

General response

We have now studied the comments from the reviewers and revised the manuscript accordingly.

- 5 The most significant changes include: removing the references to the unpublished data, adding the information of soil properties, changing the statistical tests of manual chamber measurements from t-test to linear mixed effects model, and adding the chamber measurements made at the control site into the manuscript. When adding the control data into the manuscript we noticed that all the CO₂ chamber fluxes at the clear-cut site were calculated only with the linear regression meaning that the forest floor respiration was underestimated. This has also been corrected in the revised manuscript.

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We hope the changes made into the revised version are satisfactory. See below the point-by-point response to the reviewers and the revised version of the manuscript with marked-up changes.

Response to Reviewer #1

General Comments: The study investigated all three main GHG gases (CO₂, CH₄ and N₂O) and heat fluxes after a clear cut on a moderately drained boreal organic soil. The authors used a combination of eddy-covariance and chamber method for flux determination. Studies determining the effect on GHG after clear cut exists for mineral soil, but not for organic soil. Details are nicely discussed.

My main concern is the experimental design of the study. The paper is based on two years of CO₂ measurement after the clear cut. Reference data (fluxes before the clear cut) are missing, although it is stated in the paper, that one year measurement of CO₂ fluxes before the clear cut exists. These data are not published (p.11 ll.24-25). However the main conclusion (clearcutting turned boreal forest from neutral to C source) is based on these unavailable data. In view of the generally large interannual variability of carbon balances on organic soil, the main conclusion is weakly supported. Interannual variability is not even discussed within the paper, although the first year after clear cutting is drier and warmer than the following. Without a control site including GHG measurements it is difficult to figure out the influence of the clear cut and “normal” annual variability. It exists a control plot of a reference site, but only data of water table and soil temperature is included. There is a second EC tower, measuring above the canopy (p.4 l.27). It is not clear whether GHG flux data exists and could be used as reference. There are data from chamber measurement from the year before the clear cut (starting during mid-summer 2015). Without a reference-control site and only a very short time series before the clear cut (even not a full year) for CH₄ and N₂O, data interpretation is very difficult and weak. The weather conditions in 2015 are not discussed. I would suggest including these data (CO₂ balances before clear cut and GHG of reference/control site after clear cut) in order to get a complete dataset instead of publishing a partial data set with weakly supported main conclusion. In addition I would suggest to include basic information about soil properties and to check the paper for consistent data sets. See comments below.

1. We understand the concern of the referee about the unpublished data. We have measured CO₂ exchange with the EC method at the Lettosuo site for six years before harvesting the site, and these data are fully processed and analyzed. Based on this, we can conclude with confidence that the site is on average CO₂ neutral. The neutrality is caused by the fact that the emission from the soil (peat decomposition) is approximately as large as the CO₂ uptake used for tree growth. The manuscript concerning the pre-harvest data is currently in preparation, but the expected submission/publishing date is not known yet. The original EC tower (not the one used for the submitted paper) has been measuring CO₂ exchange from a partially harvested area of the site since 2016, so we cannot use the 2016-2018 data as a control here. Unfortunately, we have had no EC measurements running within the actual control area either.

Because the manuscript presenting the pre-harvest data is already in preparation and including these data would make the present paper too extensive and potentially confusing,

we decided to remove the references to the unpublished data from the discussion and conclusions. We will only discuss the post-harvest balances and change the wording so that the change in CO₂ fluxes due to the clearcutting will not appear as a main conclusion of the paper. However, we can still draw some conclusions on the change in the CO₂ balance, and even in Reco and GPP, on the basis of previous studies concerning nutrient-rich peatland forests (Meyer et al., 2013; Ojanen et al., 2013; Uri et al., 2017).

2. In addition to the chamber measurements made within the clear-cut, already included in the manuscript, we have made similar measurements within the control area. We originally left the control area data out as the changes in fluxes at the clear-cut were so clear that we thought that the clear-cut data alone would have been sufficient. However, we see now why the control area measurements should be included in the paper, especially as few measurements were made before the harvest. We will include these chamber measurements from the control area into the revised manuscript.

I miss a discussion about the system boundaries regarding source/sink function of forests. Is the assumed sink or neutral function of the forest due to accumulation of wood?

3. We also think that the system boundaries are important when considering the overall carbon balance of the site. In this manuscript, however, we concentrated on reporting greenhouse gas fluxes between the ecosystem and the atmosphere. The measurements included in this manuscript constitute a part of a larger project, and there will also be a paper on soil hydrology and carbon export from the clear-cut area. All the results from the project will be combined into a review paper or a thesis that will provide a more complete view.
4. The pre-harvest CO₂ neutral state of Lettosuo is due to the significant tree growth at the site (unpublished data). Uri et al. (2017) have shown that in those well-drained peatland forests where the trees are relatively young, the trees can accumulate more carbon than is released from soil. We will add discussion on this to the revised manuscript.

Is the source function after the clear cut due to enhanced mineralisation of logging residues (which caused the former c sink/neutral)?

5. Even though the logging residues act as a source of CO₂ emissions and are a significant part of Reco (see our replies #3 and #4 to referee #2), they are not the main reason why the clear-cut acted as a source in this study. The main reason is the removal of photosynthesizing biomass (trees) and the destruction of ground vegetation. As there were no trees growing (see reply #4) and not much photosynthesizing vegetation, the GPP was low during the post-harvest summer.

What's about the peat mineralisation before and after clear cutting? GHG warming potential depending on the system boundary and source/sink function may change including C export from harvest. See also (Biogeosciences, 15, 3603–3624, 2018). Hommeltenberg et al. (2014, Biogeosciences, 11, 3477–3493, 2014) stated that a forested bog was a strong carbon sink based on EC measurement – however estimation of long term carbon loss rate since drainage indicated a carbon source of the site. I would extend the discussion on clear cuts

effects on GHG balances with the focus on soil type (mineral vs organic) p 13 L21 ff. How is the carbon balance in boreal forest on mineral soils? Perhaps it is possible to get an estimation of peat carbon mineralisation after clear cutting?

6. Based on the EC and tree growth measurements (unpublished data), we have estimated that the peat mineralisation rate at Lettosuo was about 1000 g C m⁻² yr⁻¹ before clearcutting. It is hard to estimate this rate reliably over a year after clearcutting due to mineralisation of logging residues, as they are both included in Reco. The chamber measurements, from which the peat mineralisation could be estimated, concentrated mostly around the summer, which makes the estimation of annual rates highly uncertain. As peat mineralisation should decrease with increasing water table level, we would expect decreased peat mineralisation after clearcutting. We will extend the discussion with the focus on soil type.

Information about soil properties are missing. The only information included is the peat type (nutrient-rich peatland). Information about soil organic carbon content, storage, C/N ratio and bulk density before and after the clear cut (or of the control site) would be valuable in order to compare these results with other organic soils sites. The use of heavy machinery (p4 L2-3) could lead to soil compaction, which could lead to a higher water table (depending on the reference point of water table measurement). Please include basic soil properties and an estimation peat thickness (reference and clear cut or before and after clearcutting).

7. Thank you for pointing this out. We will add data on soil organic carbon and nitrogen content with CN ratio and bulk density values in five different soil layers (humus, 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm). We will also add soil organic carbon and nitrogen stocks, and an estimation of peat thickness into the revised manuscript.

Soil T data is not consistent in Figures. Compare Figure 2. Soil T at 5 cm depth is warmer in winter time than in summer time compared to other soil depth temperature and has the lowest annual variation (perhaps data of 30 cm depth?). In Figure S3 clear cut temperature in winter 2017 is 0 °C without any variation. In Figure 2 all T soil depth are below 0 °C in winter 2017. In addition there seems different sensibility of temperature sensors during the year, especially at the end of 2017 there seems temperature drops of 0.5 °C. Please clarify.

8. There is a mistake in the legend of Fig. 2b, as the color scheme in the legend was shifted downwards due to a technical error. The blue color should refer to 5 cm, orange to 10 cm, green to 20 cm and red to the 30 cm temperature. We apologize for the confusion caused by this and will fix the legend.

9. The reason for the difference between Figs 2 and S3 is that they are measured with different sensors and at different places, though within 15 m from each other. The data in Fig. 2 are from the soil temperature profile measurements located at the orange dot in Fig. 1, while the temperature plotted in Fig. S3 is from the sensors located along the orange transect in Fig. 1 at 8 and 22 m from the ditch. We forgot to report the soil temperature sensors used in the transect in the methods and will add this information into the revised manuscript. Also, the resolution (0.5 °C) of the sensors located along the transect (Fig. S3) is lower than that in the profile measurement, which causes the step-like pattern in the plot.

Please use same axis label to be able to compare the same time periods. I would like to have the time mark of clear cut in all Figures (similar to Figure 2).

10. We will fix the axis labels and add the time mark of the clear-cut to all relevant figures (Figs. 8, S3 and S4) in the revised manuscript.

Figure 5 shows all accepted night-time vs T air. Below 10°C there are very few points, below 7°C no points. However, T air seemed to be below 5°C for several months (Figure 2). The soil temperature (5cm) is below 5°C (Figure 9). How does this fit together? Does this mean that the data in Figure S2 during winter 2016/ 2017 are daytime data?

11. We apologize for this, but the temperature in Fig. 5a is actually the 5 cm soil temperature (please see also reply #15) and it only includes the accepted night-time summertime data, in which the soil temperature was rarely below 10 °C. We will correct the figure label and the associated text in the revised manuscript.

Fig. 9 includes all the chamber measurement made during the respective years, so it also includes the data outside the summer period. This is why there are sub-zero temperatures in Fig. 9.

Fig. S2 includes all the accepted (both night- and daytime) half-hourly measurements made during the measurement period.

In the paper is stated that data coverage is 30% after selection (p.5 l.21). Could you please add the night-time and daytime coverage (per month) of EC data?

12. We will add the monthly night-time and daytime coverages to the supplement of the revised manuscript.

Is the uncertainty of NEE due to uneven distribution of day-time and night-time coverage during gap-filling considered? How does Figure 9 fit to Figure 5a?

13. We did not consider the uneven distribution of the data coverage in gap filling. However, this is a valid point, as the data coverage is usually much lower during the night than day and this may affect the uncertainty estimates. However, we did not consider this difference in the present study.

14. The idea of the Figs. 9 and 5a were to compare the respiration response between the years for the chamber and EC measurements, respectively. However, the time periods differ between the figures as Fig. 5a contains only the summertime EC data while Fig. 9 has all the chamber measurements made within a whole year. Therefore, one cannot directly compare the responses between these two measurement methods by using these figures.

Additional comments. I wonder why CO2 fluxes from chamber measurements are related to T soil, while EC CO2 night-time fluxes are related to T air and why T air is used in gap filling procedure. Please Comment.

15. We originally used air temperature for gap filling because air temperature data are better available from the surrounding weather stations. During the data analysis, however, we noticed that the time series of the soil temperature at the clear-cut was almost perfect (Fig.

2), so we decided to use that for gap filling the EC data instead. Unfortunately, we forgot to update this into the text, but this will be corrected in the revised manuscript.

The addition of annual cumulative footprint contributions in Figure 1 would help to evaluate the chosen suitable wind direction. Please add the used wind direction.

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16. We will add into Fig. 1 windroses that show the annual footprint contributions to the accepted flux data.

