plot. The analysis might pick up seasonal variation in radiation and temperature, but we estimate that the effect on the regression itself is low as the water table reacts rather slow to variation of both temperature and light. Furthermore, we discuss the different behavior of GPP and R_A fluxes to changes of the mentioned parameter in the section 5.3.

Figure 5a: why isn't there an alpha parameter for center and rim sites?

The values for the initial canopy quantum efficiency α were obtained from modelled fluxes of the Eddy Covariance measurement system (Holl et al., 2018). The footprint of the EC system contains both polygon rims and centers. Therefore, the same value of the α parameter was used for both microsites. We have added this in section 3.6.

Figure 6 & 7: move to supplement.

According to the suggestions of reviewer #1, the presentation of these data were revised substantially but still included in the main part of the manuscript.

Figure 8: Nice way to summarise results! This figure would be easier to interpret if the arrows scaled by the size of the flux. It takes quite a lot of staring at the figure before it becomes clear that NEE is \sim 3 times greater in the center. The figure could be even bolder by including C stock estimates for the soil and plants. Consider integrating the soil C profile data. Are there plant biomass estimates from other studies on Samoylov Island? It might get complicated but if it works then that would be a really nice synthesis of the C flux and partial C budgets for the two microsites. Add a label or legend item for the permafrost table and water table.

The size of the arrows were scaled to the size of the flux and legend items for the water table and the thaw depth were added. Furthermore, we have added estimates of SOC for both microsites. Estimates

of aboveground biomass for both microsites are lacking. There are estimates for a polygon rim and center from Samoylov Island from the literature (see Zhang et al., 2012), but they differ distinctly from what we have found at the study site (e.g. total aboveground biomass is higher at the rim than at the center). Therefore, we have decided not to include these estimates here.

Cited literature:

- Chivers, M. R., Turetsky, M. R., Waddington, J. M., Harden, J. W., and McGuire, A. D.: Effects of Experimental Water Table and Temperature Manipulations on Ecosystem CO2 Fluxes in an Alaskan Rich Fen, Ecosystems, 12, 1329-1342, 2009.
- Diaz-Pines, E., Schindlbacher, A., Pfeffer, M., Jandl, R., Zechmeister-Boltenstern, S., and Rubio, A.: Root trenching: a useful tool to estimate autotrophic soil respiration? A case study in an Austrian mountain forest, European Journal of Forest Research, 129, 101-109, 2010.
- Frank, M. J., Kuipers, J. A., van Swaaij, W. P. J. J. o. C. and Data, E.: Diffusion coefficients and viscosities of CO2+ H2O, CO2+ CH3OH, NH3+ H2O, and NH3+ CH3OH liquid mixtures, Journal of Chemical & Engineering Data, 41, 297-302, 10.1021/je950157k, 1996.
- Holl, D., Wille, C., Sachs, T., Schreiber, P., Runkle, B. R. K., Beckebanze, L., Langer, M., Boike, J., Pfeiffer, E. M., Fedorova, I., Bolshiyanov, D., Grigoriev, M., and Kutzbach, L.: A long-term (2002 to 2017) record of closed-path and open-path eddy covariance CO2 net ecosystem exchange fluxes from the Siberian Arctic. 2018.
- Murray, K., Tenhunen, J., and Nowak, R.: Photoinhibition as a control on photosynthesis and production of Sphagnum mosses, Oecologia, 96, 200-207, 1993.
- Liebner, S., Zeyer, J., Wagner, D., Schubert, C., Pfeiffer, E.-M., and Knoblauch, C.: Methane oxidation associated with submerged brown mosses reduces methane emissions from Siberian polygonal tundra, Journal of Ecology, 99, 914-922, 2011.
- Runkle, B. R. K., Sachs, T., Wille, C., Pfeiffer, E. M., and Kutzbach, L.: Bulk partitioning the growing season net ecosystem exchange of CO2 in Siberian tundra reveals the seasonality of its carbon sequestration strength, Biogeosciences, 10, 1337-1349, 2013.
- Subke, J.-A., Inglima, I., and Francesca Cotrufo, M.: Trends and methodological impacts in soil CO2 efflux partitioning: A metaanalytical review, Global Change Biology, 12, 921-943, 2006.
- Virkkala, A. M., Virtanen, T., Lehtonen, A., Rinne, J., and Luoto, M.: The current state of CO2 flux chamber studies in the Arctic tundra: A review, Progress in Physical Geography, 42, 162-184, 2018.
- Zhang, Y., Sachs, T., Li, C. and Boike, J.: Upscaling methane fluxes from closed chambers to eddy covariance based on a permafrost biogeochemistry integrated model, Global Change Biology, 18, 1428-1440, doi:10.1111/j.1365-2486.2011.02587.x, 2012.
- Zona, D., Oechel, W. C., Richards, J. H., Hastings, S., Kopetz, I., Ikawa, H., and Oberbauer, S.: Light-stress avoidance mechanisms in a Sphagnum-dominated wet coastal Arctic tundra ecosystem in Alaska, Ecology, 92, 633-644, 2011.

We sincerely thank the reviewer for the comments, which helped us to substantially improve our manuscript. Please find the comments (black) and our reply (green) below.

The manuscript by Eckhardt et al., reports one growing season of CO2 flux data, not only NEE but its components GPP, RA, and RH, and their controlling factors in Lena Delta, Russia. It is extremely difficult to measure flux in such a remote area like Siberia and the result of this study will be highly valuable to flux community. Especially, measurement of in situ RA and RH is very rare especially in the Arctic region and this will be of great interest to readers of Biogeosciences. The manuscript is generally in good shape but several aspects should be addressed for the publication.

Comments:

Paragraph starting #78: warming effects on flux components are described in this paragraph but warming is not one of the main topics of this manuscript, e.g. warming manipulation experiment. Thus, it does not seem appropriate for introduction but rather for discussion that the results of this study imply xyz in the warming scenario.

Thank you for this comment. The introduction was substantially revised focusing rather on hydrology effects on CO_2 fluxes, which are actually reported in the current manuscript (see also comments of reviewer #2). However, warming effects are still considered in the introduction since they also affect changes in hydrology, e.g. through permafrost thaw.

Line #82-4: if GEP is less sensitive to temperature than Reco, carbon sink capacity will not be affected much by temperature instead of being reduced. Or carbon storage will be reduced because of a larger amount of C emission than C uptake. Please rephrase it.

We agree, the wording is misleading here. We have revised 'carbon sink capacity' to 'carbon storage'.

Paragraph starting #186: continuous regrowth of plants implies living roots and remaining RA in the measured RH. In addition, if some roots are dying after aboveground plant biomass is removed, can they add nutrients to soils and overestimate RH? It is written that there was no significant increase in RH, but continuous and slow decay of remaining roots may affect RH. Also, was there any difference in the plant regrowth rate between the center and the rim? If so, will they affect the results?

We addressed this question with different approaches. The continuous re-growth of plants implies living roots and remaining R_A in the measured flux which we define as R_H . However, we expect minor effects of additional decay of dead roots and release of nutrients to the measured respiration fluxes. There was only a very sparse re-growth of plants at the measurement plots where we have removed the photosynthetic active biomass, so we assume that it was negligible for the flux measurements. We also haven't seen any differences in the amount of plant re-growth between rim and center plots. It is possible that nutrients were released to the soil due to dying roots and that the decay of dead roots lead to an overestimation of R_H fluxes. However, we have removed the biomass from plots in 2014 and from other plots in 2015 to see if there are effects due to dying roots and nutrient addition (see response to reviewer #2). A Student's t-test revealed no significant differences between plots that were manipulated in 2014 and 2015. The lack in a significant difference between R_H in the plots clipped in 2014 and 2015 means that either no significant amounts of CO_2 from root biomass contribute to CO_2 fluxes or that the CO_2 release from decaying roots does not diminish over the period of one year, which seems unlikely. A lack of CO_2 release from the clipped root biomass is also supported by a study of Biasi et al. (2014) who have compared the same partitioning approach with a non-disturbing ¹⁴C partitioning approach and found no significant differences in the measured R_H fluxes between the two approaches.

Paragraphs starting #227: when modeling fluxes (Reco, RH, and GPP), some constants (Q10, _) were adopted from EC data. One of the purposes of this research is to capture flux signals in microsite scale which EC cannot capture, and using constants from EC data that contain a mixture of polygon centers and rims may decrease model fit. Have you tried estimating Q10 and _ with chamber flux data? It seems plausible to estimate those values considering the number of data points.

We have tried intensively to run the models with solely chamber flux data as we also wanted to determine individual constants for polygon rim and center. However, parameter estimation during the fitting did not converge to reasonable values for Q_{10} when the fitting was made solely with chamber flux data (see response to reviewer #1). We attribute these findings to the relatively low number of samples available for fitting. Therefore, we have decided to run the models with site-specific constants obtained from EC data.

Line #308-44: what are the average values of NEE, Reco, GPP, and RH at the two microsites and how much are those differences? These will be more important than the highest and the lowest values, which took about half of this section space.

Thank you for this comment. We have substantially revised this section and decided, to forgo to show specific values of chamber fluxes (see response to reviewer #2). Instead, the differences between the microsites and the seasonality of the single fluxes were highlighted.

Line #325: RH seems correlated with Reco, but no seasonal trend in RH was observed? At least RH in the center seems to have seasonality in Figure 5. - Results of environmental controls on each flux component is not described. Please add which environmental factors did or did not affect flux components, which is one of the main objectives of this study.

There might be a slight seasonal trend of R_{eco} fluxes at the polygon rim, which may be also seen in the R_{H} fluxes from this microsite (see Fig. 5). However, at the polygon center no seasonality is seen for R_{H} fluxes (open symbols in panel d of Fig. 5 in original manuscript). We also expected a trend in the contribution of R_{H} on R_{eco} due to plant senescence and root mortality at the end of the growing season. However, neither at the rim nor at the center a seasonal trend of this contribution was observed. This is in contrast to the study from Segal and Sullivan (2014) where the contribution of R_{H} increased towards the end of the growing season, most likely due to deepening of the active layer which increases substrate availability for R_{H} production processes. This effect might be missed in this study because of smaller changes in thaw depth as well as lower soil temperatures throughout the growing season at the study site compared to other arctic tundra sites and due to a too short investigation period. The main environmental drivers of the CO_2 fluxes are PAR for GPP fluxes and the temperature for respiration fluxes (see Fig. 6 & 7 in revised manuscript). Furthermore, the hydrology is a main driver of the respiration fluxes, especially R_{eco} and R_A fluxes (see panel a & d of Fig. 4 in revised manuscript). These relationships have been shown with the good fitting of the flux models.

Paragraph starting #431: when discussing magnitude of fluxes and their explanatory factors, be more specific if the difference is between Arctic ecosystems and other ecosystems in the lower latitudes, or between this study site and other sites in the Arctic.

We have revised this paragraph accordingly and clarified, which ecosystems are compared.

Line #454: NEE ! Reco? The following sentences are describing Reco and RH. In the separate paragraph, the combined effects of GPP and Reco/RH can be described for NEE. -Environmental controls on RA is not discussed.

Thank you for this comment. We have changed NEE into R_{eco} , which is the right term here. The combined effects are discussed, as suggested, in a separate paragraph. The environmental controls of R_A fluxes are also discussed, but later in section 5.3.

Cited literature:

- Biasi, C., Jokinen, S., Marushchak, M. E., Hämäläinen, K., Trubnikova, T., Oinonen, M., and Martikainen,
 P. J.: Microbial Respiration in Arctic Upland and Peat Soils as a Source of Atmospheric Carbon
 Dioxide, Ecosystems, 17, 112-126, 2014.
- Segal, A. D. and Sullivan, P. F.: Identifying the sources and uncertainties of ecosystem respiration in Arctic tussock tundra, Biogeochemistry, 121, 489-503, 2014.

Please find below a list of all relevant changes made in the manuscript

- We streamlined the introduction section towards a focus on moisture effects on individual CO₂ fluxes in arctic tundra landscapes
- We added a comparison of the modelled chamber data with the available eddy covariance data:
 - The calculation and weighting of the fluxes for the comparison is described in the methods section 3.6
 - The results of the comparison are described in section 4.4 and diagrammed in figure
 9, which we added to the manuscript.
- We intensely revised the results sections 4.1 to put a focus simply on relevant data on relevant time scales
- We intensely revised the results sections 4.2 and 4.3 by removing the listings of individual CO₂ flux values as all relevant values are listed in the tables 1 and 2. Instead, we put a focus on describing differences of the individual CO₂ fluxes between the microsites.
- We revised the complete discussion section intensely based on the comments of the three reviewer.
- Table 2 was modified to put the focus on chamber CO₂ fluxes from other polygonal tundra microsites as well as other wet and dry microsites of arctic tundra ecosystems. Furthermore, we have rewritten the discussion section 5.2 where the comparison of CO₂ chamber fluxes is discussed.
- The discussion section 5.3 was intensely revised, based on the comments of review #2, as some ideas on autotrophic respiration fluxes were not conclusive.
- Throughout the figures, we have synchronized the colors codes of the individual CO₂ fluxes.
- We modified figure 3. Instead of half-hourly mean values daily mean values are presented.
- We replaced the figures 6 and 7 with 1:1 scatterplots of modelled and measured CO₂ flux data.
- We deposited the used data of the current manuscript on PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.898876) and added this reference
- We improved the style of figure 8 (scaled arrows) and added information on carbon stocks.

Partitioning CO₂ net ecosystem exchange fluxes on the microsite pedon scale in the Lena River Delta, Siberia

Tim Eckhardt^{1,2}, Christian Knoblauch^{1,2}, Lars Kutzbach^{1,2}, <u>David Holl^{1,2}</u>, Gillian Simpson³, Evgeny Abakumov⁴ and Eva-Maria Pfeiffer^{1,2}

¹Institute of Soil Science, Universität Hamburg, Allende-Platz 2 Hamburg, 20146, Germany
 ²Center for Earth System Research and Sustainability, Universität Hamburg, Allende-Platz 2, Hamburg, 20146, Germany
 ³School of GeoSciences, University of Edinburgh, West Mains Road, Edinburgh, EH9 3JN, Scotland, UK

⁴Department of Applied Ecology, Saint-Petersburg State University, 199178, 16-line 2, Vasilyevskiy Island,

10 Russia

Correspondence to: Tim Eckhardt (tim.eckhardt@uni-hamburg.de)

Abstract. Arctic tundra ecosystems are currently facing <u>amplified</u> rates of <u>amplified</u> climate <u>changewarming</u>. This is critical as these<u>Since these</u> ecosystems store significant amounts of <u>soil organic</u> carbon-in their soils, which can be mineralized to <u>carbon dioxide (CO₂-)</u> and <u>methane (CH₄-)</u>, rising temperatures may cause increasing greenhouse

- 15 gas fluxes to the atmosphere and released to the atmosphere. To understand how the CO₂ net ecosystem exchange (NEE) fluxes will reactrespond to changing climatic and environmental conditions, it is necessary to understand the individual responses of the physiological processes contributing to CO₂ NEE. Therefore, this study aimed: i) to partition NEE fluxes at the soil-plant-atmosphere interface in an arctic tundra ecosystem; and ii) to identify the main environmental drivers of these fluxes. Hereby, the NEE fluxes were partitioned into gross primary
- 20 productivity (GPP) and ecosystem respiration (R_{eco}) and further into autotrophic (R_A) and heterotrophic respiration (R_H). The study examined <u>CO₂</u> flux data collected during the growing season in 2015 using closed chamber measurements in a polygonal tundra landscape in the Lena River Delta, northeastern Siberia. <u>To capture the influence of soil hydrology on CO₂ fluxes, measurements were conducted at a water-saturated polygon center and a well-drained polygon rim. These chamber-measured fluxes on the microscale (1 m 10 m)-were used to model</u>
- 25 the NEE, GPP, R_{eco} , R_H , R_A and net ecosystem primary production (NPP) at the pedon scale (1 m 10 m) over the growing seasonand to determine cumulative growing season fluxes. Here, for the first time, the differing response of *in situ* measured R_A and R_H fluxes from permafrost-affected soils to hydrological conditions have been examined. Although changes in the water table depth at the polygon center sites did not affect CO₂ fluxes from R_H , rising water tables were linked to reduced CO₂ fluxes from R_{A_c} -It was shown that low R_A -fluxes are associated
- 30 to a high water table, most likely due to the submersion of mosses, while an effect of water table fluctuations on R_H fluxes was not observed. Furthermore, this work found the polygonal tundra in the Lena River Delta to be a net_sink for atmospheric CO₂ during the growing season. Spatial heterogeneity was apparent with the net CO₂ uptakeThe NEE at a the wet, depressed polygon center being-was more than twice as high as that measured than at a the drier polygon rim. In addition to higher GPP fluxes, these differences in NEE between the two microsites
- 35 were caused by higher GPP fluxes, due to a higher vascular plant density and lower R_{eco} fluxes due to oxygen limitation under water-saturated conditions at the polygon center in comparison to the rim. lower R_{eco} fluxes at the center compared to the rim. Here, the contrasting-Hence, soil hydrological conditions were one of the key drivers for the different CO₂ fluxes across this highly heterogeneous tundra landscape. caused the CO₂ flux differences between the microsites, where high water levels lad to lower decomposition rates due to anoxic conditions.