17. Thank you for pointing out the missing wind directions. They will be added into the methods section in the revised manuscript.

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I would appreciate a table including warming potential of all GHG gasses.

18. We will add the GWPs of the GHGs into the discussion text.

Figure 3: Please include water table of control site.

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19. The time series of the water table level at the control site will be added into Fig. 3 in the revised manuscript.

Response to Reviewer #2

The study tested the impact of a disturbance (clearcutting) on surface greenhouse gas (CO₂, CH₄, and N₂O) fluxes in a forested boreal peatland in southern Finland. Over a 2 year period they used both eddy covariance and chamber based methods to measure GHG fluxes, as well as a number of environmental variables known to drive gas fluxes (water table, soil temperatures). The study shows a increase in CH₄ and N₂O emissions following disturbance, however the authors deem the CH₄ to not be of importance regarding GWP. The paper is well written and contains valuable information regarding the impacts of forest management practices on the carbon balance of boreal peatlands.

My main concern is the conclusion drawn from the data presented here that clearcutting results in the forest turning in to a large CO₂ source. The study includes 2 years of CO₂ flux data collected after the clearcutting and presents the trends of these 2 years well. However, there is no reference data of the CO₂ balance of an undisturbed site and as such the study does not show that there has been an increase in a CO₂ source effect. The study mentions unpublished data that provides this information. This data needs to be either published and referenced or including in this study for the conclusions being drawn here to be substantiated and allowed. The study site is also compared to a control, undisturbed, site where there has been water table and soil temperature collected. There is no CO₂ flux data provided from this site, if data is provided from this site as reference point of the annual NEE budget of an undisturbed site in the area. A more detailed data set from this control site (including flux data as well as environmental variables, seasonal weather data) would allow for it to be used as a reference site and then an impact to the source/sink function of the site be commented upon. A map the shows the location of both sites would also be useful. I would suggest either including the unpublished data for a more complete study or a more detailed description of the control site as described above if the authors wish to maintain their conclusion that there is an increased source effect. As is presented here this conclusion cannot be claimed.

1. Thank you for the comment, and we understand the problem about referencing unpublished data. Referee #1 made the same comment (please see our reply #1 to referee #1). In short, we have no reference data for CO₂ fluxes from the control site (which is too small for eddy covariance) and also cannot use the CO₂ flux data from the original EC tower as a control dataset; therefore, we have decided to only discuss the post-harvest balances and remove all the references to the unpublished data from the revised manuscript.

We have made chamber measurements similar to the clear-cut area within the control area and will add them to the revised manuscript (please see our reply #2 to referee #1).

The map included in the manuscript (Fig. 1) already shows the location of the control area, but we will add borders around it to make it more distinctive.

My secondary concern is regards to the modelling of Reco. There is no influence of water table included in this model (Equation A3) and I would like to know what is the justification of this? The study has a good data set on water table depth throughout the years and a number of times in the paper it is mentioned that this rising water table may be influential on CO₂ fluxes and suppress them. If it is being used as reasoning for low fluxes, then it should be including in the modelling attempts. Also, what was the justification to use air temperatures and not soil temperatures in the part equation A3 that is acting similar to a Q10 value?

2. The referee is right that water table level affects the decomposition of organic matter and thus should affect CO₂ fluxes from the soil. However, it should be noted that Reco, as defined here, combines two processes: forest floor respiration (mainly soil) and the decomposition of logging residues. Water table depth affects the former but not the latter, which is mostly controlled by temperature. According to our chamber measurements (with no above-ground residues), the CO₂ emissions from the forest floor were 32% (2016) and 57% (2017) of Reco (P. 12, L. 11-17), meaning that the logging residues contribute markedly to Reco. One should also take into account that the chamber measurements also include below-ground residues (e.g. roots), so in reality the contribution of the residues to Reco is even larger.

We plotted residuals of the respiration fit (Eq. A3) against WTL for both summers (Fig. 1) and found no significant relationship between respiration and WTL. This is discussed in the original manuscript (P. 13, L. 9-14). Thus we did not include WTL as an explanatory variable in the Reco model. We will add a comment on this and the residual-vs-WTL plot to the revised version.

3. Regarding the temperature issue, please see our response to Referee #1 (reply #15). In short, we actually did use soil temperature in Eq. A3, but forgot to update this into the text and figure captions. We apologize for confusion and will fix this in the revised manuscript.

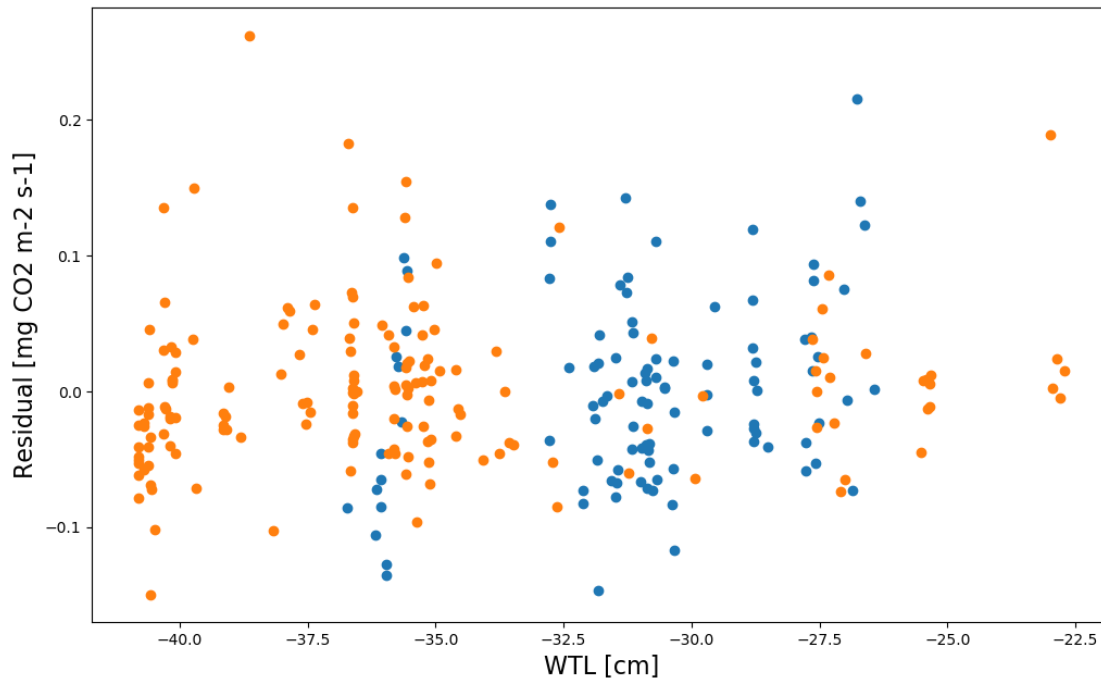


Figure 1. Hourly mean residual of the respiration fit vs. hourly mean water table level in Jun-Aug 2016 (blue) and 2017 (orange).

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Reco is represented well in the paper and seems to be the driving factor in annual NEE budgets that show a loss of CO₂ to the atmosphere. However it's is unclear what proportion of Reco is made up of R_{ff} and CO₂ lost due to enhanced mineralization of the clearcutting leftovers/debris. Some kind of graphical representation of the contribution of these two CO₂ sources to Reco would be necessary to comment on the long-term impact of peat carbon following clearcutting and not just the recently felled organic matter at the surface.

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4. As indicated above (reply #2), the CO₂ emissions from the forest floor were 32-57% of Reco, while the logging residues probably account for the rest. The aim of our study was to investigate the short-term impacts of clearcutting, and discussion of any long-term impacts would be mostly speculative. Likely, the CO₂ emissions from the logging residues will decrease in the next few years as they decompose. Also, the planted trees and the ground vegetation will grow; therefore, the transpiration will increase causing the WTL to decrease. This will again likely increase CO₂ emission from the soil to the same level as before the clearcut at some point. Anyhow, our focus is on the CO₂ emissions right after the clearcut, so we would prefer not to add any further discussion on longer-term effects.

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The idea of graphical presentation is great, and we will add a bar plot to the revised manuscript, which shows the distribution of estimated Reco to R_{residues} and R_{ff} for both summers.

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Pg. 2 L. 13 nitrogen should be nitrous?

5. Yes you're right. This will be corrected in the revised manuscript.

Pg. 6. L. 15 – 16 what was the justification of using a closure time of 10 – 11 mins? For N₂O closure time can be very site dependent, was this tested at this site to ensure the time was enough to capture representative flux measurements?

6. Yes, we tested the chamber system at our site before the clearcutting in 2015 with a longer closure time (20 min) and noticed that by selecting only the first 10 min of the data gave very similar results to using the whole 20 min dataset. Because of this, we decided to limit the closure time to 10-11 min to allow more spatial replicates to be measured during the same day. After clearcutting, the N₂O fluxes increased so much that we could have actually reduced the closure time down to 5 min. However, due to the fact that the absolute CH₄ flux decreased (from sink to small source) after clearcutting, we still had to use a closure time of 10-11 min to measure the CH₄ fluxes with sufficient accuracy. Also, keeping the closure time the same allowed a more consistent comparison between the years.

Reporting of GPP data is not consistent in the text. Pg. 9 L. 13 – 14 GPP rates are reported using positive values. Compare this to Pg. 10 L. 10 where GPP balances are reported using negative values. I would suggest using negative values for both as this paper is addressing NEE not NEP.

7. Thank you for pointing this out. We decided to use the absolute value of GPP (|GPP|) in the text to avoid the confusion that occurs commonly when talking about increasing/decreasing GPP. However, we accidentally left some negative values in one section, as pointed out by the referee. The values in that section will be changed from negative to positive in the revised manuscript.

Greenhouse gas and energy fluxes in a boreal peatland forest after clearcutting

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Abstract.

10 The most common forest management method in Fennoscandia is rotation forestry including clearcutting and forest regeneration. In clearcutting, stem wood is removed and the logging residues are either removed or left on site. Clearcutting changes the microclimate and vegetation structure at the site, both ~~of which impact~~ affecting the site's carbon balance. Peat soils with poor aeration and high carbon (~~C~~) densities are especially prone to such changes, and significant changes in ~~C stocks~~ and greenhouse gas exchange can be expected. We measured carbon dioxide (CO₂) and energy fluxes with the eddy covariance
15 method for two years (April 2016 – March 2018) ~~after clearcutting on a drained peatland drained for forestry. After the clearcutting, w~~We observed a significant rise (23 cm) in the water table level. ~~The site was also and~~ a large CO₂ source (first year: 3086 ± ~~120-148~~ g CO₂ m⁻² yr⁻¹, second year: 2072 ± ~~141-124~~ g CO₂ m⁻² yr⁻¹) ~~after the clearcutting~~. These large CO₂ emissions resulted from the ~~very low collapse of~~ gross primary production (GPP) following the removal of photosynthesizing trees and the decline of ground vegetation, ~~unable to compensate for the decomposition of logging residues and peat~~. During
20 the second summer (June–August) after the clearcutting, GPP had already increased by 96% and total ecosystem respiration decreased by 14% from the previous summer. ~~As a result, net CO₂ emissions decreased during the second summer after clearcutting compared to the first one.~~The Bowen ratios ~~mean daytime ratio of sensible to latent heat flux decreased after harvesting from 2.6 in May 2016 to 1.0 in August 2016 and were different in 2016 and 2017, starting at 2.6 in May 2016 and decreasing to less than 1.0 in August 2016, while~~ in 2017 it varied mostly within 0.6–1.0. ~~In April–September, the mean daytime~~ ~~This was due to a 33% decrease in the~~ sensible heat flux ~~was 33% lower~~ and a ~~40% increase in the~~ latent heat flux ~~40% higher in 2017 from the 2016 values~~, probably due to the recovery of ground vegetation that increased evapotranspiration and albedo of the site. In addition to CO₂ and energy fluxes, we measured methane (CH₄) and nitrous oxide (N₂O) fluxes with manual chambers. After the clearcutting, the site turned from a small CH₄ sink into a small source and from N₂O-neutral to a significant N₂O source. Compared to the large CO₂ emissions, the 100 yr global warming potential (GWP₁₀₀) of the CH₄
25 emissions was negligible. Also, the GWP₁₀₀ due to increased N₂O emissions was less than 10% of that of the CO₂ emission change.

1 Introduction

The northern peatlands cover approximately 3% of the Earth's land surface (Clarke and Rieley, 2010), most of which is located in the boreal region (Fischlin et al., 2007). The boreal and subarctic peatlands are substantial reservoirs of carbon (C), storing 270–550 Pg C in total (Turunen et al., 2002; Yu, 2011). These reservoirs are affected by peatland drainage, which has been a common practice in northern countries. In Finland, more than half of the original peatland area of 100 000 km² has been drained, mostly for forestry (Päivänen and Hånell, 2012). Drainage lowers water table level (WTL), which accelerates the peat decomposition rate due to the increased availability of oxygen. This often leads to higher carbon dioxide (CO₂) emissions from the soil (Maljanen et al., 2010; Ojanen et al., 2013). On the other hand, a well-performed drainage increases root aeration and nutrient availability, which enhances tree growth and CO₂ uptake by trees (Minkkinen et al., 2001). In addition, methane (CH₄) emissions decrease, and the soil may even turn into a net CH₄ sink if the site is well-drained (Maljanen et al., 2010; Ojanen et al., 2010). This results from the thickening of the oxic peat layer, which enhances CH₄ oxidation in the soil and from the disappearance of deep-rooted vascular plants, which in natural mires feed anaerobic microbes with fresh carbon and transport methane from ~~catotelm~~ the anoxic peat layer to atmosphere through their aerenchyma. In contrast to CH₄, ~~nitrogen-nitrous~~ oxide (N₂O) emissions often increase after drainage at nitrogen-rich minerotrophic peatlands (Maljanen et al., 2010; Ojanen et al., 2010, 2018) because nitrification (the process that produces nitrate and N₂O as a by-product) needs nitrogen and oxic conditions.

The most common method of forest management in Finland is rotation forestry including clearcutting and forest regeneration. In clearcutting, stem wood is removed, while the logging residues, i.e. foliage biomass, branches, stumps and roots, are either removed or left on site. After clearcutting, the site is prepared, e.g., by mounding or scalping, and a new tree generation is established by planting or sowing, or naturally from surrounding seed-trees. Removing the trees changes the local microclimate as more solar radiation reaches the soil surface, which increases soil temperature (Edwards and Ross-Todd, 1983; Londo et al., 1999) and its diel variation. This affects the carbon cycle, as higher soil temperature potentially increases soil respiration. In peatland forests, however, removing tree biomass raises the WTL by diminishing transpiration (Sarkkola et al., 2010), which in turn may decrease soil respiration and slow down the peat decomposition rate due to the reduced volume of aerated peat. On the other hand, photosynthesis is diminished due to the removal of trees and decline of ground vegetation. Mäkiranta et al. (2010) found that ground vegetation recovers rather fast in a peatland forest after clearcutting; however, after three years the recovery was still insufficient to compensate for the high ecosystem respiration produced by the large amount of fresh organic matter. The increase in ecosystem respiration is accounted for by the decay of logging residues and possibly also by increased soil organic matter decomposition under the ~~se logging-residues-and-by-the-decay-of-these-residues~~ (Mäkiranta et al., 2012; Ojanen et al., 2017). As boreal forest grows slowly, it may take from 8 up to 20 years to turn the forest back to a net carbon sink (Fredeen et al., 2007; Kolari et al., 2004; Mäkiranta et al., 2010; Pypker and Fredeen, 2002; Rannik et al., 2002; Schulze et al., 1999).

The CO₂ and energy fluxes between ecosystems and the atmosphere are commonly measured with the eddy covariance (EC) method (Aubinet et al., 2012). Previous work concerning clearcutting in forests with mineral soil has involved both EC (Clark et al., 2004; Humphreys et al., 2005; Kolari et al., 2004; Kowalski et al., 2004, 2003; Machimura et al., 2005; Mamkin et al., 2016; Takagi et al., 2009; Williams et al., 2013) and soil chambers (Howard et al., 2004; Londo et al., 1999; Zerva and Mencuccini, 2005). Also, soil chambers have been used on clear-cut peatland forests (Mäkiranta et al., 2010; Pearson et al., 2012), whereas EC measurements have been lacking. In addition, most of this peatland forest gas exchange research has concentrated on carbon dynamics and overlooked the possibly important variations in energy and water fluxes.

Exchange of sensible and latent heat constitutes an important part of the surface energy balance, driving many local, regional and global scale climatological processes. The available energy for these turbulent fluxes is determined predominantly by net radiation and the ground heat flux. The partitioning of available energy between the sensible and latent heat fluxes, which can be described in terms of the Bowen ratio, is strongly influenced by vegetation and soil properties (Betts et al., 2007). Also, release of latent heat to the atmosphere, i.e., evapotranspiration, is a key component of the water cycle in peatlands and forests, also affecting soil moisture and forest productivity, which further affect the GHG fluxes in a forest. In a temperate deciduous broadleaf forest, evapotranspiration has been found to recover rapidly after clearcutting: the latent heat flux increased over the first three years, while the sensible heat flux declined correspondingly (Williams et al., 2013). It is unknown if this also happens in peatland forests.

In this study, we investigated the ~~effect of clearcutting on~~ GHG and energy fluxes between the forest floor and the atmosphere and their environmental drivers after clearcutting in a boreal peatland forest in southern Finland. The study was based on EC measurements made for two years (April 2016 – March 2018) after clearcutting and on soil chamber measurements performed during the period of June 2015 – August 2017~~two years (April 2016 – March 2018) after the forest was clearcut~~. Our specific aims were:

1. To estimate the magnitude of CO₂ fluxes and their environmental drivers after clearcutting.
2. To quantify the development of surface heat fluxes after clearcutting.
3. To investigate how soil CH₄ and N₂O fluxes change due to clearcutting.

25 **2 Materials and methods**

2.1 Measurement site

The measurements were set up in a nutrient-rich peatland forest called Lettosuo, which is located in southern Finland (60°38' N, 23°57' E). The site was drained with widely-spaced, manually dug ditches probably during the 1930s, then drained more effectively in 1969 and fertilized with phosphorus and potassium. The distance between the ditches is on average 45 m, and they were ~~originally~~ dug ca. 1 m deep but have since been partially filled with vegetation. After drainage and before clearcutting in 2016, the tree stand was dominated by Scots pine (*Pinus sylvestris*) with some pubescent birch (*Betula pubescens*). The understorey included mostly Norway spruce (*Picea abies*) and some small-sized pubescent birch. The tree stand was quite

dense, which made the ground vegetation and moss layer patchy and variable due to irregular shading. Ground vegetation included herbs, such as *Trientalis europaea* and *Dryopteris carthusiana*, and dwarf shrubs, such as *Vaccinium myrtillus* (Bhuiyan et al., 2017). The moss layer was dominated by *Pleurozium schreberi* and *Dicranum polysetum* with some *Sphagnum* mosses, such as *Sphagnum capillifolium*, *S. angustifolium* and *S. russowii*, in moist patches.

5 Before clearcutting, the average soil organic carbon content at the site was 58% and carbon distribution was rather uniform across different soil layers (Table 1). The total soil nitrogen content was lowest in humus (1.7%) and varied from 2.2% up to 2.5% among the other soil layers. The CN ratio averaged at 27 which is typical for peatland forests with a fen history. The mean soil bulk density of the 0–40 cm layer was 0.14 g cm⁻³. The present-day peat thickness at Lettosuo varies mostly between 1.5 and 2.5 m. Assuming a thickness of 2 m results in soil organic carbon and nitrogen stock estimates of 156±72 kg C m⁻² and 6.4±2.9 kg N m⁻² (±SD).

10 Clearcutting was performed within a trapezoidal area of 2.35±.54 hectares (Fig. 1) between 29 February and 16 March 2016. After clearcutting, the logging residues were left at the site. The previous ground vegetation was almost totally destroyed ~~by heavy machinery~~ in the harvesting operation and the following drastic increase in solar radiation. In the following summer, some species adapted to the open, well-lighted conditions; for example, *Rubus idaeus*, *Carex canescens* and *Dryopteris*
15 *carthusiana* were observed here and there within the clear-cut site. Mounding was performed on 1–2 August 2016, and spruce (*Picea abies*) seedlings were planted in 2017. In addition to the clear-cut site, we ~~had~~ conducted GHG measurements on a similarly sized control site located south-west of the clear-cut site, where the forest was left in its original state with similar tree stand and vegetation composition as at the pre-harvest clear-cut site.

2.2 Measurement system

20 An EC system to measure turbulent CO₂ and energy fluxes was set up in the north-eastern part of the clearcut (Fig. 1), and the measurements started on 8 April 2016, approximately three weeks after the clearcutting had ended. The measurements continued until 7 April 2018. From this point on, the time periods of 8 April 2016 – 7 April 2017 and 8 April 2017 – 7 April 2018 are referred to as the first and second EC measurement year, respectively. The EC system included a three-axis sonic anemometer (uSonic-3 Scientific, METEK, Elmshorn, Germany) for wind speed and air temperature and a closed-path infrared
25 gas analyser (LI-7000, Licor Biosciences, Lincoln, NE, USA) for CO₂ and H₂O mixing ratios. A sampling rate of 10 Hz was used for the EC system. The measurement height was 2.75 m, the flow rate was about 6 l min⁻¹, and the length of the inlet tube (inner diameter 3.1 mm, Bevaline IV) was 8 m. The mouth of the inlet tube was positioned 15 cm below the sonic anemometer. Air with a zero CO₂ concentration was used as the reference gas when calibrating the gas analyser. The micrometeorological sign convention is used throughout the paper: a positive flux indicates a flux from the ecosystem to the atmosphere (net
30 emission) and a negative flux indicates a flux from the atmosphere into the ecosystem (net uptake).

Auxiliary meteorological measurements were installed at the centre of the clearcut (80 m south of the EC mast) on 24 July 2015, i.e., before the clearcutting. A similar system was installed two weeks earlier for the control site (180 m south-east of the EC mast). Air temperature and relative humidity were measured at 2 m height (HMP155, Vaisala Corporation, Vantaa,

Finland) and soil temperature profile at 5, 10, 20 and 30 cm depths (Pt100, Vaisala Corporation, Vantaa, Finland); the measurements also included net radiation (NR Lite2 Net Radiometer, Kipp & Zonen, Delft, The Netherlands), photosynthetically active photon flux density (PPFD) (PQS1 PAR Quantum Sensor, Kipp & Zonen, Delft, The Netherlands) and ground heat flux (HFP01, Hukseflux Thermal Sensors B.V., Delft, The Netherlands). In addition to these, global radiation (Pyranometer CMP3, Kipp & Zonen, Delft, The Netherlands) was measured from another EC mast above the canopy of the surrounding forest (250 m south from the clear-cut EC mast). The data were collected by data loggers (QML201C, Vaisala Corporation, Vantaa, Finland) as 30 min averages.