40 1 Introduction

More than An estimated 1,000 Petagrams of organic carbon (OC) are stored in the upper 3 m of northern permafrost-affected soils (Hugelius et al., 2014). Given the large amount of OC stored in these soils, the response of the arctic carbon (C) cycle to a changing climate is of global importance (McGuire et al., 2009). Over thousands of years, Ccarbon has been sequestered in permafrost-affected soils and sediments due to cold conditions and poor drainage resulting in water saturation and slow organic matter decomposition. Currently, arctic ecosystems are

- drainage resulting in water saturation and slow organic matter decomposition. Currently, arctic ecosystems are facing amplified warming (AMAP, 2017; Taylor et al., 2013), which will lead to the longer and deeper thawing of permafrost-affected soils (Romanovsky et al., 2010). On the one hand, the microbial decomposition of <u>newly</u> available liberated-thawed permafrost organic matter releases carbon dioxide (CO₂) and methane (CH₄) (e.g. Knoblauch et al., 2018; Knoblauch et al., 2013; Zimov et al., 2006a; Schuur et al., 2009; Grosse et al., 2011). On the other hand, higher temperatures increase the assimilation of CO₂ by tundra vegetation due to a longer-prolonged
- growing period and increased nutrient availability in the deeper layers of thawed soils (e.g. Beermann et al., 2017; Elmendorf et al., 2012; Salmon et al., 2016; Parmentier et al., 2011).

Although the CO₂ budget of the arctic tundra has been the topic of several studies (Euskirchen et al., 2017; Ueyama et al., 2013; Merbold et al., 2009; e.g. Kittler et al., 2016; Marushchak et al., 2013; Oechel et al., 2000;

- 55 Kutzbach et al., 2007b) the extent of their source or sink strength has not been well established. Based on flux measurements, atmospheric inversion and process models, McGuire et al. (2012) report that the arctic tundra still acts as a sink for atmospheric CO₂ on an annual basis with a total CO₂ uptake of 110 Teragram (Tg) C yr⁻¹. However, this value is associated with a high uncertainty ranging from 291 Tg C yr⁻¹ uptake to 91 Tg C yr⁻¹ loss. In contrast, in a meta analysis of available flux observations in the arctic tundra Belshe et al. (2013) report that
- 60 these ecosystems act as source for atmospheric CO₂ (462 Tg C yr⁻¹). However, the vast majority of the flux measurements taken into account by Belshe et al. (2013) have been conducted in North America although the Russian arctic comprises an area of 3 million km² (CAVM Team, 2003) which is a large amount of the global tundra region. With an area of 3 million km², more than half of the northern high latitude tundra ecosystems are situated in Russia- (Walker et al., 2005). To date, just a few studies on CO₂ fluxes from the vast Russian arctic
- 65 <u>tundra ecosystems are available</u> (e.g. Parmentier et al., 2011; Marushchak et al., 2013; Rößger et al., 2019; Kittler et al., 2016) <u>especially on the pedon scale</u> (Kwon et al., 2016; Corradi et al., 2005; Heikkinen et al., 2004; Zamolodchikov et al., 2000). <u>Since tundra soils are highly heterogeneous on the pedon scale in terms of temperature and moisture (Aalto et al., 2013), measurements on this scale are required to determine the response of individual CO₂ fluxes to these parameter. To cover this heterogeneity on the pedon scale chamber measurements</u>
- 70 are more appropriate than the eddy covariance (EC) method, which cover the next larger scale, even though a downscaling EC approach for an arctic ecosystem was recently presented (Rößger et al., 2019). These current uncertainties in the arctic CO₂-budget clearly show the need for intensified CO₂-flux observations in tundra ecosystems, in particular on the microsite scale (1-10 m) in northern Siberia as only a few studies are available from these ecosystems. _An improved understanding of CO₂ dynamics in permafrost-affected soils is needed to
- 75 improve estimates of future CO₂ balances of the highly heterogeneous arctic tundra regions. Without furthering knowledgedevelopments in our understanding of the response of CO₂ dynamics in permafrost-affected ecosystems on changing climatic conditions such as temperature and moisture, estimates of the carbon balance of the circumarctic tundra and its future_reactionresponse to changing climatic conditions remain biased.

The net ecosystem exchange (NEE) of CO_2 between the land surface and the atmosphere is composed of the CO_2

80 uptake by plants, termed the gross primary productivity (GPP); and the release of CO₂ from soils and plants, the

ecosystem respiration (R_{eco}) (Chapin et al., 2006). The latter can <u>be</u> further <u>be</u> split into autotrophic respiration by plants (R_A) and heterotrophic respiration (R_H) <u>consisting of microbial soil organic matter (SOM) decomposition</u>. mainly by microorganisms that decompose soil organic matter. <u>Inorganic sinks and sources of CO₂ are generally</u> neglected because of their minor contribution to NEE (Elsgaard et al., 2012; Chapin et al., 2009; Kuzyakov,

85 2006). In this study the atmospheric sign convention is used, whereby a positive NEE defines a net release of CO₂ from the soil to the atmosphere.

In order to partition NEE into the <u>its</u> underlying fluxes, measurements of GPP, R_{eco}, R_A and R_H are required. <u>These</u> individual process-based fluxes governing the CO₂ balance respond differently to changing climatic conditions such as temperature and moisture. For instance, it was shown that temperature changes in arctic soils could cause

- a significant increase of the CO₂ uptake via GPP (Shaver et al., 1998; Oberbauer et al., 2007; Natali et al., 2012; Mauritz et al., 2017), which can be, beside others, attributed to shifts in vegetation composition (Elmendorf et al., 2012; Hudson et al., 2011) and increased nutrient availability (Johnson et al., 2000; Salmon et al., 2016; Beermann et al., 2015). Furthermore, the effect of drainage on GPP remain uncertain as some studies found drainage of arctic soils to reduce GPP (Chivers et al., 2009; Kwon et al., 2016), while other studies found drainage to lead to a slight
- 95 <u>increase of GPP</u> (Olivas et al., 2010; Kittler et al., 2016). The effect of increasing soil moisture on GPP differs between ecosystems (Mauritz et al., 2017; Olivas et al., 2010; c.f. Chivers et al., 2009). As respiratory processes are temperature-sensitive (Mahecha et al., 2010), the release of CO₂ by R_{eco} increases in response to soil warming across arctic ecosystems (e.g. Hicks Pries et al., 2015; Oberbauer et al., 2007; Natali et al., 2015). An increase of R_{eco} was also observed as a result of drainage of arctic soils and vice versa a decrease with increasing water-
- 100 <u>saturation</u> (Elberling et al., 2013; Mauritz et al., 2017; Chivers et al., 2009; e.g. Kwon et al., 2016; Olivas et al., 2010), due to the presence or absence of oxygen in drained soils (Hobbie et al., 2002). However, it was also shown that R_{eco} fluxes could increase with increasing water-saturation due to higher soil temperatures in water-saturated soils (Zona et al., 2012), which highlights the interconnection of moisture and temperature in soils. In general, higher soil temperatures lead to a higher increase of R_{eco} than of GPP, which causes a reduction of the net CO₂
- 105 uptake (Parmentier et al., 2011; Oberbauer et al., 2007; Voigt et al., 2017; Mauritz et al., 2017). Also drainage of arctic soils causes a reduction of NEE (means less negative values) due to a higher increase of R_{eco} than GPP (Chivers et al., 2009; Kittler et al., 2016; Olivas et al., 2010), while the effect of increasing water-saturation of soils on NEE differs between arctic ecosystems (Chivers et al., 2009; Mauritz et al., 2017). Both soil temperature as well as moisture are predicted to change in the future due to increased temperatures and precipitation in the pan-
- 110 Arctic (Christensen et al., 2013). As R_{eco} and GPP respond differently to temperature and moisture changes it is essential not only to focus on changes to NEE, but to gain a quantitative -understanding of its components and their individual responses to environmental and climatic changes to improve model simulations of future CO₂ fluxes. Therefore, partitioning approaches of *in situ* measured CO₂ fluxes are required.
- The release of CO₂ from soils by R_{eco} is the largest efflux of C-carbon from terrestrial ecosystems to the atmosphere
 (Mahecha et al., 2010). R_A-<u>Autotrophic respiration can be separated into aboveground plant respiration and belowground plant-root</u> respiration (i.e. respiration of roots). R_H-Heterotrophic respiration is associated with the decomposition of soil organic matter (SOM)SOM by heterotrophic soil organisms. To date, only a few estimates on the contribution of R_H to R_{ece}fluxes from arctic tundra ecosystems during over the growing season have been published (Nobrega and Grogan, 2008; Biasi et al., 2014; Segal and Sullivan, 2014), with data lacking for ecosystems such as the polygonal tundra. This is critical, as warmingWarming of the aArctic soils will influence
 - Reco-RH_fluxes both directly and indirectly: rising soil temperatures Warming will increase SOM decomposition

decomposition of soil organic matter ($R_{\rm H}$), but-it will also cause permafrost to thaw, which will expose exposing previously frozen SOM to microbial decomposition (Schuur et al., 2011; Dorrepaal et al., 2009). This decomposition could substantially reduce eause a substantial reduction of the carbon sink function carbon storage 125 of in arctic tundra ecosystems, as gross ecosystem productivity has been found to be less temperature-sensitive than Reco in these ecosystems (Grogan and Chapin, 2000; Dorrepaal et al., 2009). Furthermore, Wwarming could also reduce soil moisture (Suseela et al., 2012), and increase RA due to increasing aboveground biomass (Natali et al., 2012), which can could lead to a lower contribution of R_H to R_{eco} (Hicks Pries et al., 2015; Chen et al., 2016). Furthermore, changes in soil moisture are known to affect microbial activity in soils directly with decreasing 130 activity during times of high and low soil moisture and an optimum at moderate soil moisture conditions (Moyano et al., 2013)_-The increase of R_A and R_H fluxes due to warming might be compensated for by higher net primary production (Hicks Pries et al., 2013), but whether this compensation is valid for the complete entire growing season and across the highly heterogeneous arctic ecosystems remains uncertain. Furthermore, it remains uncertain how R_A fluxes will respond to changing hydrological regimes as the impact of this parameter on R_A fluxes have never 135 been analyzed in tundra regions. As changes in soil temperature and moisture can significantly alter the individual fluxes contributing to CO₂ NEE, T the current study aims to improves the current understanding of CO_2 flux dynamics in permafrost-affected ecosystems of northeastern Siberia by (i) partitioning CO2 NEE into its underlying processes individual flux components: photosynthesis, ecosystem respiration as well as autotrophic and heterotrophic respiration at two 140 typical the pedon scale of the polygonal tundra and (ii) gaining insights into the response of these individual fluxes to different environmental parameters. Therefore, closed chamber measurements were conducted at two

sites in the polygonal tundra in northeastern Siberia over an almost complete growing season. microsites.
 Furthermore, the response of these processes to different environmental parameters such as temperature and hydrology is revealed. Finally, a CO₂ budget for a nearly complete vegetation period is determined for the two
 micrositesites using data-calibrated flux models. These models were based on the time-sensitive bulk flux partitioning model by Runkle et al. (2013), which was-has been used in different arctic ecosystems (Helbig et al.,

2017; Zona et al., 2014).

2 Study site

The investigation area is located on Samoylov Island in the southern central Lena River Delta, northeastern Siberia
(72°22'N, 126°28'E – Figure 1). The Lena river forms the largest delta in the Arctic, which can be geomorphologically divided in river terraces of different ages and flood-plain levels (Schwamborn et al., 2002). The delta is located in the continuous permafrost zone with permafrost extending to depths of 300 to 500 m (Yershov, 1998) and relatively low mean annual soil temperatures of -7.8 °C at 1.7 m depth (Boike et al., 2013). With low temperatures and low precipitation, tThe study site has an arctic continental climate, characterized by low temperatures and low precipitation. The mean annual air temperature between 1998 and 2011 was -12.5 °C, and mean annual precipitation between 1981 and 2011 was 321mm (Pogoda i Klimat, 2016), while summer rainfall is 125 mm, ranging from 52 mm to 199 mm (Boike et al., 2013). Polar day lasts from 7 May until 8 August, and polar night lasts from 15 November to 28 January. Snowmelt usually starts in the first half of June, and the growing season usually occurs spans from around mid-June until mid-September.

- 160 The study site is covered by an ice-wedge polygonal tundra on a Late-Holocene river terrace with elevations from 10 to 16 m above sea level on the eastern part of Samoylov Island. The development of polygonal structures has created depressed polygon centers surrounded by elevated polygon rims with elevation differences of about 0.5 m. Underlying permafrost prevents drainage in polygon centers with-resulting in water-saturated soils, anoxic soil conditions at shallow depths, and significant amounts of soil organic carbon of around 33 kg m⁻² in the uppermost
- 165 meter (Zubrzycki et al., 2013). In contrast, <u>due to oxic conditions in the top-soil</u>, the elevated polygon rim soils <u>have</u> accumulated less soil organic carbon of around 19 kg m⁻² (Zubrzycki et al., 2013) <u>due to oxic conditions in</u> the top soil. <u>A land cover classification based on Landsat satellite imagery revealed that if excluding large thermokarst lakes The land cover ratio of the polygonal tundra on Samoylov Island <u>is-consists of 65_% for polygonof dry tundra-rims</u>, 19_% for polygon centersof wet tundra and 16_% for open- of small water bodies including small ponds overgrown by vascular plants (Muster et al., 2012).</u>
- In this study, two different <u>micrositesites</u> were investigated: i) a wet-depressed polygon center <u>(wet tundra)</u>; and ii) its surrounding elevated polygon rim (<u>dry tundra, 72°22,442</u> N; 126°29.828 E). These <u>micrositesites</u> were located within the footprint area of an eddy covariance (EC) system <u>where CO₂ NEE fluxes were measured</u>. (Kutzbach et al., 2007b; Wille et al., 2008; Runkle et al., 2013; Holl et al., 2018a). <u>At this polygon, tT</u>he maximum
- 175 active layer depth (ALD) at the study sits was deeper at the polygon center (40 cm) than at compared to the polygon rim (30 cm). The soils at the polygon centers were classified as *Histic* or *Reductaquic Cryosols* (WRB, 2014) with a water table close to the soil surface-. Polygon rim soils were characterized by cryoturbation and therefore classified as *Turbic Glacic Cryosols* (WRB, 2014) with a water table just a few centimeters above the permafrost table. Total organic carbon (TOC) contents above 10% were found in the surface horizon (0-6-em) above the
- 180 cryoturbated horizons of the polygon rim-at the study site, while high TOC contents at the polygon center were were found at the polygon center in the entirethroughout the active layer (Zubrzycki et al., 2013). The vV egetation of theon polygon rims is dominated by mosses (*Hylocomium splendens, Polytrichum spp., Rhytidium rugosum*), some small vascular plants (*Dryas punctata* and *Astragalus frigidus*) as well as lichens (*Peltigera spp.*) and was can be classified as non-tussock sedge, dwarf-shrub, moss tundra (after (Walker et al., 2005)) as non-tussock sedge.
- 185 dwarf-shrub, moss tundra. The vegetation of the polygon centers were dominated by the hydrophilic sedge *Carex* aquatilis, which have in general much higher growth forms than at the rim, and mosses (*Drepanocladus revolvens*, *Meesia triqueta, Scorpidium scorpioides*) and classified as sedge, moss, dwarf-shrub wetland according to (Walker et al. (2005).

3 Methods

195

190 **3.1 Meteorological data**

Meteorological variables were recorded at 30 minute intervals at the nearby EC system and adjacent meteorological station 40 m southwest of the study site. Data <u>were collected</u> on <u>relative humidity and</u> air temperature (MP103A, ROTRONIC AG, Switzerland), air pressure (RPT410F, Druck Messtechnik GmbH, Germany) and photosynthetically active radiation (PAR; wavelength: 400 – 700 nanometers; QS2, Delta-T Devices Ltd., UK) as well as the incoming and reflected components of shortwave and longwave radiation, respectively (CNR 1, Kipp and Zonen, Netherlands), were collected. The radiative surface temperature (T_{surf}, in Kelvin (K)) was calculated as:

$$T_{surf} = \left(\frac{L \uparrow_B}{\varepsilon \,\sigma}\right)^{1/4} \tag{1}$$

where $L \uparrow_B$ is the upward infrared radiation (W m⁻²), σ is the Stefan-Boltzmann constant (W m⁻² K⁻⁴), and the dimensionless emissivity ε was assumed to be 0.98 after Wilber et al. (1999). Furthermore, soil temperature (T_{soil}) was measured at 2 cm soil depth in intervals of 30 minutes at an adjacent polygon rim and center.