2.3 EC data processing

Half-hourly turbulent fluxes were calculated using standard EC methods (Aubinet et al., 2012). The 10 Hz raw data were block-averaged, and a double rotation of the coordinate system was applied (McMillen, 1988). The time lag between the gas analyser and sonic anemometer signals was determined by cross-correlation analysis for each flux variable and 30 min period. Water vapour fluctuations affecting flux measurements with LI-7000 were compensated for (Webb et al., 1980); a corresponding compensation is not necessary for temperature (Rannik et al., 1997). The fluxes were corrected for systematic losses due to block averaging and attenuation of the highest frequencies in the cospectra between vertical wind speed and mixing ratio; the transfer function method of Moore (1986) was used for this. For the high-frequency losses, the transfer functions describing the flux attenuation were determined separately for CO₂ and water vapour fluxes (with half-power frequencies of 1.3 and 0.6 Hz, respectively) using temperature cospectra as the reference. These functions were convoluted with generic cospectral distributions (Kaimal and Finnigan, 1994) to calculate the flux correction as a function of wind speed and atmospheric stability.

The 30 min averaged data were screened according to the following acceptance criteria: relative stationarity (Foken and Wichura, 1996) < 100%, internal LI-7000 pressure > 60 kPa, CO₂ mixing ratio > 350 ppm, wind direction within 80–315°, number of spikes in the vertical wind speed and CO₂ concentration data < 150 of 18000. Also, the data from unsuitable wind directions and the periods of weak turbulence were discarded. For the latter, by applying a friction velocity (u^*) limit of 0.125 m s⁻¹ was applied (Fig. S1). In addition, the footprint accumulated within the target area shown in Fig. 1 was required to exceed a limit of 0.75 to ensure that the measured flux originated predominantly from the clear-cut site. The footprints were calculated using the model developed by Kormann and Meixner (2001) and input data measured with the sonic anemometer.

In addition to the vertical turbulent fluxes, the CO₂ fluxes associated with the storage of CO₂ below the measurement height were calculated from the change in the mean CO₂ concentration profile between consecutive half-hour periods. It was assumed that the CO₂ concentration in the air column from ground level to the measurement height of 2.75 m was constant.

There were only two periods when a measurement gap in the data was longer than five days: 30 September – 5 October 2016 and 28 April – 4 May 2017. After applying all the data filters described above, 30% of the 32635 half-hour periods recorded within the measurement period were accepted for further analysis (Table S1, Fig. S2). The gap-filling procedure and uncertainty analysis of the net ecosystem exchange of CO₂ (NEE) are described in Appendix.

2.4 Surface energy balance and Bowen ratio

The surface energy balance can be expressed as

$$Q_H + Q_E = Q_N - Q_G - Q_S, \quad (1)$$

where Q_H is sensible heat flux, Q_E is latent heat flux, Q_N is net radiation, Q_G is the ground heat flux, and Q_S is the sum of storage fluxes from other energy sinks and sources. In this study, we assumed that $Q_S = 0$.

The Bowen ratio, defined as

$$\beta = \frac{Q_H}{Q_E}, \quad (2)$$

is used to describe the partitioning of $Q_N - Q_G$ to Q_H and Q_E at the surface. When $\beta < 1$, more available energy at the surface is released to the atmosphere as latent heat than as sensible heat, and vice versa when $\beta > 1$. In this study, we present monthly Bowen ratios that were calculated from the monthly mean daytime (10:00–16:00, UTC+2) fluxes of Q_H and Q_E . Gap-filling of the energy fluxes is described in Appendix.

2.5 Chamber measurements of GHG fluxes

For manual chamber measurements, a sampling transects ~~was~~ were set up ~~within the middle of~~ the clear-cut ~~and control sites~~, where the GHG fluxes were measured between 29 June 2015 and 29 August 2017, mostly during the snow-free periods. The measurement interval varied between one week and one month, but there were longer gaps in autumn 2015 and spring 2016. The transect had two flux measurement plots at a distance of 4, 8, 12 and 22.5 m from the ditch, and at each distance there was an automatic WTL logger close to the flux measurement plots (see Sect. 2.7 for details). In addition, all the flux plots included a soil temperature data logger (iButton DS1921G, Maxim Integrated Products) at 5 cm depth and two of them (8 and 22.5 m from the ditch) also had a similar logger at 30 cm depth. Before starting the measurements, 2 cm deep grooves were carved into the soil surface for the chambers, and the grooves were occasionally renewed when necessary to keep the chamber sealing adequate. It should be noted that, even though logging residues were left at the site, the measurement plots did not have any above-ground residues. The fluxes were measured using a closed-chamber system with an opaque cylindrical chamber (height 30.5 cm, diameter 31.5 cm) including a mixing fan. The measurements were made in two different ways: using (1) a portable analyser and (2) a stationary analyser. As a portable analyser, we employed a Gasmeter DX4015 (Gasmeter Technologies Oy, Helsinki, Finland), based on Fourier transform infrared spectroscopy, to measure CO₂, CH₄ and N₂O mixing ratios every 5 s. At the clear-cut site, only the portable gas analyser was used. In this setup, the sampled air was circulated in a loop between the gas analyser and the chamber, and the closure time was 10–11 min. At the control site, the portable analyser was used in 2015 for all the gases, but from 2016 onwards the analyser was used only for measuring the N₂O mixing ratios. Starting from 2016 at the control site, we connected the portable gas analyser in series with a Picarro G1130 cavity ring-down spectroscopy gas analyser (Picarro Inc., Santa Clara, CA, USA) to acquire more precise CO₂ and CH₄ mixing ratios. In this system, the gas analysers were stored in a cabin and connected to the chamber with a 50 m long tubing. The instruments were compared against each other and observed to result in closely similar flux estimates with the 10–11 min closure time. The error caused by not

returning the sampled air back to the chamber was corrected for in the data analysis. A portable Gaset DX4015 gas analyser (Gaset Technologies Oy, Helsinki, Finland) based on Fourier transform infrared spectroscopy was used to measure CO₂, CH₄ and N₂O mixing ratios every 5 s. The air was circulated in a loop between the gas analyser and the chamber, and the closure time was 10–11 min.

5 The fluxes were calculated the same way for all the gases (Korkiakoski et al., 2017). In short, both linear and exponential regression models were first fitted to the mixing ratio time series using the least-squares approach. The start and end points of the chamber closure were visually identified from the data for each closure. The first minute of each measurement was discarded to ensure that the sample air was properly mixed inside the chamber. After fitting, the mass flux (F) was calculated as

$$10 \quad F = \left(\frac{dC(t)}{dt} \right)_{t=0} \frac{MPV}{RTA}, \quad (3)$$

where $\left(\frac{dC(t)}{dt} \right)_{t=0}$ is the mixing ratio change in time determined from a linear or exponential model at the beginning of the closure, M is the molecular mass of CO₂, CH₄ or N₂O (44.01, 16.04 and 44.01 g mol⁻¹, respectively), P is air pressure, R is the universal gas constant (8.315 J mol⁻¹ K⁻¹), T is the mean chamber headspace temperature during closure, and V and A are the volume and the base area of the chamber headspace, respectively. The snow depth and the height of mosses and other
15 vegetation in the chamber headspace volume were taken into account, ignoring the pore space in the soil and snow. However, if the soil surface was frozen, the measurements were not made as it was not possible to properly seal the chamber. Finally, analyser-specific flux limits were determined to choose between the linear and exponential models (Korkiakoski et al., 2017). If the flux calculated with the linear model was smaller than the limit, then this estimate was considered more robust for the noisy data and adopted for the later analysis. These limits for the ~~present-portable~~ system were 5.6 μg CO₂ m⁻² s⁻¹, 9.7 ng CH₄
20 m⁻² s⁻¹ and 12.5 ng N₂O m⁻² s⁻¹. We did not define a corresponding limit for the CO₂ flux measured with the Picarro gas analyser at the control site as the fluxes were always sufficiently large for using exponential fitting, but for CH₄ the limit was set to 0.7 ng CH₄ m⁻² s⁻¹.

The CO₂ flux measured with chambers represents forest floor respiration (R_{ff}), which is defined as the sum of heterotrophic and autotrophic respiration. As clearcutting affects soil processes, it should be noted that the R_{ff} before and after clearcutting
25 consist of different components. Before the clearcutting (the 2015 data), R_{ff} includes ground vegetation and living roots of trees and ground vegetation, but after clearcutting (2016–2017) it instead includes the survived and regrown ground vegetation and living and dead roots.

The summertime sum of R_{ff} was calculated for each summer separately by using Eq. A3 with hourly soil temperature at 5 cm depth. The uncertainty of this sum was estimated from the minimum and maximum sums based on the standard errors of model
30 parameters (R_0 and E). The minimum and maximum sums were slightly asymmetrical around the mean sum, so the largest deviation from the mean sum was adopted as a conservative uncertainty estimate.

2.6 Statistical analysis

Linear mixed effect model was used for testing for differences in the daily mean CO₂, CH₄ and N₂O fluxes between the clear-cut and control sites and between the years in the chamber measurement data. In both cases, the chamber plots were treated as a random effect. The linear mixed effects model was carried out with the R programming language (R Core Team, 2018, version 3.5.0) using the 'lme4' package. The normality of model residuals was visually checked using quantile-quantile plots. The differences were tested with Tukey's HSD post hoc test.

The statistical significance of the manual chamber gas flux differences between the years was tested with unpaired Student's t test. Before using this test, the Shapiro-Wilk test was applied to test if the data were normally distributed. When at least one of the groups was not normally distributed, the Wilcoxon rank sum test was used instead of Student's t test. If the data sets were normally distributed, Levene's test was used to check the equality of variances, and if the variances were not equal, Welch's unequal variances t-test was used. The statistical tests were made with the Python programming language (Python Software Foundation, version 2.7, <https://www.python.org>) using SciPy (<http://www.scipy.org/>) library.

2.7 Water table level measurements and analysis

The water table levels within both the clear-cut site and non-managed control site were measured for one year before (2015) and two years after the clearcutting (2016–2017). Four automatic monitoring plots consisting of dipwells (perforated plastic tubes 120 cm long, 3.5 cm diameter) were set up at the centre of each site (Fig. 1), located at a distance of 4, 8, 12 and 22.5 m in a transect perpendicular to the ditch (ditch spacing was 45 m). In addition, in order to calibrate the automatic water table measurement data, manually monitored dipwells were installed close to the automatically monitored dipwells within the clear-cut and control sites. WTL was measured manually at weekly or fortnightly intervals during March–November. From the automated dipwells, WTL was recorded with an automatic probes (TruTrack WT-HR logger, Intech Instruments Ltd, Auckland, New Zealand; Odyssey Capacitance Water Level Logger, Dataflow Systems Limited, Christchurch, New Zealand) at hourly intervals. The recorded values were then calibrated with linear regression using the manually measured WTL data from both the control and clear-cut site.

The analysis of the clearcutting effects on WTL was based on the paired treatment approach (also called the calibration period – control area method) (e.g., Kaila et al., 2014; Laurén et al., 2009). We first calculated linear regressions between the WTL within the control and clear-cut sites for the pre-treatment period using the WTL logger data from 2015. Then we used this regression model and the post-treatment WTL data from the control site to predict WTL for the clear-cut site as if it had not been harvested. The clear-cut effect was calculated as the difference between the calibrated post-clear-cut WTL measurements and the predicted background WTL values in the clear-cut site after the harvest.

3 Results

3.1 Meteorological and hydrological conditions

The mean annual air temperature at the nearby (Jokioinen, 35 km northwest of Lettosuo) weather station before the clearcutting in 2015 was 6.2 °C. The mean post-clearcut annual air temperature at the site during the first and second EC measurement year were 5.6 °C and 4.4 °C, respectively (Fig. 2a), which difference was reflected in soil temperatures (Fig. 2b). These air temperatures were slightly higher and about the same, respectively, than the long-term (1981–2010) average at a nearby (Jokioinen, 35 km northwest of Lettosuo) weather station (4.6 °C; Pirinen et al., 2012). Both All winters (DJF) were warmer (2015–2016: -3.4 °C (Jokioinen), 2016–2017: -3.0 °C, 2017–2018: -3.4 °C) than the long-term average (-5.3 °C), while the mean summer (JJA) temperature in at Jokioinen in 2015 (14.4 °C) was 0.8 °C cooler than the long-term average (15.2 °C), while the JJA temperature at the EC site in 2016 was similar to (15.3 °C) and in was similar to and the summer 2017 cooler (by 1.6 °C) cooler than in 1981–2010 the long-term average (15.2 °C). In addition, compared to the precipitation at Jokioinen (long-term average 627 mm), the first EC measurement year was drier (502 mm) and the second year similar (656 mm) (Fig. 2c) while the pre-clearcut year of 2015 was wetter (680 mm) than both post-clearcut years. Especially the autumn (SON) 2016 and winter 2016–2017 were much drier, while the springs and summers were quite similar to the long-term average conditions. Both winters had a shallower snow cover than the long-term average annual maximum (28 cm; Pirinen et al., 2012). The maximum snow depths at Jokioinen were 12 cm and 22 cm in 2016–2017 and 2017–2018, respectively. Due to the especially shallow snow cover in the first winter and the high temperatures in March, all the snow had melted by 23 March 2017 (Fig. 2d). However, in 2018, the snow cover was still intact when the measurement period ended in 7 April.

The pre-harvest soil temperatures at 30 cm depth were similar within the clearcutting and control sites, but clearcutting increased their temporal variation (Fig. S3). After clearcutting in late spring, the daily mean 30 cm soil temperature rose faster and was higher throughout the summer within the clearcut than at the control site (Fig. S3). Also, the 30 cm temperature within the clearcut started to decline earlier in autumn and was lower during winter within the clearcut than the control site. The monthly mean diel variation of soil temperature at 5 cm depth ranged from 0.8 to 1.3 °C in July–September 2015 before clearcutting (Fig. S4). After clearcutting, this variation increased to 2.3–2.9 °C and 2.1–3.7 °C in 2016 and 2017, respectively. On average the diel variation was 1.8 °C larger in July–September after the clearcutting than before it (Figs. 2b and S4). Increases in the diel temperature range were also observed at the 10 cm (1.2 °C) and 20 cm (0.33 °C) depths, but not anymore at 30 cm.

The mean WTL in July–August 2015 was -33 cm within the clear-cut area, while at the control site it was -50 cm (Fig. 3). The mean WTL within the clear-cut site was about -36 cm during the pre-treatment growing season of 2015. After clearcutting, the WTL rose and remained continuously at a significantly markedly higher level than the predicted background WTL and the measured WTL at the control site. At the clear-cut site, the WTL rose to -22 cm and -27 cm in July–August 2016 and 2017, respectively. On the other hand, the WTL at the control site sank to -55 cm during these months in both post-harvest years. The largest post-treatment rise occurred in July–October when the average WTL was -23 cm and -24 cm in the clear-cut and

–46 cm and –49 cm in the background model, corresponding to a 23 cm and 25 cm rise in WTL in 2016 and 2017, respectively (Fig. 3). As a consequence of heavy rain episodes in summer and autumn in 2017, the amplitude of WTL variations was larger in this than ~~in~~ the previous year (~~Fig. 3~~).

3.2 CO₂ exchange on an ecosystem level

5 3.2.1 Seasonal and diel variations

When the measurements started at the beginning of April 2016, the daily mean NEE was mainly $< 0.08 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ but started to increase with temperature at the end of April, after the daily mean temperature exceeded $5 \text{ }^\circ\text{C}$ (Figs. 2a and 4). There was a significant-substantial temporary drop in NEE in the first half of June after a cold spell when the daily mean temperature decreased from 20 to $10 \text{ }^\circ\text{C}$. By the end of June, NEE stabilized at around $0.21 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. From the end of August, NEE
10 decreased until reaching a stable level of $0.03 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in January 2017. At the end of March 2017, NEE started to gradually increase, and in mid-May it quickly rose to $0.08 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. After this, NEE continued to increase, stabilizing at around $0.13 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in August and then decreasing from the end of September onwards.

Even though all the big trees were removed in clearcutting and most of the ground vegetation was destroyed, some sparse small understorey trees was-were left at the site and weak photosynthesis could be observed simultaneously with the increased
15 respiration in the end of April 2016 (Fig. 4). In May, the estimated magnitude of gross primary production ($|GPP|$, Appendix A) increased to $0.05 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, which was about 25% of the respiration rate at that time. However, $|GPP|$ decreased to $0.02 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in June, after which it started to increase again, reaching its maximum at $0.08 \text{ g CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at the end of July and the beginning of August. From that point on, photosynthesis started to weaken, marking the ending of the growing season, and ceased in mid-October, about a month before the first snow. In 2017, $|GPP|$ increased from mid-May until July,
20 when it stabilized at around $0.11 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. Similarly to 2016, $|GPP|$ decreased from August onwards.

The correlation between the night-time NEE (i.e., R_{eco} in Eq. A3) and at the 5 cm soil temperature was stronger in summer 2017 than 2016 (Fig. 5a). The model fits (Eq. A3) indicate that the temperature response of ecosystem respiration (parameter E) was also stronger in 2017. However, the base respiration rate R_0 (R_{eco} at $10 \text{ }^\circ\text{C}$) was larger in the first than the second summer (0.199 vs. $0.173 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$). In addition, no correlation was found between the model residuals and WTL in
25 either summer (Fig. S5). Like the temperature response of R_{eco} , the light response of GPP was stronger in summer 2017 than 2016 (Fig. 5b). Also, the corresponding maximum gross photosynthesis rate (GP_{max} , Eq. A2) more than doubled (-0.226 vs. $-0.100 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$).

The site was on average a CO₂ source throughout the day, also during the summer. It should be noted, however, that there were still multiple half-hour periods, especially in August 2017, when the site acted as a CO₂ sink. A noticeable diel variation in
30 NEE was observed mainly from April to October (Fig. 6). Between April and August, the mean diel NEE cycle had a minimum during the morning hours (5:00–10:00, UTC+2) and the highest emissions during the evening/night (21:00–1:00). After August, the lowest emissions took place later, at around noon. On the other hand, the highest emissions were observed earlier,

at 20:00 in September and at 18:00 in October. In October, the diel cycle of NEE was still noticeable; it vanished in November and reappeared in March 2017. In spite of the different mean fluxes, the amplitudes of their diel cycle were rather similar in 2016 and 2017, except from July to September when the amplitudes were much larger in 2017. Also, unlike in 2016, systematic diel variation was still obvious in November 2017. Even though such variation indicates significant photosynthesis during the midday hours, the monthly mean diel NEE cycle consistently showed positive fluxes.

3.2.3.2 CO₂ balances

The annual CO₂ balances of the first and the second year after clearcutting were $3086 \pm 98-148$ g CO₂ m⁻² (\pm uncertainty; see Appendix) and $2072 \pm 115-124$ g CO₂ m⁻², respectively. About half of the annual CO₂ emissions during both EC measurement years took place during the summer months (JJA), totalling $1558 \pm 61-99$ g CO₂ m⁻² (Table 42, Fig. 7), and 73% (2256 ± 72 10 146 g CO₂ m⁻²) of the annual total was accumulated during the May–September period. In 2017, however, these emissions decreased to $915 \pm 80-79$ g CO₂ m⁻² (June–August) and $1401 \pm 143-109$ g CO₂ m⁻² (May–September), i.e., by 41% and 38%, respectively. The effect of storage fluxes on the CO₂ balance was negligible as the daily mean storage flux typically varied within ± 0.009 mg CO₂ m⁻² s⁻¹ during summer and within ± 0.004 mg CO₂ m⁻² s⁻¹ during the other seasons.

The most significant period of CO₂ uptake was from June to September (Fig. 7). Considering only the summer months (JJA), the integrated GPP was -389 and -761 g CO₂ m⁻² in 2016 and 2017, respectively (Table 42), i.e., the mean CO₂ uptake in the 15 the second summer after clearcutting increased by 96% from the first summer. On the other hand, the total summertime R_{eco} decreased by 14%, from 1928 g CO₂ m⁻² in 2016 to 1652 g CO₂ m⁻² in 2017 (Table 42).

3.3 Soil GHG fluxes

The ~~total pre-clearcut~~ summertime (JJA) R_{ff} measured at the soon-to-be clear-cut site in 2015 was $1213-1611 \pm 348-191$ g CO₂ 20 m⁻² (\pm uncertainty; see Sect. 2.5) and ~~most of~~ the measured CO₂ fluxes varied from 0.045 to $0.25-36$ g CO₂ m⁻² s⁻¹ (Fig. 8a). The CH₄ flux averaged over all the measurement plots was -26 ± 5 ng CH₄ m⁻² s⁻¹ before the clearcutting. All the measured CH₄ fluxes were negative (Fig. 8b) ranging from -103 to -2 ng CH₄ m⁻² s⁻¹. N₂O fluxes varied mostly from -17 to 33 ng N₂O m⁻² s⁻¹ and averaged at 1 ± 5 ng N₂O m⁻² s⁻¹ (Fig. 8c). At the control site, the summertime fluxes of CO₂ (from 0.03 to 0.39 g CO₂ m⁻² s⁻¹) and N₂O (mean: 11 ± 9 ng N₂O m⁻² s⁻¹) in 2015 were not significantly different from those at the soon-to-be clear- 25 cut site. However, the CH₄ fluxes (mean: -10 ± 3 ng CH₄ m⁻² s⁻¹) at the control site were significantly ($p < 0.02$) larger than at the soon-to-be clear-cut site.