3.2 Soil sampling and vegetation indices

Undisturbed <u>A total of six</u> soil samples were taken from the <u>thawed_active</u> layer at the polygon rim using steel rings (diameter 6 cm). At the <u>water saturated</u> polygon center, <u>an undisturbed soil monolith was one soil sample</u> taken from the <u>thawed_active</u> layer using a spade, and <u>subsequently separated_subsampled</u> into four soil layers based on their degradation status <u>of the organic matter</u>. <u>Coarse roots were removed</u>, <u>and</u> <u>Ss</u>oil samples were homogenized for analysis of soil water content (mass difference between wet and dried (105 °C) soil samples) <u>and</u>, pH (CG820, Schott AG, Mainz, Germany). <u>T</u>total <u>C-carbon</u> and nitrogen (N) contents (VarioMAX cube, Elementar Analysesysteme GmbH, Hanau, Germany), as well as total organic carbon <u>(TOC) and total inorganic</u>

210 <u>carbon contents</u> (TOIC, liquiTOC II, Elementar Analysesysteme GmbH, Hanau, Germany) were determined from dried (105 °C for more than 24 hours) and milled soil samples. and total inorganic C (difference between total C and TOC). To analyze vegetation indices, gridded quadrats of 10 cm x 10 cm squares were placed over the collars, and a visual identification of the plant species present as well as their abundance (% surface cover) was conducted in four grid squares.

215 **3.3 Net ecosystem exchange and ecosystem respiration**

A total of eight PVC collarframes (50 cm x 50 cm), four at each micrositesite, were installed in July 2014 in preparation for NEE and Reco flux measurements with closed chambers the following year. The collarframes were equipped with a U-shaped frame filled with water to avoid gas exchange between the chamber headspace and ambient air. The chamber (50 cm x 50 cm x 50 cm) used for NEE and Reco flux measurements was made of clear 220 plexiglas-acrylic glass (Plexiglas SunActive GS, Evonik Industries AG, Germany). The chamber was equipped with a fan for continuous mixing of headspace air (axial fan, 12V/DC, Conrad Electronic SE, Germany). Furthermore, a PAR sensor (SKP212, Skye Instruments Ltd., UK) and a temperature probe (107 Thermistor probe, Campbell Scientific Ltd., USA) were installed inside the chamber. Including the volume inside the chamber collarframes, the chamber enclosed a volume of 124 - 143 L. For Reco measurements (dark chamber 225 measurements), the chamber was covered with an opaque boxmaterial (dark chamber measurements). Boardwalks were installed at both micrositesites to avoid disturbance. The volumetric soil water content (VWC) was measured with a GS3 sensor (Decagon Devices, Inc., USA) during each measurement directly beside the chamber collar frame atim a depth of 5 cm. A diver (Schlumberger Ltd., USA) was installed at the polygon center to measure water table (WT) depth every 15 minutes. To prevent pressure-induced gas release during chamber closure 230 (Christiansen et al., 2011), two holes (3 cm in diameter) at the top of the chamber were left open while placing the chamber on the collarframes and then closed for measurements. Soil temperatures between the surface and the frozen ground in 5 cm intervals and thaw depth were measured daily at both micrositesites. For each chamber flux measurement, CO_2 concentrations in the chamber headspace were continuously measured with an Ultra-Portable Gas Analyzergas analyzer (UGGA 30-p, Los Gatos Research, USA). The chamber headspace air was pumped in 235 a closed loop system via transparent polyurethane tubes (inner diameter 4 mm, each 10 m length) through the analyzer with a flowrate of 200 mL min⁻¹. The CO₂ concentration was logged (CR800series, Campbell Scientific Ltd., USA) together with PAR as well as soil and air temperature at a frequency of 1 Hz. Each chamber measurement-closure period was restricted to 120 sec to minimize warming inside the chamber relative to the ambient environmenttemperature.

240 Chamber measurements were conducted from 11 July until 22 September 2015. The chamber measurements were done at least every third day between 6 am and 9 pm (local time), apart from the period 2-9 August and 17-24 August. Two consecutive measurements were performed at each collarframe: first, NEE (n = 679) was measured with the transparent chamber, followed by an R_{eco} measurement (n = 679) with the dark chamber shortly after. The four collarframes of one micrositesite were measured in sequenceconsecutively before moving to the other micrositesite. GPP fluxes were calculated from the sum of the measured R_{eco} and NEE fluxes.

3.4 Heterotrophic respiration

- For R_H measurements the root-trenching method was applied at both micrositesites. It is challenging to separate belowground respiration fluxes into autotrophic and heterotrophic components because roots and microorganisms are closely linked within the rhizosphere (Hanson et al., 2000). There isare a wide range of methods forto partitioning ecosystem respirationReco (Subke et al., 2006; Kuzyakov, 2006), each with its associated advantages and disadvantages. Root trenching for example, despite some disturbance on the plant-soil interface, can give accurate estimates of the rates of R_A and R_H (Diaz-Pines et al., 2010) and produces similar results as a non-disturbing ¹⁴C partitioning approach in an arctic tundra ecosystem (Biasi et al., 2014) and a partitioning approach based on ¹³C (Chemidlin Prévost-Bouré et al., 2009). In this study, bBy inserting PVC collarframes below the main rooting zone at 20 cm deep into the soil, which is below the main rooting zone, lateral roots were cut off. All living plant biomass including living moss tissue inside the collarframes were-was removed carefully in 2014. To prevent re-growth, the living plant biomass was removed periodically over the measurement period. This removal causes the die-off of roots, and <u>in a period of</u> days after the disturbance R_H equals NEE. A total of eight
- 260 <u>collar frames</u>, four at each <u>micrositesite</u>, were prepared for R_H measurements. R_H fluxes (n = 662) were measured during the same periods and with the same <u>measurement intervalclosure period</u> as NEE and R_{eco} measurements on unaltered plots.

To test if R_H fluxes are related to artefacts from the root-trenching approach biased due to the additional decomposition of residual roots, four additional PVC collar frames (two per micrositesite) were installed in 2015

265 following the sampling and preparation protocol of 2014. A total of 302 R_H flux measurements were made on these newly installed plots. The differences between-of the mean R_H fluxes of each single plot-that was trenched in 2014 and those trenched in and 2015 were analyzed using a sStudent's t-test.

 R_A fluxes at the unaltered sites were calculated by subtracting the mean of the measured R_H fluxes from measured at the four replicate plots at the trenched sites from the mean of the measured R_{eco} fluxes at the unaltered sites from the mean of the measured R_{eco} fluxes at the unaltered sites from the mean of the measured R_{eco} fluxes at the unaltered sites from the mean of the measured R_{eco} fluxes at the unaltered sites from the mean of the measured R_{eco} fluxes at the unaltered sites from the mean of the measured R_{eco} fluxes at the unaltered sites from the mean of the measured R_{eco} fluxes at the unaltered sites from the mean of the measured R_{eco} fluxes at the unaltered sites from the mean of the measured R_{eco} fluxes at the unaltered sites from R_{eco} fluxes from R_{eco} fluxes at the unaltered sites from R_{eco} fluxes at the unaltered sites from R_{eco} fluxes from R_{eco} fluxes at the unaltered sites from R_{eco} fluxes at the una

270 <u>of</u> the same day. The calculated R_A fluxes <u>were</u> summed with <u>the calculated</u> GPP to estimate the net primary productivity (NPP) fluxes.

3.5 Flux calculation

 CO_2 fluxes (µg CO_2 m⁻² s⁻¹) were calculated using MATLAB® R2015a (The MathWorks Inc., Natick, MA, 2000) with a routine that uses different regression models to describe the change in the chamber headspace CO_2

275 concentration over time and conducts statistical analysis to aid model selection (Eckhardt and Kutzbach, 2016; Kutzbach et al., 2007a).

Due to possible perturbations while placing the chamber on the collar frame, the first 30 seconds of each 2-minute measurement period were discarded and the remaining 90 data points were used for flux calculations. The precision of the gas analyzer with 1 s signal filtering is < 0.3 ppm for CO₂- according to the manufacturer. Typically, t<u>T</u>he

- 280 root mean square error (RMSE) of chamber measurements and the fitting of the linear and non-linear regression models did not exceed this value under typical performance of chamber measurements and the fitting of the linear and non-linear regression models., and hHigher RMSE values indicated failed model fitting or disturbed chamber measurements. Therefore, if RMSE exceeded 0.3 ppm, the concentration-over-time curve was re-inspected. Variation of PAR during chamber measurements due to shifts in cloud cover leads to irregular CO₂ concentration
- 285 time series and perturbation of the calculated CO_2 fluxes (Schneider et al., 2012). These perturbed concentration time series show distinct autocorrelation of the residuals of the regression models and were filtered out by using a threshold for residual autocorrelation indicated by the Durbin-Watson test (Durbin and Watson, 1950). The flux curve was re-inspected If if the RMSE exceeded 0.3 ppm or showed a distinct autocorrelation, the flux curve was re inspected to see if irregularities could be removed by adjusting the time seriessize of the flux calculation
- 290 window. If irregularities could be removed by adjusting the size of the flux calculation window, the adjusting the time series, the flux curve was re-calculated and if not, the dataset measurement was discarded. Overall, about 3% (n = 47) of the CO₂ flux measurements (NEE, R_{eco} and R_H measurements) were discarded from the dataset, because they did not meet the abovementioned quality criteria.
- It was Studies have shown that CO₂ fluxes calculated with linear regression models can be seriously biased 295 (Kutzbach et al., 2007a), while non-linear regression models significantly improve flux calculations (Pihlatie et al., 2013). However, we found that the change in temporal evolution of CO₂ concentration in the chamber was best modelled-best with a linear regression model, as determined by the Akaike Information Criterion corrected for small samples sizes (AIC_c) (Burnham and Anderson, 2004). This is in good agreement with other studies, which have shown that in some cases a linear regression model can produce a better CO₂ flux estimate for a non-linear 300 concentration-over-time curve than a non-linear regression model (Koskinen et al., 2014; Görres et al., 2014).

3.6 Modelling CO₂ fluxes at the pedon scale

In this study the atmospheric sign convention is used, whereby a positive NEE defines a net release of CO_2 -from the soil to the atmosphere. To determine their single contribution to the NEE, dDifferent a range of numerical models were fitted to the measured CO2-fluxes to quantify seasonal GPP, Reco, and R_H-fluxes...

- 305 Different numerical models were fitted to the measured Reco and R_H fluxes and to the calculated GPP fluxes to quantify seasonal GPP, R_{eco} , and R_{H} fluxes. To calibrate the models, these used functions were fitted to the GPP, Reco, and R_H fluxes. The resulting fitting parameters were used to reproduce the fluxes over the complete measurement period. Model calibration was done by applying a 15-day moving window over the measurement period moving on a daily basis one day intervals. If less than eight chamber measurements were performed
- 310 during these 15 days, the moving window was extended to 19 days. Subsequently, the modelled fluxes for each measurement plot were averaged for each micrositesite. CO2 fluxes from each of the four measurement plots were used separately for model calibration and the summed fluxes were used to analyze differences between both micrositesites using a student's t-test.

The empirical Q₁₀ model (van't Hoff, 1898) was fitted to the measured R_{eco} and R_H fluxes:

$$= R_{hase} \times O_{10} \frac{\frac{T_{a,surf,soil} - T_{ref}}{\gamma}}{\gamma}$$
(2)

where the fit parameter R_{base} was is the basal respiration at the reference temperature T_{ref} (15 °C). Tref The reference temperature and γ (10 °C) were held constant according to Mahecha et al. (2010). Q_{10} was a fit parameter indicating describing the ecosystem sensitivity of respiration to a 10 °C change in temperature. For this study a fixed Q_{10} value of 1.52 was used, which represents the seasonal mean value of the bulk partitioning model for the CO₂ fluxes in the EC footprint area established by (Runkle et al. (2013)). Air temperature (T_a), surface temperature (T_{surf}), and

- soil temperature (T_{soil}) measured at a depth of <u>2</u>5 cm were tested as input variables.
 The model calibration was done with MATLAB® R2015a (The MathWorks Inc., Natick, MA, 2000). The model parameters were estimated by nonlinear least-squares regression fitting (nlinfit function), and the uncertainty of the parameters was determined by calculating the 95% confidence intervals using the nlparci function. The selection of the best performing temperature as input variable for the R_{eco} and R_H model was based on comparing the R²_{adj} of the model runs with different temperatures as input variable. The selected input variable was chosen
 - for all measurement plots of the same $\frac{\text{microsite}_{site}}{\text{might have had a better R}^2_{adj}}$.

330

315

320

R_{eco,H}

To estimate GPP, the chamber-measured R_{eco} fluxes were subtracted from the NEE fluxes separately-for each measurement plot. The rectangular hyperbola function was fitted to the calculated GPP fluxes as a function of PAR (in µmol m⁻² s⁻¹):

$$GPP = -\frac{P_{max} \times \alpha \times PAR}{P_{max} + \alpha \times PAR}$$
(3)

where the fit parameter P_{max} was the maximum canopy photosynthetic potential (hypothetical maximum of $P_{max}GPP$ at infinite PAR). The values for the initial canopy quantum efficiency α (dimensionlessin µg m⁻² s⁻¹ / μ mol m⁻² s⁻¹; initial slope of the P_{max} -PAR curveGPP model at PAR = 0) were obtained from modelling the CO₂ fluxes with EC data (Holl et al., 2018b)(Kutzbach et al., unpublished). From the determined values when α was held variable, a function was formulated that accounts for the seasonality of α with specific values for every cach day of the growing season using the following function:

$$\alpha = b \times exp^{\left(-\frac{abs\left((x-c)^d\right)}{2 \times e^2}\right)} + f$$
(4)

340 where b = 0.042, c = 209.5, d = 2, e = 25.51, f = 0.008 and x = day of year 2015. Afterwards, these values (variable on daily basis) were used <u>for both sites</u> to reproduce GPP fluxes from chamber measurements over the complete measurement period.

Although the transmissivity of the chamber material was high with (> 902_% for wavelengths between 380 and 780 nano meter (Evonik, 2015)), it caused a reduction in the amount of incoming radiation reaching the surface.
During the complete measurement period, the PAR values measured inside the chamber were on average 20% lower than the PAR values measured outside the chamber (data not shown). Therefore, GPP modelling was conducted in two steps. First, the GPP model was calibrated using PAR values measured inside the chamber; and secondly, the reproduction of GPP fluxes over the growing season was carried out using PAR values measured outside the chamber. Without this two-step calibration the CO2 uptakeGPP fluxes rates would have been underestimated.

The NEE fluxes were calculated as the sum of the modelled GPP and R_{eco} fluxes. The R_A fluxes were calculated as the difference of the modelled R_{eco} and R_H fluxes. Furthermore, NPP was calculated from the sum of R_A and GPP fluxes.

As both sites are within the footprint of an EC station, which determines CO₂ fluxes on a larger spatial scale (100 355 to 1000 meter), the resulting NEE from the modelling approach was compared with NEE of the same period obtained from EC measurements reported by Holl et al. (2019)-. For this upscaling, the resulting NEE fluxes from the chamber model were weighted (NEE_{chamber}) based on the half-hourly relative contributions of the surface classes defined by Muster et al. (2012) to the EC footprint using the following equation: $NEE_{chamber} = NEE_{c} \times Cover_{wet} + NEE_{R} \times Cover_{dry}$ (5)

where NEE_{C} and NEE_{R} are the modelled half-hourly chamber NEE for polygon center and rim, respectively and 360 Cover_{wet} and Cover_{drv} the relative contribution of the surface classes polygon center and rim, respectively to the EC footprint as given in Holl et al. (2019).

4 Results

4.1 Meteorological data, and environmental conditions, and soil characteristics

365 From mid-July to the end of September 2015, soil temperatures at 2 cm depth at the polygon rim showed a higher diurnal variability than at the center. The highest soil temperatures were measured in mid-July and at the beginning of August. At the end of September, the temperatures became slightly negative (Figure 2). The mean daily air temperature over the study period ranged between-from23 °C toand -2 °C (Figure 2a). Three warm periods were recorded, one in mid-July (up to 27 °C) and one at the beginning of August (up to 25 °C) and a third warm period 370 was recorded at the beginning of September with temperatures of up to 20 °C. The average air temperature in August 2015 (9 °C) was similar to the long-term mean air temperature over-for the period 1998-2011 (Boike et al., 2013). Compared to the long-term mean, it was about 1°C colder during July (9 °C), whereas September was around 2 °C warmer than the reference period (3 °C). The total precipitation from mid-July to end of September 2015 was 78 mm which is below the mean precipitation of 96 ± 48 mm between 2003 and 2010 (Boike et al., 375 2013).

390

decreasing.

From mid-July to the end of September 2015, soil temperatures at 2 cm depth at the polygon rim showed a higher diurnal variability than at the center. The highest soil temperatures were measured in mid-July and at the beginning of August. At the end of September, the temperatures became slightly negative (Figure 2b). At the polygon rim, the thaw depth increased from the beginning of the campaign in mid-July until mid-September to reach a maximum 380 depth of 36 cm. Maximum thaw depth was reached at the polygon center much earlier in the season (mid-July) and remained relatively constant until mid-September. From mid September onwards the thaw depth decreased slightly until the end of September at both microsites. The water table depth at the polygon center wasere tightly coupled to rainfall. The VWC at 5 cm soil depth was on average 30% at the polygon rim, with highest values observed after rainfall events (Figure 2c). The daily averaged PAR values showed a strong seasonality with

385 decreasing daily mean values towards the end of the season, although there was a period at the end of July with rather low daily averaged PAR values.