After the clearcutting, the total summertime R_{ff} decreased to $619-980 \pm 299-184$ g CO₂ m⁻² in summer 2016 ~~but partly recovered and remained at the same level to~~ $946-(1047 \pm 129-113)$ g CO₂ m⁻² in 2017. These numbers were 51% and 63% of the R_{eco} for summers 2016 and 2017, respectively (Fig. 9). Also, the temperature response of R_{ff} got weaker and the R_0 30 parameter (R_{ff} at 10 °C) decreased while at the control site the responses remained quite similar over the years (Fig. 9-10). The strength of temperature response and R_0 partly recovered in 2017 but were still weaker than before the clearcutting. In contrast to the R_{ff} at the clear-cut, the summertime R_{ff} at the control site increased from 1852 ± 1353 g CO₂ m⁻² in 2015 to 2280 ± 346 g

CO₂ m⁻² and 2438±225 g CO₂ m⁻² in 2016 and 2017, respectively. However, the increase was significant only when comparing the summers 2015 and 2017 ($p < 0.05$). The clear-cut and control sites were significantly different from each other in both summers ($p < 0.001$) after clearcutting.

CH₄ fluxes changed markedly after the clearcutting as the previously small mean CH₄ sink turned into a small CH₄ source in the first (4 ± 3 ng CH₄ m⁻² s⁻¹) and second (6 ± 2 ng CH₄ m⁻² s⁻¹) year after the clearcutting (Fig. 8b); the changes were significant for both years ($p < 0.001$ ~~for 2016; $p < 0.001$ for 2017~~). However, the post-clearcut years were not significantly different from each other ($p = 0.89385$). The post-clearcut fluxes varied mostly from -14 to 28 ng CH₄ m⁻² s⁻¹ with some occasional emission peaks reaching up to 140 ng CH₄ m⁻² s⁻¹. Most of the measured fluxes were positive (emission), even though a single measurement plot could act both as a source and a sink on different measurement days. The control site remained as a CH₄ sink in 2016 and 2017 and neither of the mean summer fluxes was significantly different from the pre-harvest summer mean. However, the mean CH₄ fluxes were significantly different ($p < 0.001$) between the sites in both post-harvest summers.

Similarly to CH₄, the post-clearcut N₂O fluxes were significantly higher than the pre-clearcut ones ($p = < 0.0012$ ~~for 2016; $p < 0.001$ for 2017~~), and the post-clearcut years did not differ significantly from each other ($p = 0.778$). After the clearcutting, the mean annual fluxes were 228 ± 26 and 212 ± 21 ng N₂O m⁻² s⁻¹ in 2016 and 2017, respectively (Fig. 8c). All the measurement plots turned to large N₂O sources, and the largest measured emission was 1339 ng N₂O m⁻² s⁻¹. All the measured fluxes were positive, except for a plot furthest from the ditch that acted as a temporary N₂O sink in 2017, especially in the June–July period. The N₂O fluxes at the control site remained low in summer 2016 (mean: 16 ± 11 ng N₂O m⁻² s⁻¹), but increased in summer 2017 (mean: 70 ± 10 ng N₂O m⁻² s⁻¹). However, the post-harvest emissions at the control site were significantly lower than those at the clear-cut site ($p < 0.001$). Both the spatial and temporal variation were large: the largest emissions occurred in June while from July onwards the emissions decreased (Fig. 8c).

3.4 Energy fluxes

The daily sums of sensible heat (Q_H) were about 1 MJ m⁻² day⁻¹ on average at the start of the EC measurement period in April 2016 and increased to a maximum of 4.7 MJ m⁻² day⁻¹ in June (Fig. 4011). In July, the daily Q_H sum was already decreasing with the decreasing net radiation (Q_N), and it turned negative in October. On the other hand, the daily sums of latent heat flux (Q_E) were quite stable from April until August averaging at 1.0 ± 0.04 MJ m⁻² day⁻¹ (\pm standard error of mean). In September, Q_E started to decrease and reached zero at the end of October. The ground heat flux (Q_G) varied within 0–0.5 MJ m⁻² day⁻¹ from April to August, after which it varied mostly between -0.5 and 0 MJ m⁻² day⁻¹ until the end of April 2017.

In 2017, the seasonal dynamics of the energy fluxes were similar to 2016, but the magnitude of fluxes changed considerably. The summertime average daily sum of Q_H decreased from 1.8 to 1.2 MJ m⁻² day⁻¹, while that of Q_E increased from 1.3 to 2.3 MJ m⁻² day⁻¹. Also, the monthly sums of these fluxes ~~changed significantly~~ were markedly different in the second year after the clearcutting. During the period of the highest fluxes (April–September), the Q_H sum was 33% smaller in 2017 than 2016, while the Q_E and Q_N sums were higher by 40% and 13%, respectively. ~~There was no significant changes~~ in Q_G were minor.

The monthly mean midday Q_H in May and June 2016 were 206 W m^{-2} and 165 W m^{-2} , respectively (Fig. ~~44a~~12a). After June, the midday Q_H started to decrease with decreasing Q_N , and the night-time Q_H turned from zero to slightly negative. The midday Q_E also increased from April to June, reaching 88 W m^{-2} , and remained quite stable until September. The resulting monthly mean daytime Bowen ratio (β), increased from 1.7 in April to 2.6 in May 2016 and then declined to 0.8 in August. In 2017, the mean midday Q_H was similar to that in 2016, except in July and September when the fluxes were 34% and 23% lower, respectively, than in 2016 (Fig. ~~44b~~12b). However, the daily maximum Q_E was either similar to or higher (up to 48%) than Q_H in all months except May 2017. Correspondingly, β was lower than one (0.6–1.0) during the period of high fluxes in 2017, except in May when it was 1.7.

4 Discussion

10 Dynamics of the CO_2 fluxes and flux components

~~At our site, the switch of the annual NEE from approximately zero to a large source, which took place after the clearcutting, can be explained by a decrease in the total |GPP| by about 88%, as estimated from the EC measurements in 2015 (Lohila, unpublished data), following the removal of photosynthesizing trees and the decline of ground vegetation. The study site was a large source of CO_2 during the two EC measurement years after clearcutting, but the emissions were 33% smaller in the second than the first year. |GPP| remained low and stable during the first summer after clearcutting, and the daytime NEE correlated only weakly with PPFD, reflecting the fact that neither vascular ground vegetation nor moss cover had developed significantly substantially by that time. However, during the second summer, the total |GPP| increased by 96% from the first post-clearcut summer, and the increase in the coverage of ground vegetation was already noticeable (although not directly measured). This relatively fast recovery of ground vegetation is similar to the leaf area index changes observed by Mäkiranta et al. (2010) after clearcutting in a nutrient-poor peatland forest. The EC based estimate of accumulated R_{eco} decreased by 29% (40%) in the first (second) year after clearcutting from the 2015 value (Lohila, unpublished data), even though decomposing logging residues were left at the site and the summer following the clearcutting was slightly warmer than the one before it. R_{eco} was larger in the first than in the second post-harvest year which could be due to the first year being warmer or due to changes in the respiration of either residues or forest floor in the second year. The chamber measurements, which were not affected by aboveground logging residues, showed a ~~49~~39% and ~~22~~35% decrease in R_{ff} after clearcutting in the first and second summer after clearcutting, respectively. Possible reasons for this decrease include reduced peat decomposition due to raised WTL, ceased autotrophic respiration of (the harvested) trees roots and decreased autotrophic respiration of ground vegetation, even though the latter slightly recovered during the summer as the ground vegetation started to regrow. The CO_2 flux from the decomposing belowground logging residues (roots) was not sufficiently large to compensate for this decrease in R_{ff} . After the removal of the canopy, more solar radiation reached the surface, heating it more during the daytime, while the heat transfer from the soil to the atmosphere was enhanced during the night; together these resulted in a higher diel variation in soil temperature. On the other hand, the insulating impact of logging residues may have partly dampened the amplitude of the diel~~

~~temperature cycle.~~ In summer 2016, R_{ff} was ~~32.51%~~ of the R_{eco} suggesting that ~~two-third~~ of the R_{eco} during that time originated from the aboveground logging residues, which were not included in the chamber measurements of R_{ff} . ~~However,~~
5 In summer 2017, ~~however, the total R_{ff} increased by 35% and R_{eco} decreased by 14%, but R_{ff} remained about the same,~~ indicating that a larger proportion (~~57.63%~~) of R_{eco} originated from the forest floor respiration than in the previous summer.

5 This could be due to ~~an increase in both autotrophic and heterotrophic respiration while the amount and the~~ ~~the decrease in~~ decomposition rate of the aboveground logging residues ~~due to lower temperatures and because the residues had already partly~~ ~~decomposed during the previous summer. However, the lower temperatures would also decrease R_{ff} , but this did not happen~~ ~~because in 2017 WTL was 5 cm lower, which enhanced peat decomposition.~~ ~~decreased (Mäkiranta et al., 2012).~~ In addition, the NEE in summer 2017 was approximately equal to R_{ff} , which means that the increase in $[GPP]$ was sufficient to balance the
10 CO_2 emissions from the logging residues, but not from soil and plants.

~~After the removal of the canopy, more solar radiation reached the ground surface, heating it more during the daytime, while~~ ~~the heat transfer from the soil to the atmosphere was enhanced during the night; together these resulted in a higher diel variation~~ ~~in soil temperature. On the other hand, the insulating impact of logging residues may have partly dampened the amplitude of~~ ~~the diel temperature cycle, as observed by~~ (Ojanen et al., 2017). The higher soil temperatures during the daytime may have
15 enhanced peat respiration in the layer closest to the surface. However, it has been shown in previous studies that the temperature response of respiration weakens when the soil gets dry, often resulting in lower respiration rates (Mäkiranta et al., 2009, 2010). Such weakening of the temperature response was also observed at Lettosuo ~~especially in the first summer after the harvest~~ ~~when the almost bare soil surface was exposed to more solar radiation after clearcutting. Also, the summer 2016 was warmer~~ ~~and dryer than on average, which probably enhanced this effect.~~ Moreover, the addition of logging residues may have increased
20 R_{eco} ~~significantly~~ ~~substantially~~, as demonstrated by Mäkiranta et al. (2012) who observed that the plots with logging residues had a CO_2 efflux twice as high as the plots without them. However, a later study by Ojanen et al. (2017) did not show a consistent increase in soil organic matter decomposition rates ~~at similar sites.~~ ~~On the other hand, the soil decomposition rate~~ ~~was likely decreased by the raised WTL, which reduced the aerated peat volume, and drying of the almost bare soil surface,~~ ~~which was exposed to more solar radiation after clearcutting. Furthermore, the decline of ground vegetation after the~~
25 ~~clearcutting reduced autotrophic respiration, even though this process slightly recovered during the summer as the ground~~ ~~vegetation started to regrow.~~

In previous studies, a decrease has been observed in both R_{eco} (Kowalski et al., 2004, 2003; Takagi et al., 2009) and R_{ff} (Mäkiranta et al., 2010; Takagi et al., 2009; Zerva and Mencuccini, 2005) after clearcutting in peatland and upland forests. However, also increasing R_{eco} and R_{ff} have been reported (Kowalski et al., 2004; Londo et al., 1999). The differences between
30 these results are most likely caused by a different effect of harvest on soil microbial activity, which is mostly controlled by soil temperature, moisture and nutrient availability (Davidson et al., 1998; Fontaine et al., 2004, 2007; Lloyd and Taylor, 1994). Other possible reasons for this variability include differences in, for example, root respiration, the type and amount of logging residue, and WTL, especially in peatland forests.