Photosynthetically active radiation showed strong diurnal variability, with lowest PAR values during nighttime. From mid July until 12 August, mean nighttime (9 pm - 3 am) PAR values did not drop below 5 µmol m² s⁺¹ (Figure 2). Afterwards, with upcoming polar night conditions, the number of periods with PAR values below 5 µmol m⁻² s⁻¹ increased. Midday PAR values above 1000 µmol m⁻² s⁻¹ were measured in mid July, at the beginning of August, and once at the end of August. Throughout September, the daily maximum PAR values were

The total soil <u>C-carbon</u> content was lower at the polygon rim (2-12%) than <u>at</u> the polygon center (10-20%) and showed a reduction-decrease with depth, which was more pronounced at the polygon rim. The estimated SOC

- 395 stocks within 30 cm depth were about 11 Kkg m⁻² and about 21 Kkg m⁻² at the polygon rim and center, respectively. The total inorganic carbon content was at both sites in each soil depth 0.2 %. At the polygon center the N content showed little variability with depth, with being around 0.6%, and the C/N ratio decreased from 33.1 at the surface to 16.9 at the bottom of the active layer. In contrast, in the polygon rim, the N content was considerably higher in
- the organic rich layer compared to the mineral soil layer (0.5% vs. 0.1%), and the difference of the C/N ratio at
 different soil depths was smaller than in the center. Strongly acidic pH values were measured throughout the active
 layer of both microsites, with values around 5.3 at the polygon center, while in the organic rich layer and in the
 mineral soil layer at the rim the pH was moderately acidic with values of 5.7 and 6.0, respectively.

4.2 Carbon dioxide Chamber CO2 fluxes

towards the end of the season.

In general, the CO₂ uptake (NEE) at the polygon center was higher (means more negative values) than at the rim 405 (Figure 3). The highest NEE fluxes were measured at the end of July with $97 \pm 27 \ \mu g \ CO_2 \ m^2 \ s^+$ and $-209 \pm 17 \ \mu g \ CO_2 \ m^2 \ s^-$ at the rim and center (Figure 3), respectively. In September, both micrositesites acted as small net CO₂ sources of atmospheric CO₂. The net CO₂-uptake at the center was generally higher than at the rim. The highest net CO₂ release at the polygon rim was measured on 17 August with $16 \pm 5 \ \mu g \ CO_2 \ m^2 \ s^-$, and at the polygon center on 19 September with $22 \pm 3 \ \mu g \ CO_2 \ m^2 \ s^-$. The standard error of the flux calculation was about around 3.5 and 2.3 \mu g CO₂ m⁻² s⁻¹ for the polygon center and rim, respectively, and decreased slightly

Inseason. In contrast to the NEE fluxes, the measured R_{eco} fluxes were on average higher at the rim compared to the center. The lowest ecosystem respiration fluxes at the polygon center were observed on 23 July with $10 \pm 3 \ \mu g \ CO_2 \ m^{-2} \ s^{-1}$ and at the polygon rim on 21 September with $17 \pm 1 \ \mu g \ CO_2 \ m^{-2} \ s^{-1}$. The highest ecosystem

415 respiration fluxes of 80 ± 11 and $88 \pm 10 \ \mu g \ CO_2 \ m^2 \ s^4$ for rim and center, respectively, were measured at beginning of 9 August, when the air temperature exceeded 20 °C. In general, the release of CO₂ by R_H was higher at the polygon rim than at the center and showed no seasonality (Figure 3). An increase in R_H fluxes after periodical re-clipping of the vegetation were not observed. Comparing R_H fluxes from measurement plots that were trenched in 2014 with those trenched in 2015 revealed no significant

420 <u>differences (t-test, p > 0.05) between the years of root-trenching (data not shown).</u>
 The net CO₂ uptake increased from mid-July until it peaked during the vegetation maximum at the end of July and beginning of August.

Due to a period with rather low daily averaged PAR at the end of July, the uptake was partly lower as at the beginning of the measurement period at both sites. After reaching peak net CO₂ uptake at the beginning of August,

- Subsequently, the uptake NEE decreased until the end of September. This seasonality was more pronounced at the polygon center than at the polygon rim. Interestingly, towards September the net CO₂ uptake by NEE at the polygon rim exhibited an increase for a period of about one week, before until it decreased again towards the end of September. R_{eco} fluxes showed a similar, but less distinct seasonal pattern, and the peak of the highest R_{eco} fluxes was in mid-August. In contrast, R_H fluxes showed no seasonal trend at the polygon center, while at the polygon rim the R_H fluxes were also highest when R_{eco} and uptake by NEE reached their maxima.
- As GPP, NPP and R_A fluxes were calculated from the measured NEE, R_{eco} and R_H fluxes, these fluxes show similar patterns of seasonality. The highest GPP and NPP fluxes were observed during the vegetation maximum, with a

more pronounced seasonality at the polygon center compared to the rim. In general, R_A fluxes were within the same range at both sites which is in contrast to the calculated GPP fluxes, which were almost twice as high at the

- 435 <u>polygon center than at the rim.</u> The lowest GPP fluxes were calculated for the end of September with $-10 \pm 3 \ \mu g \ CO_2 \ m^{-2} \ s^{-1}$ and $-16 \pm 6 \ \mu g \ CO_2 \ m^{-2} \ s^{-1}$ for the polygon center and rim, respectively (Figure 3). The highest GPP fluxes at the polygon rim were found at the end of July and beginning of August with $-143 \pm 33 \ \mu g \ CO_2 \ m^{-2} \ s^{-1}$ as well as at the polygon center with $-245 \pm 19 \ \mu g \ CO_2 \ m^{-2} \ s^{-1}$.
- The calculated R_A fluxes at the polygon center were on average $18 \pm 14 \ \mu g \ CO_2 \ m^2 \ s^+$ with highest fluxes of 440 $56 \pm 10 \ \mu g \ CO_2 \ m^2 \ s^+$ measured on 17 August. At the polygon rim, the averaged calculated R_A flux was $16 \pm 8 \ \mu g \ CO_2 \ m^2 \ s^+$. At this microsite, the highest R_A flux of $42 \pm 7 \ \mu g \ CO_2 \ m^2 \ s^+$ was observed on 18 July, and the lowest R_A flux was observed at mid September with $3 \pm 9 \ \mu g \ CO_2 \ m^2 \ s^+$.

As observed for the GPP fluxes, calculated NPP fluxes showed a distinct seasonality (Figure 3). The mean NPP fluxes were -94 ± 61 and $-55 \pm 26 \ \mu g \ CO_2 \ m^2 \ s^4$ at the polygon center and rim, respectively. The highest NPP flux at the center was on 30 July with $-222 \pm 18 \ \mu g \ CO_2 \ m^2 \ s^4$, which is three days earlier than the maximum GPP

- flux was determined. Similar to the highest GPP fluxes, the highest NPP flux at the rim was determined on 27 July with $-115 \pm 29 \ \mu g \ CO_2 \ m^2 \ s^{-1}$. The lowest NPP fluxes were determined in September with $-10 \pm 11 \ \mu g \ CO_2 \ m^2 \ s^{-1}$ at the rim and $-2 \pm 6 \ \mu g \ CO_2 \ m^2 \ s^{-1}$ at the center.
- The highest releases of CO₂ by R_H were measured on 9 August at the polygon center and rim with 38 ± 6 and $51 \pm 12 \ \mu g \ CO_2 \ m^2 \ s^4$, respectively. The lowest R_H fluxes of $3 \pm 1 \ \mu g \ CO_2 \ m^2 \ s^4$ were measured at the center on 3 September, while at the rim lowest R_H fluxes of $10 \pm 3 \ \mu g \ CO_2 \ m^2 \ s^4$ were observed at the end of September. Increased R_H fluxes after periodical re-elipping of the vegetation were not observed. The comparison of R_H fluxes from measurement plots that were trenched in 2014 with those that were trenched in 2015 revealed no significant differences (t test, p > 0.05) between the years of root trenching (data not shown).
- Interestingly, the R_{eco} fluxes were linearly correlated with WT fluctuations from the beginning of July until the end of August (Figure 4<u>d</u>). In contrast-to this, neither a trend of higher R_H fluxes during times of high WT, nor lower R_H fluxes during times of low WT were observed. Instead, the R_A fluxes showed a <u>good-significant</u> correlation ($R^2 = 0.71$; p < 0.05) with WT fluctuations.

4.3 Modelled CO₂ fluxes

445

The fitting parameter of the GPP model (Equation 3), P_{max} , showed strong spatial and temporal variability (Figure 460 5b). The α values (Equation 4) used for the GPP model showed a high temporal variability with a mean of 1.47 ± 0.62 . This value increased sharply towards the peak vegetation period at the end of July and decreased thereafter until afterwards towards the end of the growing season. The P_{max} values showed a strong temporal variability (high standard deviation) at the polygon center (mean: $250.7 \pm 101.9 \ \mu g \ CO_2 \ m^{-2} \ s^{-1}$). Considerable differences in P_{max} were also observed between the polygon rim and the center. The averaged P_{max} at the polygon 465 $(135.4 \pm 37.2 \ \mu g \ CO_2 \ m^{-2} \ s^{-1})$ was substantially lower than rim at the polygon center $(250.7 \pm 101.9 \ \mu g \ \text{CO}_2 \ \text{m}^{-2} \ \text{s}^{-1})$. As with the measured NEE fluxes, P_{max} values displayed an increase at the polygon rim towards the end of September. The fitting parameter of the Reco and R_H model (Equation 2), R_{base}, also showed a-strong spatial and temporal variability (Figure 5d). In general, Rbase was higher at the polygon rim. The averaged R_{base} values for the R_{H} model fit differed substantially between micrositesites with 14.6 ± 2.1 µg CO₂ m⁻² s⁻¹ at the 470 polygon center and $29.0 \pm 2.9 \ \mu g \ \mu g \ CO_2 \ m^{-2} \ s^{-1}$ at the polygon rim.

Polygon center R_{eco} fluxes were best modelled using surface temperature as explanatory variable. The best model fit of polygon center R_{eco} fluxes ($R^2_{adj} = 0.70$) was achieved when the surface temperature was used as explanatory variable; while for the polygon rim the soil temperature showed the best fitting ($R^2_{adj} = 0.46$). In contrast to the

- 475 R_{eco} fluxes, the best model fit for polygon center R_H fluxes was achieved were best modelled when the air temperature was used as explanatory variable ($R^2_{adj} = 0.55$). At the polygon rim, using the soil temperature as explanatory variable showed the best fitting ($R^2_{adj} = 0.45$) when modelling R_H fluxes. However, dD ifferences in the goodness of the fits for the R_{eco} flux model were small. The R^2_{adj} of the GPP model was 0.82 for the polygon center and 0.45 for the polygon rim.
- 480 At the polygon rim, the averaged modelled R_{eee} fluxes were higher than at the center (Table 1), However the difference between the microsites was not statistically significant (t test, p > 0.05). The modelled GPP, R_{eco} and R_{H} fluxes were used to calculate the NEE, R_{A} and NPP fluxes. All fluxes showed similar seasonal patterns as fluxes from chamber measurements. The comparison between modelled and measured fluxes showed highly significant correlation ($R^2 = 0.39 0.88$, p < 0.001, Figure 6 and 7). However, the fluxes at the polygon rim tended to be
- 485 underestimated by the model if the respiration fluxes were high and the other fluxes were low (close to zero or positive NEE). A similar trend was observed for the respiration fluxes from the polygon center. Furthermore, NEE, GPP and NPP fluxes seem to be generally underestimated by the flux models. However, this offset was to be expected due to the use of different PAR values for flux calculation (see section 3.6). The highest Reee values were encountered at both microsites at the beginning of August (Figure 6 and Figure 7). At the polygon rim, the lowest
- 490 R_{eco} fluxes where obtained at the end of September, while the lowest fluxes at the polygon center where observed on 21 July, associated with the highest water table during the campaign.
 At the polygon center, the modelled R_H-fluxes were substantially lower than at the polygon rim, and this difference

At the polygon center, the modelled R_H fluxes were substantially lower than at the polygon rim, and this difference between the microsites was highly significant (t test, p < 0.001). The lowest R_H fluxes at the center were encountered on 3 September, a period of low air temperatures. The highest R_H flux was observed when
 temperatures first rose above 25 °C in July. The highest and lowest modelled R_H fluxes at the polygon rim were

encountered at the same time as the highest and lowest modelled R_{eco} fluxes (8 August and 20 September). When comparing modelled data for R_{H} and the R_{eco} over the whole measurement period, the contribution of R_{H} to R_{eco} was on average 42 % at the center and 60 % at the rim.

The modelled GPP fluxes showed a distinct seasonal trend. From the mid of July until 12 August, photosynthesis took place for 24 hours per day because of polar day conditions, even though the CO₂ uptake was low during nighttime. Afterwards, periods when GPP was zero extended due to extended night conditions. At both microsites, the diurnal amplitude of GPP increased from the beginning of the campaign until it reached a maximum in mid-August. After this peak, the GPP fluxes at the center continuously decreased until the lowest daily maximum GPP on 21 September at the polygon center. Interestingly, the lowest daily GPP maximum at the polygon rim was

505 observed about a week earlier than at the polygon center. Later, the GPP at the polygon rim increased again. The difference in GPP fluxes between the microsites was statistically significant (p < 0.01). The R^2_{adj} of the GPP model was 0.82 for the polygon center and 0.45 for the polygon rim.

The modelled GPP and R_{eee} fluxes were used to calculate NEE fluxes. The highest net CO₂-uptake at the rim was encountered on 23 July and on 16 August at the polygon center, while the highest net CO₂ release was measured
 at both microsites on 17 August. The diurnal amplitude of NEE oscillation was greatest between the end of July and mid-August. The modelled R_{eee} and R_H fluxes were used to calculate R_A fluxes. Therefore, the lowest and

highest R_A fluxes were similar to the R_{eeo} and R_H fluxes. The modelled R_A fluxes correlated substantially with WT

fluctuations with lowest RA fluxes during times of lowest WT. The NPP fluxes were calculated from the sum of GPP and R_A fluxes. At both microsites the highest NPP was encountered in mid-August, while the lowest daily net primary productivity was in mid September. At the polygon center the NPP showed a distinct seasonal trend,

4.4 Integrated fluxes

while at the polygon rim this trend less clear.

515

Based on the modelled chamber CO₂ fluxes, the time-integrated CO₂ fluxes were calculated for the period between mid-July and end of September 2015 were calculated (Table 1, Figure 8). The integrated GPP flux at the polygon center was substantially significantly (t-test, p < 0.01) higher than at the polygon rim-and statistically significant 520 (t test, p < 0.01). In contrast, the integrated R_H fluxes at the polygon rim were almost double those at the polygon center ($p \le 0.001$). This trend was also observed for R_{eco} fluxes, although here the difference was not as large as seen for R_H fluxes and was not significant (p > 0.05). Furthermore, the flux differences in R_A between the sites were rather small. Much higher GPP fluxes in association with lower R_H and similar R_A fluxes led to an The 525 integrated net CO₂-uptakeNEE (NEE), which was more than twice as high at the polygon center ($-68 \pm 12 \ \mu g \ CO_2$) $m^{-1} s^{-1}$) than at the rim (-26 ± 19 µg CO₂ m⁻¹ s⁻¹) and led to an almost twice as high furthermore NPP at the center than at the rim. The comparison of upscaled NEE from modelled chamber data correlated highly significant ($R^2 =$ 0.88, p < 0.001) with modelled NEE from EC data (Figure 9). However, the upscaled NEE from modelled chamber data tended to underestimate the highest uptake and release by NEE in comparison to modelled NEE from EC data. The integrated GPP flux at the polygon center was substantially higher than at the polygon rim. Interestingly, 530 the integrated Reco flux at the rim was higher than at the center, and an almost twice as high R_H flux at the rim was observed. The integrated RA fluxes at polygon center and rim were within the same range. During the vegetation

5 Discussion

535 This study presented the first values of NEE, GPP, NPP as well as R_{eco} , R_{H} and R_{A} fluxes obtained from direct measurements and modelling approaches for different-dry and wet micrositesites of the polygonal tundra-were presented. These fluxes are of crucial importance as they show the different response that the underlying processes governing CO2 NEE have to environmental controls over the growing season, both spatially and temporally. Both the water saturated polygon center and the non-saturated polygon rim acted as net sinks for atmospheric CO2 for

period, the NPP was almost twice as high at the center compared to the rim.

- 540 the period from mid July to end of September 2015. The CO₂-sink strength differed substantially between the microsites, which is related to the different hydrological conditions and vegetation composition. The R_H fluxes were higher at the polygon rim compared to the center due to drier soil conditions at the rim. RA fluxes from both sites were similar although the vascular plant cover at the center was higher, probably due to water-saturated conditions at the center. In <u>-Theaddition</u>, the integrated Reco fluxes at the rim were higher than at the center, due to
- 545 higher R_H and similar R_A fluxes at both sites. The mean GPP fluxes are much higher at the center compared to the rim due to differences in vegetation between the sites. Together with RA fluxes that are within the same range between the sites, the differences in GPP lead to an almost two times higher NPP at the center compared to the rim. In sum, both the water-saturated polygon center and the non-saturated polygon rim acted as net sinks for atmospheric CO₂ for the period mid-July to end of September 2015. However, the CO₂ sink strength differed substantially between wet and dry tundra, which can be related to the different hydrological conditions and
- 550

<u>vegetation composition</u> This is remarkable as R_{eco} fluxes are expected to rise with increasing GPP fluxes (Bubier et al., 2003), since CO₂-uptake via photosynthesis is the source of R_A -fluxes. However, despite substantial higher GPP fluxes, the R_A -fluxes at the center were within the same range as those at the rim. Furthermore, higher R_{eco} fluxes at the polygon rim compared to the center were also caused by the higher rim R_H -fluxes due to drier soil conditions. Overall, the differences in R_A and GPP fluxes between the two microsites led to NPP at the polygonal eenter being almost two-times higher than at the polygon rim.

555

560

565

5.1 CO₂ fluxes from arctic tundra sites

To the best of our knowledge, CO₂ fluxes from polygon rim and center sites were reported merely from Barrow, <u>Alaska (Table 2)</u>. The modelled R_{eee} fluxes at both studied microsites were at the lower end of those reported for other arctic tundra sites with similar vegetation and soil composition (Table 2). The daily averaged net CO₂ uptake at the polygon center from this study is twice as high as reported from any other study concerning CO₂ fluxes from polygonal tundra. Instead, beside this study, just the study by Olivas et al. (2011) reported the polygonal tundra to be a net sink, while other studies (Oechel et al., 1995; Lara et al., 2012; Lara and Tweedie, 2014) reported the polygonal tundra to be a net source of CO₂ over the growing season. The GPP fluxes from the polygon center from this study exceed the GPP fluxes from Barrow reported by Oechel et al. (1995) and (Lara et al., 2012), but are distinctly lower than those reported by (Olivas et al., 2011) and (Lara and Tweedie, 2014). In terms of respiration, the R_{eco} fluxes from this study at both sites are lower compared than the reported R_{eco} fluxes from the polygonal tundra at Barrow. However, the inter-annual variability of reported CO₂ fluxes from Barrow is rather high, which

also could be caused by different vegetation and soil composition between the sites at Barrow.
 A comparison of the CO₂ fluxes from the wet and dry site from this study with other wet and dry sites of the arctic tundra revealed rather low photosynthesis and respiration rates from the polygonal tundra on Samoylov Island (Table 2). The R_{eco} fluxes from this study on both sites are lowest compared to other sites and the GPP fluxes of

the polygon rim from this study are at the lower end compared to other dry sites, while the GPP fluxes of the

- polygon center are in between the fluxes from other wet sites. Only one study from a *Carex* shrub site in Cherskii
 575 reported higher NEE fluxes (Kwon et al., 2016) compared to the polygon center from this study. Both the moderate GPP and low R_{eco} fluxes at the polygon center lead to rather high net CO₂ uptake compared to other arctic tundra sites. Solely, a wet tundra site in the Komi Republic, Russia , a wet sedge site at Daring Lake, Canada (Nobrega and Grogan, 2008) and a polygon center site in Alaska (Oechel et al., 1995) showed R_{eco} fluxes that were within the same range as in this study. The comparison of partitioned CO₂ fluxes from different arctic tundra sites
- 580 highlighted the importance of individual GPP and Reee fluxes to explain NEE fluxes. The comparatively low Reee fluxes and moderate GPP fluxes reported from this study led to relatively high NEE fluxes at the polygon center, compared to other tundra sites. Furthermore, the highest net CO₂ uptake fluxes were reported from wet and sedge-dominated sites. The GPP fluxes at the two studied microsites are lower than reported fluxes from most arctic study sites .

585 5.2 Environmental controlsFactors controlling-on CO₂ fluxes

The rather moderate GPP and low R_{eco} fluxes of the polygonal tundra on Samoylov Island compared to other arctic sites might be due to differences in vegetation composition, organic matter contents, low nutrient availability as well as low temperatures and radiation at the study site. The polygonal tundra on Samoylov Island had to beis considered as an ecosystem with rather low moderate GPP due to its low vascular plant coverage with a maximum

- 590 leaf coverage of 0.3 (Kutzbach et al., 2007b). Mosses, which have a high leaf-coverage (> 0.9), were dominant at both micrositesites and have, similar to lichens, a much lower photosynthetic capacity than vascular plants (Brown et al., 1980). Furthermore, In general, photosynthesis of vascular plants as well as respiration fluxes is restricted are lowered due to in arctic tundra ecosystems due to the low nutrient availability in arctic tundra ecosystems (Shaver et al., 1998). Alt-ow nutrient availability is typical for most tundra soils due to water saturated conditionsion and
- low soil temperatures (Johnson et al., 2000)₂₇ these conditions ensure-cause low microbial decomposition rates (Hobbie et al., 2002), which in turn result in a low supply of bioavailable nutrients (Beermann et al., 2015). However, following Sanders et al. (2010) the Nnitrogen stocksturnover rates of the soils found at the studyied micrositesites were can be estimated as rather low compared to other arctic tundra sites. Additionally, the long-term average net radiation at the study site from (June to August, 1999-2011) was with a mean of 85 W m⁻² (1999-2011), which is lower than values those reported from most other arctic tundra sites in Alaska and Greenland (Boike et al., 2013; e.g. Wendler and Eaton, 1990; Oechel et al., 2014; Soegaard et al., 2001; Lynch et al., 1999). These factors might explain the comparatively low GPP Recoffuxes and moderate GPP fluxes at the polygon rim and center compared to other arctic tundra sites.
- <u>The dDifferences_observed</u> in GPP between the <u>polygon</u> rim and center can be related to the vascular plant coverage. The polygon center had a much higher abundance of sedges, while the rim was moss-dominated and the sparsely spread vascular plants had shorter and fewer leaves. Therefore, the photosynthetic capacity <u>is higher at</u> the polygon center than at the rimof the center is higher than the rim, resulting in <u>the center having a</u> higher GPP. Additionally, limited water availability due to the elevation of the polygon rim caused moisture to run_off, with a drier or desiccated moss layer potentially contributingwhich may have contributed to <u>a</u> lower GPP (Olivas et al.,
- 610 2011). On the other hand, Olivas et al. (2011) found GPP fluxes to be higher at a polygon rim than at a polygon center in the Alaskan coastal plains. They related low GPP fluxes at the <u>polygon</u> center to submersion of the moss layer and vascular plants. At the polygon center of the current study, the WT was frequently below the soil surface so that submersion of erect vascular plants was not <u>regularly</u> observed <u>regularly</u>, and <u>even most part of</u> the moss layer <u>itself</u> was not submerged for most of the time. This difference in GPP between the Alaskan study sites (Olivas
- et al., 2011) and those presented in this study reveals the importance important influence, beside the vegetation composition, of water level and its fluctuations throughout the season on CO₂ fluxes.
 Differences in respirationNEE fluxes between the wet and dry two-micrositesites can also be related to their different soil conditions. The cold and water-logged conditions, typical foref the polygon centers, inhibited reduced decomposition and mineralization of SOM due to oxygen limitation, which caused causing low microbial
- 620 activity and therefore low R_H (Hobbie et al., 2002; Walz et al., 2017). Furthermore, the moisture run-off at the rim created drier conditions in the top-soils at the rim, which increased soil oxygen availability and therefore <u>subsequently</u> enhanced R_H and R_{eco} (Oechel et al., 1998). <u>In addition, T</u>the <u>higher stronger</u> diurnal amplitude of the soil temperature, a product of the thermic buffer function of the standing water at the center, at the polygon rim compared to the center led to higher daily soil temperatures. at the polygon rim compared to the center. Both
- 625 the higher increased temperatures and oxygen supply at the polygon rim relative to the center enhanced microbial decomposition and therefore causing higher R_H fluxes to be observed at the polygon rim compared to the polygon center. Hence As such, the low net carbon CO₂ uptake (NEE) at the rim occurred are caused not only because of by low GPP, but also due to by higher R_{ecoH} fluxes compared to the center. The higher NEE at the polygon center compared to the rim is mainly driven by substantially higher GPP, and lower R_H fluxes, which are due to differences in second enter to the rest of the rest of the rest of the substantially higher GPP.
- 630 differences in vascular plant cover, temperature and hydrology. This finding is in good agreement with Nobrega

and Grogan (2008) who compared a wet sedge, with a dry heath, and a mesic birch site and found that the net carbon-highest CO₂ uptake at the wet sedge site was highest because of due to limited respiration \underline{R}_{eco} due to associated with the water-logged conditions.

- Interestingly, measurements of CO₂ fluxes at the polygon rim showed an increase of net CO₂ uptake 635 NEE throughout September, whereas at the polygon center the net CO₂ uptake<u>NEE</u> appeared to continuously decrease (lower net uptake of CO2). This increase in late season NEE at the polygon rim cannot be explained by rising PAR or temperature, but- Rather, the increase of net CO2 uptake at the rim towards the end of September may be related to the photosynthetic activity of mosses. At the study site, Kutzbach et al. (2007b) considered-the September at the EC footprint area as period where moss photosynthesis dominates C uptakeGPP. -occurs mostly 640 due to moss photosynthesis. During this time of the growing season, mosses can still assimilate substantial amounts of CO_2 because they tend to reach light saturation at lower irradiance (Harley et al., 1989). The photosynthetic activity of mosses declines rapidly when they face desiccation, because they cannot actively control their tissue water content (Turetsky et al., 2012). Additionally, Hit has been was also shown that mosses face light stress during times of high PAR (Murray et al., 1993). This light stress causes delayed senescence and more late-season 645 photosynthesis (Zona et al., 2011). Therefore, On Samoylov, the photosynthetic activity onat the moss-dominated polygon rim is expected to be low during warm and dry periods such as those seen at the beginning of September 2015, and during times of high PAR. In contrast, with continuous rainfall, dew formation and the lower PAR observed in mid-September, the mosses on the polygon rim are likely to have resumed their metabolic activity,
- 650 reported the highest contribution of mosses to GPP at the beginning and end of the growing season. With continuous rainfall, dew formation and lower PAR in mid September, the mosses are likely resume metabolic active, which led to increasing net CO₂ uptake at the rim.

which led to increasing NEE at the rim. These findings are in good agreement with Olivas et al. (2011), who

5.3 Partitioning respiration fluxes in arctic tundra ecosystems

- To date only a handful of few studies have estimated growing season R_H fluxes from arctic tundra ecosystems over 655 a growing season under in situ conditions (Nobrega and Grogan, 2008; Biasi et al., 2014). Surprisingly, the differences in R_H flux estimates reported in the literature-between these estimates and those presented in this study were rather low. Differences in $R_{\rm H}$ fluxes measured with the trenching method may be caused result from by differences in the time between trenching and start of the measurement. Nobrega and Grogan (2008) for example started their $R_{\rm H}$ measurements one day after clipping, while measurements in this study as well as in the study and 660 that of Biasi et al. (2014) started about one year after treatment. Therefore, even-although these studies employed a similar partitioning approach for seasonal estimates of R_H fluxes was similar for all studies, any comparison must be made with caution. The few R_H flux estimates reported in the literature from other arctic tundra sites were higher than the R_H values from the Lena River Delta (0.5 ± 0.1 and 0.3 ± 0.02 g C m⁻² d⁻¹ at polygon rim and center, respectively). Higher growing season R_H fluxes than found in this study throughout the growing season $(0.8-1.8 \text{ g C m}^{-2} \text{ d}^{-1})$ were have been measured at a mesic birch and a dry heath site at Daring Lake in Canada 665 (Nobrega and Grogan, 2008) and at a bare peat site $(1.0 \text{ g C m}^{-2} \text{ d}^{-1})$ in the subarctic tundra at Seida, Russia (Biasi et al., 2014). Both sites contained substantially higher amounts of SOC in the organic-rich layer than the soil at the polygon rim and were well-aerated compared to the soil at the polygon center, which both mostboth of which likely caused a higher organic matter decomposition rate and could explain the higher R_H fluxes than found at the
- 670 polygonal tundra micrositesites. Similar R_H fluxes to those reported in our study were measured at a wet sedge site

in Daring Lake (0.4 g C m⁻² d⁻¹) (Nobrega and Grogan, 2008), where soil and environmental conditions like WT, ALD, soil temperature, vegetation and SOC were similar to the Samoylov sites and at vegetated peat sites in Seida (0.4-0.6 g C m⁻² d⁻¹) (Biasi et al., 2014). Despite these differences, the averaged contributions of R_H to R_{eco} of 42% at the center and 60% at the rim are in good agreement with those observed at Seida (37 – 64%) and Daring Lake

- (44 64%). Similar contributions were-have also been determined from an arctic tussock tundra sites, where R_H makes up approximately 40% of growing season R_{eco} (Segal and Sullivan, 2014; Nowinski et al., 2010) and from a moist acidic tussock tundra site (Hicks Pries et al., 2013). In contrast to these results, in a subarctic peatland Dorrepaal et al. (2009) -determined-report a substantially higher contribution of R_H to R_{eco} with of about 70% in a subarctic peatland. The different contributionce in the contribution of R_H to R_{eco} between at the polygon rim and
- 680 center at our study site<u>on Samoylov Island</u> can be related to differences in vascular plant coverage and moisture conditions between both these micrositesites. HThe higher GPP at the center than at relative to the rim also caused also higher rates of R_A-and in turn lowered-lowering the contribution of R_H to R_{eco}. Additionally, anoxic soil conditions due to standing water, like atwhich characterized the polygon center, were not favorable forreduced SOM decomposition rates of SOM. Furthermore, Moyano et al. (2013) and Nobrega and Grogan (2008) -concluded

685 <u>have shown</u> that consistently moderate moisture conditions, as at the polygon rim, promotes fast decomposition of SOM<u>microbial activity</u> and therefore <u>ensures enable</u> higher R_H rates than at the center. <u>Interestingly, aA</u>t the polygon center, we observed significant correlations of the WT <u>significantly correlated</u> with

R_{eco} and R_A fluxes, but no correlation between R_H fluxes and WT<u>was found. In contrast to this, none of the determined respiration fluxes (R_{eco}, R_H, R_A) correlated with VWC at the polygon rim, which might be due to a rather low range of VWC (28 – 34 %). The R_A fluxes might<u>may</u> be negatively affected by high WT due to submersion of the moss layer and partwise vascular leavesfs as submersion can lead to plant stress, reducing productivity and nutrient turnover (Gebauer et al., 1995). Low soil moisture contents can limit the growth and productivity of an ecosystem (Chen et al., 2015) as desiccation lowers the photosynthetic activity (Turetsky et al., 2012), and in turn lowers R_A fluxes. (Moyano et al., 2013) However, if this R_A fluxes would be reduced due to
</u>

- 695 <u>low photosynthetic activity-were the case</u>, we would expect a correlation between GPP and <u>R_A fluxes-WT</u>, as observed at the polygon rim ($R^2 = 0.48$, p < 0.05) which was but not observed at the center ($R^2 = 0.01$, p > 0.05).-Instead, only half as much CO₂ is released by R_A at the center compared to the rim at similar GPP fluxes, as the <u>GPP : R_A ratio indicates (10.5 vs. 5.1 for the polygon center and rim, respectively)</u>. However, it is likely that R_A is reduced due to the water-saturated soils as shown previously for R_{eco} fluxes in the Arctic (e.g. Christensen et al.,
- 700 1998) maybe due to slow diffusion under water-saturated conditions (Frank et al., 1996). Furthermore, it might be possible that R_H fluxes are not affected by water table fluctuations as the decomposition of SOM could take place in deeper layers. it is likely that the respired CO₂ is Wetzel et al. (1984) 'recycled' due to of slow diffusion through the moss layer (Frank et al., 1996). <u>CO₂ through the water phaseEvidence for this process was already shown in polygonal ponds (Liebner et al., 2011)</u>. This finding is in contrast to a set of studies who which
- 705 <u>attributedexplained</u> correlations between R_{eco} fluxes and WT fluctuations <u>solely with to</u> the impact of oxygen availability on R_H fluxes (Juszczak et al., 2013; Chimner and Cooper, 2003; Dorrepaal et al., 2009), or observed an impact of moisture conditions on R_H fluxes across multiple peatland ecosystems (Estop-Aragonés et al., 2018), while another study has shown no effect between water table fluctuations and R_{eco} fluxes (Chivers et al., 2009). <u>However, the partitioning approach used in this study showed that R_H fluxes are not responding to water table</u>
- 710 <u>fluctuations. Instead the CO₂ release by R_A is correlated with water table fluctuations.</u> However, <u>T</u> these findings show the importance of the soil water content <u>hydrologic conditions</u> for R_{eco} fluxes and the need for partitioning

approaches to understand the response of the <u>underlying processes</u> individual of R_{eco} fluxes on to changing hydrologic conditions.

In order tTo determine the individual impacts of hydrological conditions and temperature on the R_H and R_A fluxes, it would be useful to perform both warming and wetting experiments *in situ*. So far, <u>although</u> a number of studies have determined the temperature response of NEE, GPP, and R_{eco} fluxes in arctic ecosystems with warming experiments (e.g. Natali et al., 2011; Frey et al., 2008; Voigt et al., 2017), however, much less research has focused on the response of R_A and R_H fluxes to increasinged temperatures (Hicks Pries et al., 2015). Wetting experiments in arctic tundra ecosystems to determine the individual response of R_A and R_H fluxes to changing hydrological conditions are <u>also</u> lacking so far. As climate change will likely lead to strong changes in the hydrological regimes of Siberian tundra regions (Zimov et al., 2006c; Merbold et al., 2009), the responses of respiration fluxes to altered hydrological as climate warming will likely lead to severe changes of the hydrological regimes in Siberian tundra regions (Merbold et al., 2009; Zimov et al., 2006b).