In peat soils, the decomposition of organic matter is mainly controlled by soil temperature and WTL (Blodau et al., 2004; Mäkiranta et al., 2009; Silvola et al., 1996), but soil temperature is typically the most influential factor explaining the temporal dynamics in R_{ff} (e.g. Mäkiranta et al., 2008; Ojanen et al., 2010). At Lettosuo, the correlation between the half-hourly R_{eco} and soil temperature was mostly weak. This could be due to logging residues as their decomposition rate probably does not depend
5 as much on soil temperature as on the temperature and moisture of the logging residues themselves. At times, especially when the temperature range was larger (in May and June), a significant relationship (correlation coefficient peaking at 0.57) was observed, and there was also an obvious temperature response that followed the annual cycle. Also, when WTL is closer (> -15 cm) to the surface, it is usually a significant predictor of R_{ff} in peat soils (Chimner and Cooper, 2003; Riutta et al., 2007). At Lettosuo after clearcutting, WTL varied mostly within 20–30 cm below the soil surface, and there was no correlation
10 between R_{eco} and WTL after removing the effect of soil temperature on R_{eco} (~~data not shown~~ Fig. S5). Because R_{eco} combines many respiration components in addition to R_{ff} , it is likely that the high CO_2 efflux from logging residues, for example, masks the possible WTL effect on R_{ff} .

Our results show that after clearcutting a peatland forest ~~becomes-is~~ a large source of CO_2 to the atmosphere. ~~Growing~~
15 ~~nutrient-rich drained~~ peatland forests ~~with a growing tree stand have generally been found to be are commonly~~ CO_2 neutral or small sinks ~~of CO_2~~ (Meyer et al., 2013; Ojanen et al., 2013; Uri et al., 2017). ~~as the carbon accumulated by trees typically balances the carbon emissions caused by the decomposing peat layer. This suggests that also~~ Lettosuo ~~probably~~ was ~~also~~
~~about~~ close to CO_2 neutral ~~state~~ before the clearcutting (~~Lohila, unpublished data~~). ~~so~~ Thus the impact of clearcutting from CO_2 neutral ~~the change~~ to a source of $3086 \pm 120-148$ g CO_2 m⁻² yr⁻¹ in the first year after clearcutting ~~is~~ ~~must be considered~~
20 substantial. ~~This also means that, even at the forest had been a CO_2 sink at a certain growth stage, due to these emissions it may still need to be considered a net CO_2 source in terms of the long-term balance (Hommeltenberg et al., 2014). In this study, however, we only focus on the immediate impact of clearcutting.~~

Mäkiranta et al. (2010) measured CO_2 exchange in a clear-cut nutrient-poor peatland forest with soil chambers during a growing season (May–October) and reported slightly smaller NEE (1990 g CO_2 m⁻² season⁻¹) than the NEE we measured at Lettosuo during a similar timeframe (2340 g CO_2 m⁻² season⁻¹). Among mineral soil forests, on the other hand, the annual
25 CO_2 exchange measured with the EC method right after the clearcutting varies a lot; the annual balances ranging from ca. 400 to 4700 g CO_2 m⁻² yr⁻¹ (Amiro et al., 2010; Clark et al., 2004; Humphreys et al., 2005; Kowalski et al., 2004, 2003; Takagi et al., 2009; Williams et al., 2013). If considering only mineral soil forests, the forests in warmer climates typically emit more carbon after the harvest, but they also recover faster than the boreal forests (Amiro et al., 2010). Compared to the studies cited above, the clear-cut site at Lettosuo was the second largest source of CO_2 immediately after clearcutting, being second only to
30 the Slash pine plantation in Florida (Clark et al., 2004). The high CO_2 emission at Lettosuo as compared to other clearcut sites ~~on mineral soil~~ is apparently due to the decomposition of the ~~oxic~~ peat ~~soil-layer~~ in this nutrient-rich forest, ~~which are known to act as CO_2 sources up to 1000 g CO_2 m⁻² yr⁻¹~~ (Ojanen et al., 2013; Uri et al., 2017). ~~Mineral soil forests do not have a peat layer or any other carbon storage that could cause CO_2 emissions of such magnitude.~~

Soil CH₄ and N₂O fluxes

The CH₄ flux in peat soils is mostly controlled by WTL (Martikainen et al., 1995; Roulet et al., 1993), which divides the peat column into anoxic and oxic layers in which CH₄ production and oxidation occur, respectively. After clearcutting, the WTL rose from ~~the -36-33 cm~~ in 2015 to ~~-23-22 cm~~ in 2016 during July-August, and the highest estimated rise in WTL occurred in July-October when clear-cutting was estimated to raise WTL by 23 cm on average when compared to the background model. This made the ~~near-surface~~top-soil oxic layer much thinner and the conditions ~~for CH₄ oxidation~~ less favourable for CH₄ oxidation, allowing a smaller amount of the CH₄ ~~created-produced~~ in the anoxic layer to be oxidized before reaching the atmosphere. The WTL rise was enough to turn the clear-cut site from a CH₄ sink into a small CH₄ source while the control site remained a consistent CH₄ sink. Logging residues do not affect the CH₄ fluxes (Mäkiranta et al., 2012), but as was the case with R_{ff}, it is possible that the dryness of the year 2016 reduced the CH₄ emissions after the harvest. A similar turn of a clear-cut site from a CH₄ sink to a source has previously been found for both peat (Zerva and Mencuccini, 2005) and mineral soils (Sundqvist et al., 2014). However, Huttunen et al. (2003) measured mostly net CH₄ sinks uptake in two drained peatland forests sites in southern Finland also after clearcutting, and the difference between the control and clear-cut sites was not statistically significant at in either site case.

The N₂O fluxes were highly variable both before and after clearcutting. However, there was a strong increase from the mean pre-clearcut average flux of 1 ± 5 ng N₂O m⁻² s⁻¹ to the post-clearcut flux of 228 ± 26 ng N₂O m⁻² s⁻¹. On the other hand, the emissions were small at the control site in 2016, but increased in 2017, especially in June, even though the increase was markedly smaller than at the clear-cut site. This is probably due to higher precipitation in 2017, which increased soil moisture and enhanced denitrification. Increases of N₂O emissions after clearcutting have also been observed in peat and mineral soil forests ~~after clearcutting~~ by Huttunen et al. (2003) and Saari et al. (2009), but the fluxes at these sites were an order of magnitude smaller than at Lettosuo. It should be noted that the N₂O measurements in this study do not include any above-ground logging residues, which are expected to raise N₂O emissions further; Mäkiranta et al. (2012) found about three times as large N₂O emissions from the plots with logging residues as from the plots without them.

Compared to the change in NEE (i.e. CO₂ fluxes) at the site, the change in CH₄ emissions is negligible when considering its climatic impact in terms of the global warming potential over 100 yr (GWP₁₀₀ = 34; IPCC, 2013). Even though the change in N₂O fluxes to the present level at our site was large, the climatic effect of N₂O was only about 10% of that due to the even larger change in NEE, when considering GWP over a period of up to 100 years (GWP₁₀₀ = 298; IPCC, 2013).

Energy fluxes

The mean daily Q_E at Lettosuo during the spring and summer right after the clearcutting varied mostly within 0.5–2.5 MJ m⁻² day⁻¹ and within 1.0–4.0 MJ m⁻² day⁻¹ during the second spring and summer. Compared to the values of 2–10 MJ m⁻² day⁻¹ measured in an upland forest in Western Russia (Mamkin et al., 2016), our numbers are low. In the case of Q_H , the fluxes at Lettosuo were systematically lower than those reported by Mamkin et al. (2016), but the difference was not as large as for Q_E .

-At Lettosuo, β was lower in the second summer after the clearcutting as compared to the first summer; in summer 2016 β was >1 most of the time, whereas in summer 2017 it was <1 for the whole summer. Thus the pattern was somewhat different from the results of Mamkin et al. (2016) who reported that $\beta < 1$ already throughout the first summer after the clearcutting. One reason for the smaller Q_E at Lettosuo could be the drier-than-normal summers in 2016 and 2017 and the drier surface layer of the peat.

In summer 2017 at Lettosuo, Q_H decreased slightly and Q_E almost doubled compared to 2016, suggesting a recovery of transpiration due to the gradual recovery of ground vegetation. This is in agreement with the results obtained by Williams et al. (2013) for a clear-cut Norway spruce plantation in the north-east USA, where a recovery of evapotranspiration and a decrease in Q_H were observed across the years after the clearcutting. Moreover, the recovered ground vegetation at Lettosuo most likely increased albedo and thus prevented the soil from heating as much as in 2016, resulting in a smaller Q_H over the whole summer. The clear-cut site at Lettosuo is small, but a larger scale clearcutting would probably affect local and regional climate due to changes in surface energy balance fluxes. This is because Q_H and Q_E affect the properties and growth rate of the planetary boundary layer, influencing convection and the long-range transport of heat and humidity.

5 Conclusions

Based on our ~~new and previous~~ measurements, we conclude that after clearcutting a nutrient-rich peatland forest ~~turns it into~~ is a large CO₂ source. ~~This results~~ This is due both to the decomposition of peat and logging residues and to the reduction of gross primary production from as a result of the removal of photosynthesizing trees and the decline of ground vegetation and understorey. ~~At Lettosuo, clearcutting caused an 86% decrease in the annual GPP, whereas R_{eco} decreased by 20%.~~ Removing the trees decreased transpiration, which caused the WTL to rise by 23 cm compared to the background model during July-October, which in turn likely decreased the peat decomposition rate due to the decreased volume of aerobic peat. Plant respiration also decreased as the plants were removed or destroyed. On the other hand, decomposition of logging residues ~~likely~~ increased CO₂ emissions from the site; the emissions from the residues were estimated to be 49% of the total ecosystem respiration in the first summer after clearcutting. In the second summer ~~after the clearcutting~~, ground vegetation and its primary production ~~GPP~~ recovered noticeably ~~and R_{eco} decreased.~~ On the other hand, the CO₂ emissions from the logging residues decreased as part of the residues had decomposed during the previous summer. ~~This~~ In total, these changes reduced the net CO₂ emissions of the site by 41% compared to the first summer.

The soil turned from a small CH₄ sink into a small source after clearcutting due to the WTL rise. However, the radiative forcing related to this change was insignificant compared to that due to the change in NEE. Clearcutting turned the soil into a significant substantial source of N₂O. This change produced a 100 yr GWP of about 10% of that due to the increased NEE at the site.

The mean daytime latent heat flux almost doubled from the first to the second year after clear-cutting, suggesting that the transpiration ~~through of~~ ground vegetation had significantly recovered. The recovered ground vegetation most likely also increased albedo and thus prevented the soil from heating as much as in 2016, which resulted in a smaller sensible heat flux.

Overall, the results ~~in~~of this study show that clearcutting peatland forests exerts a strong climatic warming effect through accelerated emissions of greenhouse gases. However, this study only demonstrates a short-term impact of two years, and more extensive measurements are required to gain knowledge of the long-term effects of clearcutting in peatland forests.