6 Conclusion

The contributions of GPP, R_{eco}, R_H and R_A to CO₂ NEE fluxes in a drained (rim) and water-saturated (center) micrositesite in the arctic polygonal tundra of northeast Siberia have been quantified in this study. Both investigated micrositesites acted as CO₂ sinks during the measurement period mid-July to end of September 2015.
The polygon center acted aswas a considerably stronger CO₂ sink than the polygon rim. The main drivers behind these differences in CO₂ fluxes at the microsites-pedon scale were the higher GPP at the polygon center as well as lower R_H and R_A-fluxes at the polygon center. The substantial differences in NEE differences identified in NEE between the dry and wet tundra sites two investigated microsites highlight the importance of microscale pedon scale measurements for reliable estimates of CO₂ surface-atmosphere fluxes from arctic tundra sites and the important role of soil moisture conditions on CO₂ fluxes. Hereby, it was shown that R_A and R_H-fluxes respond differently depending on hydrological conditionswater table changes, with a low_release of CO₂ by R_A fluxes during times of a high water tables. Therefore, it is recommended that future studies determining partitionedon CO₂ fluxes from arctic tundra ecosystems should focus on the role of hydrological conditions as a driver of these fluxes, to obtain a more in depth insight into this relationship.

740

750

Data availability. All data sets shown are available at https://doi.pangaea.de/10.1594/PANGAEA.898876 (last access: 5 March 2019; Eckhardt et al., *in review*).

<u>Author contributions.</u> TE, CK, LK and EMP and CK designed the study. GS and TE performed the chamber
 measurements and laboratory analysis. <u>DH and TE performed the visualization of flux comparisons.</u> TE wrote the manuscript with contributions from all authors.

Acknowledgements. We would like to thank the members of the joint Russian-German field campaigns LENA 2014 and LENA 2015, especially Mikhail N. Gregoriev (Permafrost Institute, Yakutsk, Russia), Waldemar Schneider and Günter Stoof (Alfred Wegener Institute for Polar and Marine Research, Potsdam, Germany) and

the crew of the Russian research station Samoylov for logistical as well as technical support. We are grateful to Josefine Walz and Mercedes Molina Gámez for valuable help with chamber measurements, and Norman Roessger for intensive support on model development (all Institute of Soil Science, Universität Hamburg). This work was supported by the German Ministry of Education and Research (CarboPerm-Project, BMBF Grant No. 03G0836A

and the KoPf-Project, BMBF Grant No. 03F0764A). <u>All-German</u> co-authors got additional support from the Cluster of Excellence CliSAP (EXC177) at University of Hamburg funded by the German Research Foundation (DFG). <u>We are also grateful for the reviews of Albertus J. Dolman and two anonymous reviewer and the comments of the editor Lutz Merbold on a previous version of this paper.</u>

References

795

760 Aalto, J., le Roux, P. C. and Luoto, M.: Vegetation mediates soil temperature and moisture in arctic-alpine environments, Arctic, Antarctic, and Alpine Research, 45, 429-439, 10.1657/1938-4246-45.4.429, 2013. AMAP: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017, Arctic Monitoring and Assessment

Programme (AMAP), Oslo, Norway. xiv, 269, 2017.

Beermann, F., Teltewskoi, A., Fiencke, C., Pfeiffer, E. M. and Kutzbach, L.: Stoichiometric analysis of nutrient availability (N, P, K) within soils of polygonal tundra, Biogeochemistry, 122, 211-227, 10.1007/s10533-014-0037-4, 2015.

Beermann, F., Langer, M., Wetterich, S., Strauss, J., Boike, J., Fiencke, C., Schirrmeister, L., Pfeiffer, E.-M. and Kutzbach, L.: Permafrost Thaw and Liberation of Inorganic Nitrogen in Eastern Siberia, 28, 605-618, 10.1002/ppp.1958, 2017.

- Belshe, E. F., Schuur, E. A. and Bolker, B. M.: Tundra ecosystems observed to be CO2 sources due to differential amplification of the carbon cycle, Ecology Letters, 16, 1307-1315, 10.1111/ele.12164, 2013.
 Biasi, C., Jokinen, S., Marushchak, M. E., Hämäläinen, K., Trubnikova, T., Oinonen, M. and Martikainen, P. J.: Microbial Respiration in Arctic Upland and Peat Soils as a Source of Atmospheric Carbon Dioxide, Ecosystems, 17, 112-126, 10.1007/s10021-013-9710-z, 2014.
- 775 Boike, J., Kattenstroth, B., Abramova, K., Bornemann, N., Chetverova, A., Fedorova, I., Fröb, K., Grigoriev, M., Grüber, M., Kutzbach, L., Langer, M., Minke, M., Muster, S., Piel, K., Pfeiffer, E. M., Stoof, G., Westermann, S., Wischnewski, K., Wille, C. and Hubberten, H. W.: Baseline characteristics of climate, permafrost and land cover from a new permafrost observatory in the Lena River Delta, Siberia (1998-2011), Biogeosciences, 10, 2105-2128, 10.5194/bg-10-2105-2013, 2013.
- Brown, J., Miller, P. C., Tieszen, L. L. and Bunnell, F.: An arctic ecosystem: the coastal tundra at Barrow, Alaska, Dowden, Hutchinson & Ross, Inc., Stroudsberg, PA, USA, 1980.
 Bubier, J., Crill, P., Mosedale, A., Frolking, S. and Linder, E.: Peatland responses to varying interannual moisture conditions as measured by automatic CO2 chambers, Global Biogeochemical Cycles, 17, doi:10.1029/2002GB001946, 2003.
- Burnham, K. P. and Anderson, D. R.: Multimodel inference understanding AIC and BIC in model selection, Sociological Methods & Research, 33, 261-304, 10.1177/0049124104268644, 2004.
 Chapin, F. S., Woodwell, G. M., Randerson, J. T., Rastetter, E. B., Lovett, G. M., Baldocchi, D. D., Clark, D. A., Harmon, M. E., Schimel, D. S., Valentini, R., Wirth, C., Aber, J. D., Cole, J. J., Goulden, M. L., Harden, J. W., Heimann, M., Howarth, R. W., Matson, P. A., McGuire, A. D., Melillo, J. M., Mooney, H. A., Neff, J. C.,
- 790 Houghton, R. A., Pace, M. L., Ryan, M. G., Running, S. W., Sala, O. E., Schlesinger, W. H. and Schulze, E.-D.: Reconciling Carbon-cycle Concepts, Terminology, and Methods, Ecosystems, 9, 1041-1050, 10.1007/s10021-005-0105-7, 2006.

Chapin, F. S., McFarland, J., McGuire, A. D., Euskirchen, E. S., Ruess, R. W. and Kielland, K.: The changing global carbon cycle: linking plant–soil carbon dynamics to global consequences, Journal of Ecology, 97, 840-850, 2009.

- Chemidlin Prévost-Bouré, N., Ngao, J., Berveiller, D., Bonal, D., Damesin, C., Dufrêne, E., Lata, J.-C., Le Dantec, V., Longdoz, B., Ponton, S., Soudani, K. and Epron, D.: Root exclusion through trenching does not affect the isotopic composition of soil CO2 efflux, Plant and Soil, 319, 1-13, 10.1007/s11104-008-9844-5, 2009.
- Chen, J., Shi, W. Y. and Cao, J. J.: Effects of Grazing on Ecosystem CO2 Exchange in a Meadow Grassland on
 the Tibetan Plateau During the Growing Season, Environmental Management, 55, 347-359, 10.1007/s00267-014-0390-z, 2015.

Chen, J., Luo, Y., Xia, J., Shi, Z., Jiang, L., Niu, S., Zhou, X. and Cao, J.: Differential responses of ecosystem respiration components to experimental warming in a meadow grassland on the Tibetan Plateau, Agricultural and Forest Meteorology, 220, 21-29, <u>10.1016/j.agrformet.2016.01.010</u>, 2016.

- 805 Chimner, R. A. and Cooper, D. J.: Influence of water table levels on CO2 emissions in a Colorado subalpine fen: an in situ microcosm study, Soil Biology and Biochemistry, 35, 345-351, <u>10.1016/S0038-0717(02)00284-5</u>, 2003. Chivers, M. R., Turetsky, M. R., Waddington, J. M., Harden, J. W. and McGuire, A. D.: Effects of Experimental Water Table and Temperature Manipulations on Ecosystem CO2 Fluxes in an Alaskan Rich Fen, Ecosystems, 12, 1329-1342, 10.1007/s10021-009-9292-y, 2009.
- 810 Christensen, J. H., Kanikicharla, K. K., Marshall, G. and Turner, J.: Climate phenomena and their relevance for future regional climate change. In: *Climate Change 2013: The physical science basis. Contribution of Working Group I to the fifth Assessment of the Intergovernmental Panel on Climate Change*, Cambridge, Cambridge University Press, 1217-1308, 2013.
- Christensen, T. R., Jonasson, S., Michelsen, A., Callaghan, T. V. and Havström, M.: Environmental controls on soil respiration in the Eurasian and Greenlandic Arctic, Journal of Geophysical Research, 103, 29015-29021, 10.1029/98JD00084, 1998.
 Christiansen, J. R., Korhonen, J. F. J., Juszczak, R., Giebels, M. and Pihlatie, M.: Assessing the effects of chamber

placement, manual sampling and headspace mixing on CH4 fluxes in a laboratory experiment, Plant and Soil, 343, 171-185, 10.1007/s11104-010-0701-y, 2011.

820 Corradi, C., Kolle, O., Walter, K., Zimov, S. A. and Schulze, E. D.: Carbon dioxide and methane exchange of a north-east Siberian tussock tundra, Global Change Biology, 11, 1910-1925, 10.1111/j.1365-2486.2005.01023.x, 2005.

Diaz-Pines, E., Schindlbacher, A., Pfeffer, M., Jandl, R., Zechmeister-Boltenstern, S. and Rubio, A.: Root trenching: a useful tool to estimate autotrophic soil respiration? A case study in an Austrian mountain forest, European Journal of Forest Research, 129, 101-109, 10.1007/s10342-008-0250-6, 2010.

- European Journal of Forest Research, 129, 101-109, 10.1007/s10342-008-0250-6, 2010.
 Dorrepaal, E., Toet, S., van Logtestijn, R. S. P., Swart, E., van de Weg, M. J., Callaghan, T. V. and Aerts, R.: Carbon respiration from subsurface peat accelerated by climate warming in the subarctic, Nature, 460, 616-U679, 10.1038/nature08216, 2009.
- Durbin, J. and Watson, G. S.: Testing for serial correlation in least squares regression: 1, Biometrika, 37, 409-428, 10.1093/biomet/37.3-4.409, 1950.
- Elberling, B., Michelsen, A., Schädel, C., Schuur, E. A., Christiansen, H. H., Berg, L., Tamstorf, M. P. and Sigsgaard, C. J. N. C. C.: Long-term CO2 production following permafrost thaw, 3, 890, 10.1038/NCLIMATE1955, 2013.
- Elmendorf, S. C., Henry, G. H. R., Hollister, R. D., Björk, R. G., Boulanger-Lapointe, N., Cooper, E. J.,
 Cornelissen, J. H. C., Day, T. A., Dorrepaal, E., Elumeeva, T. G., Gill, M., Gould, W. A., Harte, J., Hik, D. S.,
 Hofgaard, A., Johnson, D. R., Johnstone, J. F., Jónsdóttir, I. S., Jorgenson, J. C., Klanderud, K., Klein, J. A., Koh,
 S., Kudo, G., Lara, M., Lévesque, E., Magnússon, B., May, J. L., Mercado-Di'az, J. A., Michelsen, A., Molau, U.,
 Myers-Smith, I. H., Oberbauer, S. F., Onipchenko, V. G., Rixen, C., Martin Schmidt, N., Shaver, G. R., Spasojevic,
 M. J., Þórhallsdóttir, Þ. E., Tolvanen, A., Troxler, T., Tweedie, C. E., Villareal, S., Wahren, C.-H., Walker, X.,
- Webber, P. J., Welker, J. M. and Wipf, S.: Plot-scale evidence of tundra vegetation change and links to recent summer warming, Nature Climate Change, 2, 453, 10.1038/nclimate1465, 2012.
 Elsgaard, L., Görres, C.-M., Hoffmann, C. C., Blicher-Mathiesen, G., Schelde, K. and Petersen, S. O.: Net ecosystem exchange of CO2 and carbon balance for eight temperate organic soils under agricultural management.
- Agriculture, Ecosystems & Environment, 162, 52-67, <u>10.1016/j.agee.2012.09.001</u>, 2012.
 Estop-Aragonés, C., Cooper, M. D., Fisher, J. P., Thierry, A., Garnett, M. H., Charman, D. J., Murton, J. B., Phoenix, G. K., Treharne, R. and Sanderson, N. K.: Limited release of previously-frozen C and increased new peat
- Phoenix, G. K., Trenarne, R. and Sanderson, N. K.: Limited release of previously-frozen C and increased new peat formation after thaw in permafrost peatlands, Soil Biology and Biochemistry, 118, 115-129, 2018.
 Euskirchen, E. S., Bret-Harte, M. S., Shaver, G. R., Edgar, C. W. and Romanovsky, V. E.: Long-Term Release of Carbon Dioxide from Arctic Tundra Ecosystems in Alaska, Ecosystems, 20, 960-974, 10.1007/s10021-016-0085-
- 9, 2017. Frank, M. J., Kuipers, J. A., van Swaaij, W. P. J. J. o. C. and Data, E.: Diffusion coefficients and viscosities of CO2+ H2O, CO2+ CH3OH, NH3+ H2O, and NH3+ CH3OH liquid mixtures, Journal of Chemical & Engineering Data, 41, 297-302, 10.1021/je950157k, 1996.
- Frey, S. D., Drijber, R., Smith, H. and Melillo, J.: Microbial biomass, functional capacity, and community structure
 after 12 years of soil warming, Soil Biology and Biochemistry, 40, 2904-2907, <u>10.1016/j.soilbio.2008.07.020</u>, 2008.

Gebauer, R. L. E., Reynolds, J. F. and Tenhunen, J. D.: Growth and allocation of the arctic sedges Eriohorum angustifolium and E. vaginatum: effects of variable soil oxygen and nutrient availability, Oecologia, 104, 330-339, 10.1007/bf00328369, 1995.

860 Görres, C. M., Kutzbach, L. and Elsgaard, L.: Comparative modeling of annual CO2 flux of temperate peat soils under permanent grassland management, Agriculture, Ecosystems & Environment, 186, 64-76, <u>10.1016/j.agee.2014.01.014</u>, 2014.

Grogan, P. and Chapin, F. S.: Initial effects of experimental warming on above- and belowground components of net ecosystem CO2 exchange in arctic tundra, Oecologia, 125, 512-520, 10.1007/s004420000490, 2000.

- 865 Grosse, G., Harden, J., Turetsky, M., McGuire, A. D., Camill, P., Tarnocai, C., Frolking, S., Schuur, E. A. G., Jorgenson, T., Marchenko, S., Romanovsky, V., Wickland, K. P., French, N., Waldrop, M., Bourgeau-Chavez, L. and Striegl, R. G.: Vulnerability of high-latitude soil organic carbon in North America to disturbance, Journal of Geophysical Research-Biogeosciences, 116, G00K06, 10.1029/2010jg001507, 2011.
- Hanson, P. J., Edwards, N. T., Garten, C. T. and Andrews, J. A.: Separating root and soil microbial contributions
 to soil respiration: A review of methods and observations, Biogeochemistry, 48, 115-146, 10.1023/a:1006244819642, 2000.
 Harley, P. C., Tenhunen, J. D., Murray, K. J. and Beyers, J.: Irradiance and temperature effects on photosynthesis of tussock tundra Sphagnum mosses from the foothills of the Philip Smith Mountains, Alaska, Oecologia, 79, 251-259, 10.1007/bf00388485, 1989.
- Heikkinen, J. E. P., Virtanen, T., Huttunen, J. T., Elsakov, V. and Martikainen, P. J.: Carbon balance in East European tundra, Global Biogeochemical Cycles, 18, 10.1029/2003GB002054, 2004.
 Helbig, M., Chasmer, L. E., Desai, A. R., Kljun, N., Quinton, W. L. and Sonnentag, O.: Direct and indirect climate change effects on carbon dioxide fluxes in a thawing boreal forest-wetland landscape, Global Change Biology, 23, 3231-3248, 10.1111/gcb.13638, 2017.
- 880 Hicks Pries, C. E., Schuur, E. A. and Crummer, K. G.: Thawing permafrost increases old soil and autotrophic respiration in tundra: partitioning ecosystem respiration using delta 13C and 14C, Global Change Biology, 19, 649-661, 10.1111/gcb.12058, 2013.

Hicks Pries, C. E., van Logtestijn, R. S., Schuur, E. A., Natali, S. M., Cornelissen, J. H., Aerts, R. and Dorrepaal,
E.: Decadal warming causes a consistent and persistent shift from heterotrophic to autotrophic respiration in
contrasting permafrost ecosystems, Global Change Biology, 21, 4508-4519, 10.1111/gcb.13032, 2015.

Hobbie, S. E., Nadelhoffer, K. J. and Högberg, P.: A synthesis: The role of nutrients as constraints on carbon balances in boreal and arctic regions, Plant and Soil, 242, 163-170, 10.1023/a:1019670731128, 2002. Holl, D., Wille, C., Sachs, T., Schreiber, P., Runkle, B. R. K., Beckebanze, L., Langer, M., Boike, J., Pfeiffer, E.

M., Fedorova, I., Bolshianov, D. Y., Grigoriev, M. N. and Kutzbach, L.: A long-term (2002 to 2017) record of

- closed-path and open-path eddy covariance CO2 net ecosystem exchange fluxes from the Siberian Arctic, Earth Syst. Sci. Data Discuss., 2018, 1-26, 10.5194/essd-2018-98, 2018a.
 Holl, D., Wille, C., Sachs, T., Schreiber, P., Runkle, B. R. K., Beckebanze, L., Langer, M., Boike, J., Pfeiffer, E. M., Fedorova, I., Bolshianov, D. Y., Grigoriev, M. N. and Kutzbach, L.: A long-term (2002 to 2017) record of closed-path and open-path eddy covariance CO2 net ecosystem exchange fluxes from the Siberian Arctic, Earth
- Syst. Sci. Data, 11, 221-240, 10.5194/essd-11-221-2019, 2019.
 Hudson, J. M. G., Henry, G. H. R. and Cornwell, W. K.: Taller and larger: shifts in Arctic tundra leaf traits after 16 years of experimental warming, Global Change Biology, 17, 1013-1021, doi:10.1111/j.1365-2486.2010.02294.x, 2011.
- Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E. A. G., Ping, C. L., Schirrmeister, L., Grosse, G.,
 Michaelson, G. J., Koven, C. D., O'Donnell, J. A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J. and
 Kuhry, P.: Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified
 data gaps, Biogeosciences, 11, 6573-6593, 10.5194/bg-11-6573-2014, 2014.
 Johnson, L. C., Shaver, G. R., Cades, D. H., Rastetter, E., Nadelhoffer, K., Giblin, A., Laundre, J. and Stanley, A.:
- Plant carbon-nutrient interactions control CO2 exchange in Alaskan wet sedge tundra ecosystems, Ecology, 81, 453-469, doi:10.1890/0012-9658(2000)081[0453:PCNICC]2.0.CO;2, 2000.
- Juszczak, R., Humphreys, E., Acosta, M., Michalak-Galczewska, M., Kayzer, D. and Olejnik, J.: Ecosystem respiration in a heterogeneous temperate peatland and its sensitivity to peat temperature and water table depth, Plant and Soil, 366, 505-520, 10.1007/s11104-012-1441-y, 2013.
- Kittler, F., Burjack, I., Corradi, C. A. R., Heimann, M., Kolle, O., Merbold, L., Zimov, N., Zimov, S. and Göckede,
 M.: Impacts of a decadal drainage disturbance on surface–atmosphere fluxes of carbon dioxide in a permafrost ecosystem, Biogeosciences, 13, 5315-5332, 10.5194/bg-13-5315-2016, 2016.
 Knoblauch, C., Beer, C., Sosnin, A., Wagner, D. and Pfeiffer, E. M.: Predicting long-term carbon mineralization and trace gas production from thawing permafrost of Northeast Siberia, Global Change Biology, 19, 1160-1172, 10.1111/gcb.12116, 2013.
- 915 Knoblauch, C., Beer, C., Liebner, S., Grigoriev, M. N. and Pfeiffer, E.-M.: Methane production as key to the greenhouse gas budget of thawing permafrost, Nature Climate Change, 8, 309-312, 10.1038/s41558-018-0095-z, 2018.

Koskinen, M., Minkkinen, K., Ojanen, P., Kamarainen, M., Laurila, T. and Lohila, A.: Measurements of CO2 exchange with an automated chamber system throughout the year: challenges in measuring night-time respiration on porous peat soil, Biogeosciences, 11, 347-363, 10.5194/bg-11-347-2014, 2014.

Kutzbach, L., Schneider, J., Sachs, T., Giebels, M., Nykänen, H., Shurpali, N. J., Martikainen, P. J., Alm, J. and Wilmking, M.: CO2 flux determination by closed-chamber methods can be seriously biased by inappropriate application of linear regression, Biogeosciences, 4, 1005-1025, 10.5194/bg-4-1005-2007, 2007a.

Kutzbach, L., Wille, C. and Pfeiffer, E. M.: The exchange of carbon dioxide between wet arctic tundra and the
 atmosphere at the Lena River Delta, Northern Siberia, Biogeosciences, 4, 869-890, 10.5194/bg-4-869-2007, 2007b.

Kuzyakov, Y.: Sources of CO2 efflux from soil and review of partitioning methods, Soil Biology and Biochemistry, 38, 425-448, <u>10.1016/j.soilbio.2005.08.020</u>, 2006.

Kwon, M. J., Heimann, M., Kolle, O., Luus, K. A., Schuur, E. A. G., Zimov, N., Zimov, S. A. and Göckede, M.:
Long-term drainage reduces CO2 uptake and increases CO2 emission on a Siberian floodplain due to shifts in vegetation community and soil thermal characteristics, Biogeosciences, 13, 4219-4235, 10.5194/bg-13-4219-2016, 2016.

Lara, M. J., Villarreal, S., Johnson, D. R., Hollister, R. D., Webber, P. J. and Tweedie, C. E.: Estimated change in tundra ecosystem function near Barrow, Alaska between 1972 and 2010, Environmental Research Letters, 7, 10.1088/1748-9326/7/1/015507, 2012.

Lara, M. J. and Tweedie, C. E.: CO2 and CH4 Fluxes across Polygon Geomorphic Types, Barrow, Alaska, 2006-2010. Next Generation Ecosystem Experiments Arctic Data Collection, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, USA. Dataset accessed on 04 Dec 2018 at https://doi.org/10.5440/1156852, 2014.

935

- 940 Liebner, S., Zeyer, J., Wagner, D., Schubert, C., Pfeiffer, E.-M. and Knoblauch, C.: Methane oxidation associated with submerged brown mosses reduces methane emissions from Siberian polygonal tundra, Journal of Ecology, 99, 914-922, doi:10.1111/j.1365-2745.2011.01823.x, 2011.
- Lynch, A. H., Chapin, F. S., Hinzman, L. D., Wu, W., Lilly, E., Vourlitis, G. and Kim, E.: Surface Energy Balance on the Arctic Tundra: Measurements and Models, Journal of Climate, 12, 2585-2606, 10.1175/1520-0442(1999)012<2585:sebota>2.0.co;2, 1999.
- Mahecha, M. D., Reichstein, M., Carvalhais, N., Lasslop, G., Lange, H., Seneviratne, S. I., Vargas, R., Ammann, C., Arain, M. A., Cescatti, A., Janssens, I. A., Migliavacca, M., Montagnani, L. and Richardson, A. D.: Global Convergence in the Temperature Sensitivity of Respiration at Ecosystem Level, Science, 329, 838-840, 10.1126/science.1189587, 2010.
- 950 Marushchak, M. E., Kiepe, I., Biasi, C., Elsakov, V., Friborg, T., Johansson, T., Soegaard, H., Virtanen, T. and Martikainen, P. J.: Carbon dioxide balance of subarctic tundra from plot to regional scales, Biogeosciences, 10, 437-452, 10.5194/bg-10-437-2013, 2013.
- Mauritz, M., Bracho, R., Celis, G., Hutchings, J., Natali, S. M., Pegoraro, E., Salmon, V. G., Schadel, C., Webb, E. E. and Schuur, E. A. G.: Nonlinear CO2 flux response to 7 years of experimentally induced permafrost thaw, Global Change Biology, 23, 3646-3666, 10.1111/gcb.13661, 2017.
- McGuire, A. D., Anderson, L. G., Christensen, T. R., Dallimore, S., Guo, L. D., Hayes, D. J., Heimann, M., Lorenson, T. D., Macdonald, R. W. and Roulet, N.: Sensitivity of the carbon cycle in the Arctic to climate change, Ecological Monographs, 79, 523-555, 10.1890/08-2025.1, 2009.
- McGuire, A. D., Christensen, T. R., Hayes, D., Heroult, A., Euskirchen, E., Kimball, J. S., Koven, C., Lafleur, P.,
 Miller, P. A., Oechel, W., Peylin, P., Williams, M. and Yi, Y.: An assessment of the carbon balance of Arctic tundra: comparisons among observations, process models, and atmospheric inversions, Biogeosciences, 9, 3185-3204, 10.5194/bg-9-3185-2012, 2012.
 Marbeld, L., Kutsch, W. L., Corradi, C., Kalle, O., Bahmann, C., Stay, P. C., Zimoy, S. A. and Schulze, F. D.;

Merbold, L., Kutsch, W. L., Corradi, C., Kolle, O., Rebmann, C., Stoy, P. C., Zimov, S. A. and Schulze, E. D.: Artificial drainage and associated carbon fluxes (CO2/CH4) in a tundra ecosystem, Global Change Biology, 15, 2599-2614, 10.1111/j.1365-2486.2009.01962.x, 2009.

- Moyano, F. E., Manzoni, S., Chenu, C. J. S. B. and Biochemistry: Responses of soil heterotrophic respiration to moisture availability: An exploration of processes and models, Soil Biology and Biochemistry, 59, 72-85, 2013.
 Murray, K., Tenhunen, J. and Nowak, R.: Photoinhibition as a control on photosynthesis and production of Sphagnum mosses, Oecologia, 96, 200-207, 1993.
- Muster, S., Langer, M., Heim, B., Westermann, S. and Boike, J.: Subpixel heterogeneity of ice-wedge polygonal tundra: a multi-scale analysis of land cover and evapotranspiration in the Lena River Delta, Siberia, Tellus B: Chemical and Physical Meteorology, 64, 17301, 10.3402/tellusb.v64i0.17301, 2012.
 NASA: Landsat Programme: Lena Delta in Landsat 7, available at:
- https://earthobservatory.nasa.gov/images/2704/lena-river-delta (last access 13 Nov 2018), 2002.
 Natali, S. M., Schuur, E. A. G., Trucco, C., Hicks Pries, C. E., Crummer, K. G. and Baron Lopez, A. F.: Effects of experimental warming of air, soil and permafrost on carbon balance in Alaskan tundra, Global Change Biology, 17, 1394-1407, 10.1111/j.1365-2486.2010.02303.x, 2011.
- Natali, S. M., Schuur, E. A. G. and Rubin, R. L.: Increased plant productivity in Alaskan tundra as a result of experimental warming of soil and permafrost, Journal of Ecology, 100, 488-498, 10.1111/j.1365-2745.2011.01925.x, 2012.
- Natali, S. M., Schuur, E. A. G., Mauritz, M., Schade, J. D., Celis, G., Crummer, K. G., Johnston, C., Krapek, J., Pegoraro, E., Salmon, V. G. and Webb, E. E.: Permafrost thaw and soil moisture driving CO2 and CH4 release from upland tundra, Journal of Geophysical Research: Biogeosciences, 120, 525-537, doi:10.1002/2014JG002872, 2015.

985 Nobrega, S. and Grogan, P.: Landscape and Ecosystem-Level Controls on Net Carbon Dioxide Exchange along a Natural Moisture Gradient in Canadian Low Arctic Tundra, Ecosystems, 11, 377-396, 10.1007/s10021-008-9128-1, 2008.

Nowinski, N. S., Taneva, L., Trumbore, S. E. and Welker, J. M.: Decomposition of old organic matter as a result of deeper active layers in a snow depth manipulation experiment, Oecologia, 163, 785-792, 10.1007/s00442-009-1556-x, 2010.

Oberbauer, S. F., Tweedie, C. E., Welker, J. M., Fahnestock, J. T., Henry, G. H. R., Webber, P. J., Hollister, R. D., Walker, M. D., Kuchy, A., Elmore, E. and Starr, G.: Tundra CO2 fluxes in response to experimental warming across latitundinal and moisture gradients, 77, 221-238, doi:10.1890/06-0649, 2007.

990

- Oechel, W. C., Vourlitis, G. L., Hastings, S. J. and Bochkarev, S. A.: Change in Arctic CO2 Flux Over Two
 Decades: Effects of Climate Change at Barrow, Alaska, Ecological Applications, 5, 846-855, doi:10.2307/1941992, 1995.
 Oechel, W. C., Vourlitis, G. L., Hastings, S. J., Ault, R. P. and Bryant, P.: The effects of water table manipulation and elevated temperature on the net CO2 flux of wet sedge tundra ecosystems, Global Change Biology, 4, 77-90,
- doi:10.1046/j.1365-2486.1998.00110.x, 1998.
 1000 Oechel, W. C., Vourlitis, G. L., Hastings, S. J., Zulueta, R. C., Hinzman, L. and Kane, D.: Acclimation of ecosystem CO2 exchange in the Alaskan Arctic in response to decadal climate warming, Nature, 406, 978-981, 10.1038/35023137, 2000.

Oechel, W. C., Laskowski, C. A., Burba, G., Gioli, B. and Kalhori, A. A. M.: Annual patterns and budget of CO2 flux in an Arctic tussock tundra ecosystem, Journal of Geophysical Research: Biogeosciences, 119, 323-339, doi:10.1002/2013JG002431, 2014.

- Olivas, P. C., Oberbauer, S. F., Tweedie, C. E., Oechel, W. C. and Kuchy, A.: Responses of CO2 flux components of Alaskan Coastal Plain tundra to shifts in water table, Journal of Geophysical Research: Biogeosciences, 115, doi:10.1029/2009JG001254, 2010.
- Olivas, P. C., Oberbauer, S. F., Tweedie, C., Oechel, W. C., Lin, D. and Kuchy, A.: Effects of Fine-Scale
 Topography on CO2 Flux Components of Alaskan Coastal Plain Tundra: Response to Contrasting Growing
 Seasons, Arctic, Antarctic, and Alpine Research, 43, 256-266, 10.1657/1938-4246-43.2.256, 2011.
 Parmentier, F., Van Der Molen, M., Van Huissteden, J., Karsanaev, S., Kononov, A., Suzdalov, D., Maximov, T.
 and Dolman, A.: Longer growing seasons do not increase net carbon uptake in the northeastern Siberian tundra,
- Journal of Geophysical Research: Biogeosciences, 116, doi.org/10.1029/2011JG001653, 2011.
 Pihlatie, M. K., Christiansen, J. R., Aaltonen, H., Korhonen, J. F., Nordbo, A., Rasilo, T., Benanti, G., Giebels, M., Helmy, M. and Sheehy, J.: Comparison of static chambers to measure CH4 emissions from soils, Agricultural

and forest meteorology, 171, 124-136, doi.org/10.1016/j.agrformet.2012.11.008, 2013. Pogoda i Klimat: Climate Tiksi [WWW Document]. Accessed 8 May 2016, URL http://www.pogodaiklimat.ru/climate/21824.htm., 2016.

1020 Romanovsky, V. E., Smith, S. L. and Christiansen, H. H.: Permafrost thermal state in the polar Northern Hemisphere during the international polar year 2007–2009: a synthesis, Permafrost and Periglacial Processes, 21, 106-116, 10.1002/ppp.689, 2010.

Rößger, N., Wille, C., Holl, D., Göckede, M. and Kutzbach, L.: Scaling and balancing carbon dioxide fluxes in a heterogeneous tundra ecosystem of the Lena River Delta, Biogeosciences Discuss., 2019, 1-40, 10.5194/bg-2019-10, 2019.

Runkle, B. R. K., Sachs, T., Wille, C., Pfeiffer, E. M. and Kutzbach, L.: Bulk partitioning the growing season net ecosystem exchange of CO2 in Siberian tundra reveals the seasonality of its carbon sequestration strength, Biogeosciences, 10, 1337-1349, 10.5194/bg-10-1337-2013, 2013.

Salmon, V. G., Soucy, P., Mauritz, M., Celis, G., Natali, S. M., Mack, M. C. and Schuur, E. A.: Nitrogen availability increases in a tundra ecosystem during five years of experimental permafrost thaw, Global Change Biology, 22, 1927-1941, 10.1111/gcb.13204, 2016.
Sanders, T., Fiencke, C. and Pfeiffer, E.-M. J. P.: Small-scale variability of dissolved inorganic nitrogen (DIN), Change Science and Science an

C/N ratios and ammonia oxidizing capacities in various permafrost affected soils of Samoylov Island, Lena River Delta, Northeast Siberia, 80, 23-35, 2010.

1035 Schneider, J., Kutzbach, L. and Wilmking, M.: Carbon dioxide exchange fluxes of a boreal peatland over a complete growing season, Komi Republic, NW Russia, Biogeochemistry, 111, 485-513, 10.1007/s10533-011-9684-x, 2012.

Schuur, E. A. G., Vogel, J. G., Crummer, K. G., Lee, H., Sickman, J. O. and Osterkamp, T. E.: The effect of permafrost thaw on old carbon release and net carbon exchange from tundra, Nature, 459, 556-559, 1040 10.1038/nature08031, 2009.

Schuur, E. A. G., Abbott, B. and Network, P. C.: High risk of permafrost thaw, Nature, 480, 32-33, 10.1038/480032a, 2011.

Schwamborn, G., Rachold, V. and Grigoriev, M. N.: Late Quaternary sedimentation history of the Lena Delta, Quaternary International, 89, 119-134, <u>https://doi.org/10.1016/S1040-6182(01)00084-2</u>, 2002.

- Segal, A. D. and Sullivan, P. F.: Identifying the sources and uncertainties of ecosystem respiration in Arctic tussock tundra, Biogeochemistry, 121, 489-503, 10.1007/s10533-014-0017-8, 2014.
 Shaver, G., Johnson, L., Cades, D., Murray, G., Laundre, J., Rastetter, E., Nadelhoffer, K. and Giblin, A. J. E. M.: Biomass and CO2 flux in wet sedge tundras: responses to nutrients, temperature, and light, Ecological Monographs, 68, 75-97, 1998.
- Soegaard, H., Hasholt, B., Friborg, T. and Nordstroem, C.: Surface energy- and water balance in a higharcticenvironment in NE Greenland, Theoretical and Applied Climatology, 70, 35-51, 10.1007/s007040170004, 2001.

Subke, J.-A., Inglima, I. and Cotrufo, M. F.: Trends and methodological impacts in soil CO2 efflux partitioning: A metaanalytical review, Global Change Biology, 12, 921-943, 10.1111/j.1365-2486.2006.01117.x, 2006.

1055 Suseela, V., Conant, R. T., Wallenstein, M. D. and Dukes, J. S.: Effects of soil moisture on the temperature sensitivity of heterotrophic respiration vary seasonally in an old-field climate change experiment, Global Change Biology, 18, 336-348, 10.1111/j.1365-2486.2011.02516.x, 2012.

Taylor, P. C., Cai, M., Hu, A., Meehl, G. A., Washington, W. and Zhang, G. J.: A decomposition of feedback contributions to polar warming amplification, Journal of Climate, 26, 7023-7043, doi.org/10.1175/JCLI-D-12-00696.1, 2013.

- Turetsky, M. R., Bond-Lamberty, B., Euskirchen, E., Talbot, J., Frolking, S., McGuire, A. D. and Tuittila, E. S.: The resilience and functional role of moss in boreal and arctic ecosystems, New Phytologist, 196, 49-67, 10.1111/j.1469-8137.2012.04254.x, 2012.
- Ueyama, M., Iwata, H., Harazono, Y., Euskirchen, E. S., Oechel, W. C. and Zona, D.: Growing season and spatial
 variations of carbon fluxes of Arctic and boreal ecosystems in Alaska (USA), Ecological Applications, 23, 1798-1816, doi.org/10.1890/11-0875.1, 2013.
 van't Hoff, J. H.: Lectures on theoretical and physical chemistry, Part 1: Chemical dynamics, Edward Arnold,
- London, 1898.
 Voigt, C., Lamprecht, R. E., Marushchak, M. E., Lind, S. E., Novakovskiy, A., Aurela, M., Martikainen, P. J. and
 Biasi, C.: Warming of subarctic tundra increases emissions of all three important greenhouse gases carbon dioxide, methane, and nitrous oxide, Global Change Biology, 23, 3121-3138, 10.1111/gcb.13563, 2017.
- Vourlitis, G. L., Oechel, W. C., Hope, A., Stow, D., Boynton, B., Verfaillie, J., Zulueta, R. and Hastings, S. J.: Physiological models for scaling plot measurements of CO2 flux across an Arctic tundra landscape, Ecological Applications, 10, 60-72, doi:10.1890/1051-0761(2000)010[0060:PMFSPM]2.0.CO;2, 2000.
- 1075 Walker, D. A., Raynolds, M. K., Daniëls, F. J. A., Einarsson, E., Elvebakk, A., Gould, W. A., Katenin, A. E., Kholod, S. S., Markon, C. J., Melnikov, E. S., Moskalenko, N. G., Talbot, S. S., Yurtsev, B. A. and Franklin, J.: The Circumpolar Arctic vegetation map, Journal of Vegetation Science, 16, 267-282, 10.1658/1100-9233(2005)016[0267:TCAVM]2.0.CO;2, 2005.
- Walz, J., Knoblauch, C., Böhme, L. and Pfeiffer, E.-M.: Regulation of soil organic matter decomposition in
 permafrost-affected Siberian tundra soils Impact of oxygen availability, freezing and thawing, temperature, and
 labile organic matter, Soil Biology and Biochemistry, 110, 34-43, doi.org/10.1016/j.soilbio.2017.03.001, 2017.
- Wendler, G. and Eaton, F.: Surface radiation budget at Barrow, Alaska, Theoretical and Applied Climatology, 41, 107-115, 10.1007/bf00866433, 1990.
- Wetzel, R. G., Brammer, E. S. and Forsberg, C. J. A. b.: Photosynthesis of submersed macrophytes in acidified
 lakes. I. Carbon fluxes and recycling of CO2 in Juncus bulbosus L, 19, 329-342, doi.org/10.1016/0304-3770(84)90047-0, 1984.

Wilber, A. C., Kratz, D. P. and Gupta, S. K.: Surface Emissivity Maps for Use in Satellite Retrievals of Longwave Radiation, NASA Langley Technical Report Server, 1999.

Wille, C., Kutzbach, L., Sachs, T., Wagner, D. and Pfeiffer, E.-M.: Methane emission from Siberian arctic
 polygonal tundra: eddy covariance measurements and modeling, Global Change Biology, 14, 1395-1408, doi:10.1111/j.1365-2486.2008.01586.x, 2008.

WRB, I. W. G.: World reference base for soil resources 2014 international soil classification system for naming soils and creating legends for soil maps, FAO, Rome, 2014.

Yershov, E. D.: General Geocryology, Cambridge University Press, Cambridge, 1998.

- Zamolodchikov, D., Karelin, D. and Ivaschenko, A.: Sensitivity of Tundra Carbon Balance to Ambient Temperature, Water, Air, and Soil Pollution, 119, 157-169, 10.1023/a:1005194613088, 2000.
 Zimov, S. A., Davydov, S. P., Zimova, G. M., Davydova, A. I., Schuur, E. A. G., Dutta, K. and Chapin, F. S.: Permafrost carbon: Stock and decomposability of a globally significant carbon pool, Geophysical Research Letters, 33, L20502, 10.1029/2006gl027484, 2006a.
- 1100 Zimov, S. A., Schuur, E. A. and Chapin, F. S.: Permafrost and the global carbon budget, Science, 312, 1612-1613, 2006b.

Zimov, S. A., Schuur, E. A. G. and Chapin, F. S.: Permafrost and the global carbon budget, Science, 312, 1612-1613, 10.1126/science.1128908, 2006c. Zona, D., Lipson, D., Zulueta, R., Oberbauer, S. and Oechel, W.: Microtopographic controls on ecosystem
 functioning in the Arctic Coastal Plain, Journal of Geophysical Research: Biogeosciences, 116, doi.org/10.1029/2009JG001241, 2011.
 Zona, D., Lipson, D. A., Paw U, K. T., Oberbauer, S. F., Olivas, P., Gioli, B. and Oechel, W. C.: Increased CO2 loss from vegetated drained lake tundra ecosystems due to flooding, Global Biogeochemical Cycles, 26, doi:10.1029/2011GB004037, 2012.

1110 Zona, D., Lipson, D. A., Richards, J. H., Phoenix, G. K., Liljedahl, A. K., Ueyama, M., Sturtevant, C. S. and Oechel, W. C.: Delayed responses of an Arctic ecosystem to an extreme summer: impacts on net ecosystem exchange and vegetation functioning, Biogeosciences, 11, 5877-5888, 10.5194/bg-11-5877-2014, 2014. Zubrzycki, S., Kutzbach, L., Grosse, G., Desyatkin, A. and Pfeiffer, E. M.: Organic carbon and total nitrogen stocks in soils of the Lena River Delta, Biogeosciences, 10, 3507-3524, 10.5194/bg-10-3507-2013, 2013.

		polygon center	polygon rim	
		$in \mu g CO_2 m^{-2} s^{-1}$	in $\mu g CO_2 m^{-2} s^{-1}$	
NEE	mean	-68 ± 12	-26 ± 19	
	range	-288 ± 53 to 54 ± 2	-117 ± 60 to 49 ± 10	
GPP	mean	-98 ± 10	-61 ± 17	
	range	up to -342 ± 53	up to -163 ± 57	
R _{eco}	mean	29 ± 11	35 ± 9	
	range	12 ± 3 to 69 ± 7	21 ± 3 to 77 ± 14	
R _H	mean	11 ± 3	21 ± 5	
	range	6 ± 1 to 27 ± 2	14 ± 4 to 46 ± 13	
R _A	mean	19 ± 11	14 ± 5	
	range	1 ± 3 to 55 ± 4	5 ± 5 to 32 ± 19	
NPP	mean	-85 ± 12	-49 ± 20	
	range	up to -300 ± 53	up to -142 ± 57	

Table 1 – Means and range of the modelled fluxes in $\mu g \ CO_2 \ m^{\text{-2}} \ s^{\text{-1}}.$

Table 2 - Comparison of daily averaged CO2 fluxes from different aretic tundrapolygonal tundra sites, which are120comparable similar in vegetation and soil composition to our study site. All listed fluxes were measured with the closed chamber technique.

Location	Tundra type	Period	NEE	GPP	R _{eco}	Ref
			(g C m ⁻² d ⁻¹)	(g C m ⁻² d ⁻¹)	(g C m ⁻² d ⁻¹)	
Lena River Delta, RU	pol. rim	Jul-Sep 2015	-0.6 ± 0.4	-1.4 ± 0.4	0.8 ± 0.2	а
(72°N,127°E)	pol. center		-1.6 ± 0.3	-2.3 ± 0.2	0.7 ± 0.1	
Barrow, US (71°N, 157°W)	pol. rim	Jun-Aug 2005	-0.1 ± 0.5	-3.7 ± 0.2	3.6 ± 0.3	<u>b</u> f
	pol. center		-0.2 ± 0.2	-3.1 ± 0.1	2.9 ± 0.1	
	pol. rim	Jun-Aug 2006	$\textbf{-}0.7\pm0.2$	-3.1 ± 0.3	2.4 ± 0.2	
	pol. center		-0.8 ± 0.2	$\textbf{-2.3}\pm0.2$	1.5 ± 0.2	
Barrow, US (71°N, 157°W)	pol. center	Jun-Aug 1992	0.04 ± 0.05	-0.8 ± 0.1	0.8 ± 0.1	<u>Gc</u>
Barrow, US (71°N, 157°W)	pol. center	Jul-Aug 2008	0.1 ± 0.8	-3.9 ± 1.8	3.9 ± 1.8	<u>d</u>
Barrow, US (71°N, 157°W)	pol. center	Jul-Aug 2010	$\underline{0.5\pm0.8}$	-1.7 ± 0.8	<u>2.1 ± 1.2</u>	<u>e</u>
Daring Lake, CA (65°N,	dry heath	Jun-Sep 2004	-0.01 ± 0.1	-1.7 ± 0.3	1.8 ± 0.2	<u>f</u>
<u>111°W)</u>	wet sedge		-0.9 ± 0.1	<u>-1.7 ± 0.1</u>	0.8 ± 0.1	
Cherskii, RU (68°N, 161°E)	carex shrub	Jul-Aug 2013	-0.5 ± 0.1	-2.5 ± 0.1	2.0 ± 0.1	g
		Jul-Aug 2014	-2.2 ± 0.2	-6.2 ± 0.1	4.0 ± 0.2	
Vorkuta, RU (67°N, 63°E)	sedge bog	Jun-Aug 1996	-1.0 ± 0.2	-3.2 ± 0.4	2.2 ± 0.3	<u>h</u>
<u>Vorkuta, RU (67°N, 63°E)</u>	wet tundra	Jun-Sep 2001	<u>-1.1*</u>	<u>-1.9*</u>	<u>0.9*</u>	<u>i</u>
	<u>dry tundra</u>	Jun-Sep 2001	<u>1.2*</u>	<u>-1.9*</u>	<u>3.2*</u>	
Prudhoe Bay, US (70°N,	wet tundra	Jun-Aug 1994	-0.6 ± 0.4	-5.2 ± 0.6	4.6 ± 0.3	i
<u>149°W)</u>						
Lena River Delta, RU	dry tundra	Jun-Sep 2014	-0.9 ± 3.0	-3.6 ± 3.4	2.7 ± 0.9	<u>k</u>
<u>(72°N, 127°E)</u>		Jun-Sep 2015	-0.7 ± 2.6	-2.7 ± 3.2	1.9 ± 1.0	
	wet tundra	Jun-Sep 2014	-0.4 ± 1.9	-2.3 ± 2.3	1.9 ± 0.7	
		Jun-Sep 2015	-0.7 ± 2.4	-2.9 ± 2.7	2.2 ± 0.7	

a: this study; <u>b:</u> Olivas et al. (2011); <u>cg</u>: Oechel et al. (1995); <u>d</u>: Lara and Tweedie (2014); <u>e</u>: Lara et al. (2012); <u>f</u>: Nobrega and Grogan (2008); <u>g</u>: Kwon et al. (2016); <u>h</u>: Zamolodchikov et al. (2000); <u>i</u>: Heikkinen et al. (2004), <u>*</u>: <u>standard deviation estimated</u>; <u>j</u>: Vourlitis et al. (2000); <u>k</u>: (Rößger et al., 2019)

1125



Figure <u>11</u> - The study site on Samoylov Island, Lena River Delta in Northeastern Siberia (72°22'N, 126°28'E). (Satellite images – left: NASA (2002) <u>NASA Landsat Programme: Lena Delta in Landsat 7; available at: , 2002</u>; middle: Boike et al. (2012); right: Boike et al. (2015)



Figure 2 - Meteorological conditions from mid of July to end September. Panel (a) <u>Half-hourly air temperature</u> measured at 2 m height at the eddy covariance tower and surface temperature; (b) soil temperatures measured at 2 cm depth at <u>polygonthe</u> rim and center microsite and daily precipitation measured at the eddy covariance tower; (cb) water table relative to the soil surface measured at the polygon center and volumetric water content measured at the polygon rim; (c) <u>Half hourly air temperature measured at 2 m height at the eddy covariance tower and surface temperature</u>; (d) daily measured thaw depth at the polygon rim and center; (e) <u>Daily precipitation measured at the eddy covariance tower</u>.



1140Figure 3 - Chamber measured NEE, Reco and RH fluxes as well as calculated GPP, NPP and RA fluxes. The error bars
denote the standard deviation of the four replicate measurements at each micrositesite. Panel (a) fluxes of NEE (n = 83),
Reco (n = 85) and RH (n = 85) at the polygon center; (b) calculated fluxes of GPP (n = 83), NPP (n = 83) and RA (n = 85)
at the polygon center; panel (c) measured fluxes of NEE (n = 83), Reco (n = 85) and RH (n = 85) at the polygon rim; (d)
calculated fluxes of GPP (n = 83), NPP (n = 83), NPP (n = 83) and RA (n = 85)



Figure 4 - Relationships between water table fluctuations and (a) R_{eco} fluxes, (b) R_{H} fluxes, (c) R_{A} fluxes and (d) GPP fluxes during the period July-August at the polygon center. Negative values on the x-axis indicate a water table below the soil surface.



I

Figure 5 - Fitting parameters of the fitted CO₂ flux models. The values are given with the standard deviation of the model results from the single measurement plots (light grey error bars) and the confidence intervals (95%) of the fitting parameters (dark grey error bars).



Figure 6 - Modelled and measured CO₂ fluxes at the polygon center <u>in μg m⁻² s⁻¹</u>. Measured fluxes are available for NEE (<u>panel a</u>), R_{eco} (<u>panel b</u>) and R_H.-(<u>panel c</u>). NEE model fluxes were calculated from modelled GPP (<u>panel e</u>) minus modelled R_{eco}, R_A model fluxes (<u>panel d</u>) from modelled R_{eco} minus modelled R_H and NPP model fluxes (<u>panel f</u>) from modelled GPP minus modelled R_A. Note the different scales of the <u>y</u>-axes.



160 Figure 7 - Modelled and measured CO₂ fluxes at the polygon rim in μg m⁻² s⁻¹. Measured fluxes are available for NEE (panel a), R_{eco} (panel b) and R_{H⁵} (panel c). NEE model fluxes were calculated from modelled GPP (panel e) minus modelled R_{eco}, R_A model fluxes (panel d) from modelled R_{eco} minus modelled R_H and NPP model fluxes (panel f) from modelled GPP minus modelled R_A. Note the different scales of the y-axes.



Figure 8 – Integrated CO₂ fluxes at the polygon rim and center. The values were calculated from the model results and are given in g CO₂ m⁻². In total, both <u>micrositesites</u> acted as a net CO₂ sink during the growing season. NEE= net ecosystem exchange; GPP= gross primary productivity; R_{eco} = ecosystem respiration; R_{H} = heterotrophic respiration; R_{A} = autotrophic respiration and NPP= net primary productivity; <u>WT= water table</u>; <u>TD= thaw depth</u>.



Figure 9 – Comparison of chamber and half-hourly averaged EC NEE fluxes. The chamber NEE was calculated based on the contribution of each surface class to the EC footprint (equation 5).