Appendix A: Gap-filling CO₂ data

To calculate seasonal and annual CO₂ balances, full time series are needed and thus any gaps in the CO₂ flux data need to be filled. For this, and to analyse the components of the carbon balance, we partitioned the measured CO₂ flux, i.e., net ecosystem exchange (NEE), into gross primary production (GPP) and total ecosystem respiration (R_{eco}):

$$5 \quad \text{NEE} = \text{GPP} + R_{\text{eco}} \quad (\text{A1})$$

For gap-filling, we expressed GPP as a function of irradiance (e.g., Aurela et al., 2015):

$$\text{GPP} = \frac{\alpha \times \text{PPFD} \times \text{GP}_{\text{max}}}{\alpha \times \text{PPFD} + \text{GP}_{\text{max}}}, \quad (\text{A2})$$

where PPFD is the photosynthetic photon flux density, α is the initial slope of the NEE response to PPFD, and GP_{max} is the asymptotic gross photosynthesis rate in optimal light conditions. R_{eco} was assumed to follow the Arrhenius-type model described by Lloyd and Taylor (1994):

$$10 \quad R_{\text{eco}} = R_0 \times \exp \left[E \left(\frac{1}{T_0} - \frac{1}{T_{\text{air}} - T_{\text{soil}} - T_1} \right) \right], \quad (\text{A3})$$

where R_0 is the ecosystem respiration at 10 °C, E is the temperature sensitivity of the respiration, $T_{\text{air}} - T_{\text{soil}}$ is the measured air soil temperature at 5 cm depth, $T_0 = 56.02$ K and $T_1 = 227.13$ K.

The parameters E and R_0 were defined from the night-time data ($\text{PPFD} < 20 \mu\text{mol m}^{-2} \text{s}^{-1}$) in two parts. First, the parameter E , which was allowed to vary within 200–500 K, was determined with a 15 day moving window for each day, with the minimum number of observations set to 12. If there were not enough observations within a time window, then the window size was increased by one day both in the beginning and the end until enough data were found. The resulting window size varied between 15 and 27 days, but only 22 gap-filled days had a longer window than 15 days. Next, all the E values that hit the allowed boundary values (200 and 500 K) were discarded and filled with 14 day moving medians. Finally, a 15 day moving window, similar to the one in the first part, was used to determine R_0 by using the fixed E values. Also, using the same moving window, GP_{max} and α were determined from the daytime data. However, from 1 November 2016 until 8 March 2017 with no significant CO₂ uptake, a 5 day moving average was used to fill the gaps in the measured NEE.

All the calculations and analyses were made with the Python programming language (Python Software Foundation, version 2.7, <https://www.python.org>). For the fits, the least-squares method was used through the “polyfit” function of NumPy (<http://www.numpy.org/>) library for the linear regression and the “curve_fit” function of SciPy (<http://www.scipy.org/>) library for the nonlinear fits.

Appendix B: Uncertainty analysis of NEE

The CO₂ balance obtained from EC measurements has multiple potential error sources due to instrumental, statistical and methodological uncertainties. We included the most significant, although not all, random error sources. The random error

including the statistical measurement error (E_{meas}) inherent in EC measurements and the error caused by gap filling of missing data (E_{gap}) was estimated as follows (Räsänen et al., 2017):

$$E_{\text{meas/gap}} = \sqrt{\sum_i \frac{(\text{NEE}_{i,\text{obs}} - \text{NEE}_{i,\text{mod}})^2}{n_{\text{obs/mod}}} \sqrt{n_{\text{meas/gap}}}, \quad (\text{B1})$$

where NEE_{obs} is the 30 min flux that passed all the filtering procedures and NEE_{mod} is the corresponding fitted NEE (Eqs. A1–A3), and $n_{\text{meas/gap}}$ the number of the measured or gap-filled data. This method provides a conservative estimate for E_{meas} (Aurela et al., 2002) and for E_{gap} includes the effect of random variability on the model fits.

The annual systematic error caused by the friction velocity filtering (E_{ustar}) was estimated by recalculating the annual balance with modified data sets that were screened with two different u_* limits (0.075 and 0.175 m s⁻¹). E_{ustar} was calculated as the average difference between the annual balance calculated with the optimal u_* threshold (0.125 m s⁻¹) and with the annual balances calculated with the modified u_* limits. Similarly, two additional different footprint limits (0.65 and 0.85) were adopted to estimate the annual error caused by the footprint filtering (E_{fp}).

The total uncertainty of the annual balance (E_{tot}) was calculated with the standard error propagation principle:

$$E_{\text{tot}} = \sqrt{E_{\text{meas}}^2 + E_{\text{gap}}^2 + E_{\text{ustar}}^2 + E_{\text{fp}}^2} \quad (\text{B2})$$

Appendix C: Gap-filling energy fluxes

Energy fluxes were gap-filled in several steps following the procedure described by Kowalski et al. (2003). First, the gaps in daytime Q_{H} ($Q_{\text{N}} > 0$) were filled with monthly linear regressions with net radiation. Next, the night-time ($Q_{\text{N}} < 0$) gaps in Q_{H} were replaced by the corresponding Q_{N} . Finally, the daytime gaps in Q_{E} were filled in such a way that the monthly mean energy balance closure was achieved, while during the night the missing Q_{E} data were set to 0.

Data availability. The measured flux and meteorological data are available in Zenodo (<https://zenodo.org/>) research data depository.

Competing interests. The authors declare that they have no conflict of interest.

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Table 1. Mean soil organic carbon, nitrogen, CN ratio and bulk density and their standard deviation in different soil layers determined before the harvest (n=3-33).

Layer	Soil organic carbon (%)	Soil nitrogen (%)	CN ratio	Bulk density (g cm ⁻³)
Humus	56.2 ± 2.3	1.7 ± 0.4	33.2 ± 2.3	0.005 ± 0.003
0-10 cm	55.2 ± 2.1	2.2 ± 0.2	24.9 ± 2.1	0.12 ± 0.03
10-20 cm	58.9 ± 1.6	2.5 ± 0.2	23.8 ± 1.6	0.18 ± 0.02
20-30 cm	59.1 ± 0.8	2.4 ± 0.2	24.6 ± 0.8	0.13 ± 0.03
30-40 cm	59.2 ± 0.3	2.2 ± 0.1	26.4 ± 0.3	0.13 ± 0.04

Table 12. Annual and summertime (JJA) balances of net ecosystem exchange (NEE), modelled gross primary production (GPP) and modelled total ecosystem respiration (R_{tot} / R_{eco}), and the modelled summertime sums of forest floor respiration (R_{ff}).

	Annual		Summer (JJA)	
	Apr 2016 - Mar 2017	Apr 2017 - Mar 2018	2016	2017
NEE [$\text{g CO}_2 \text{ m}^{-2}$]	3086±148	2072±124	1558±99	915±79
GPP [$\text{g CO}_2 \text{ m}^{-2}$]	659	1106	389	761
R_{eco} [$\text{g CO}_2 \text{ m}^{-2}$]	3727	3135	1928	1652
R_{ff} [$\text{g CO}_2 \text{ m}^{-2}$]	-	-	980±299	1047±113

5



Figure 1. Aerial view of the clear-cut site and the surrounding forest at Lettosuo. The red dot shows the location of the eddy covariance mast, and the red lines surround the target area ($80^{\circ} - 315^{\circ}$). The meteorological measurements were conducted at the location indicated by the orange dot, while the orange line marks the water table, soil temperature and chamber measurements (4, 8, 12 and 22.5 m from the ditch). Similar measurements of greenhouse gas fluxes, water table and soil temperature within the control site, surrounded by the green lines, are shown with a light blue line. The windroses on the left show the cumulative footprint contributions (in %) of the accepted flux data.

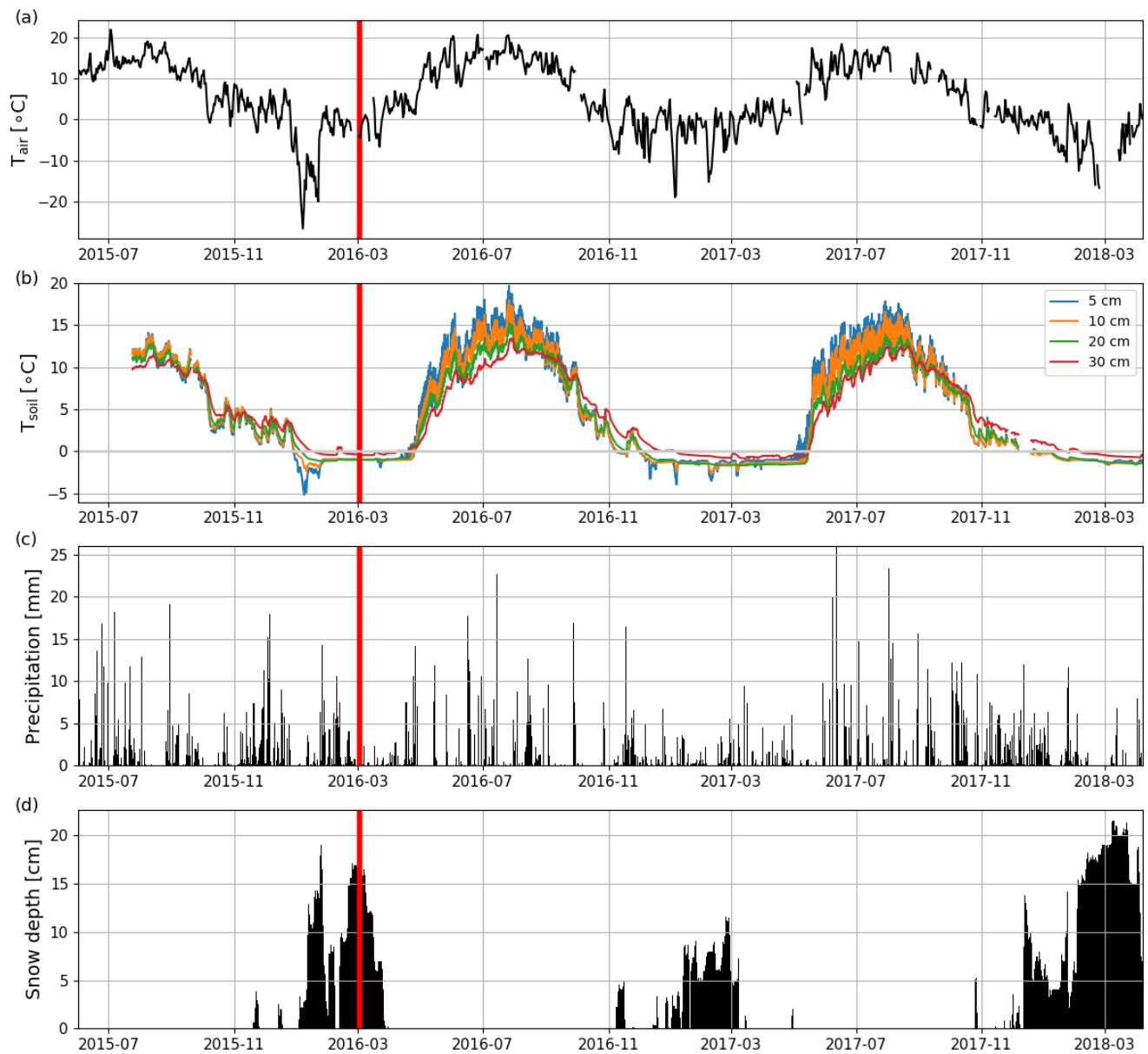


Figure 2. Time series of (a) daily mean air temperature (T_{air}) and (b) hourly mean soil temperatures at 5, 10, 20 and 30 cm depths (T_{soil}) measured at Lettosuo, and (c) daily precipitation sum and (d) daily mean snow level recorded at the Jokioinen observatory (35 km northwest of Lettosuo). The clearcutting (red vertical line) was carried out in February–

5 March 2016.

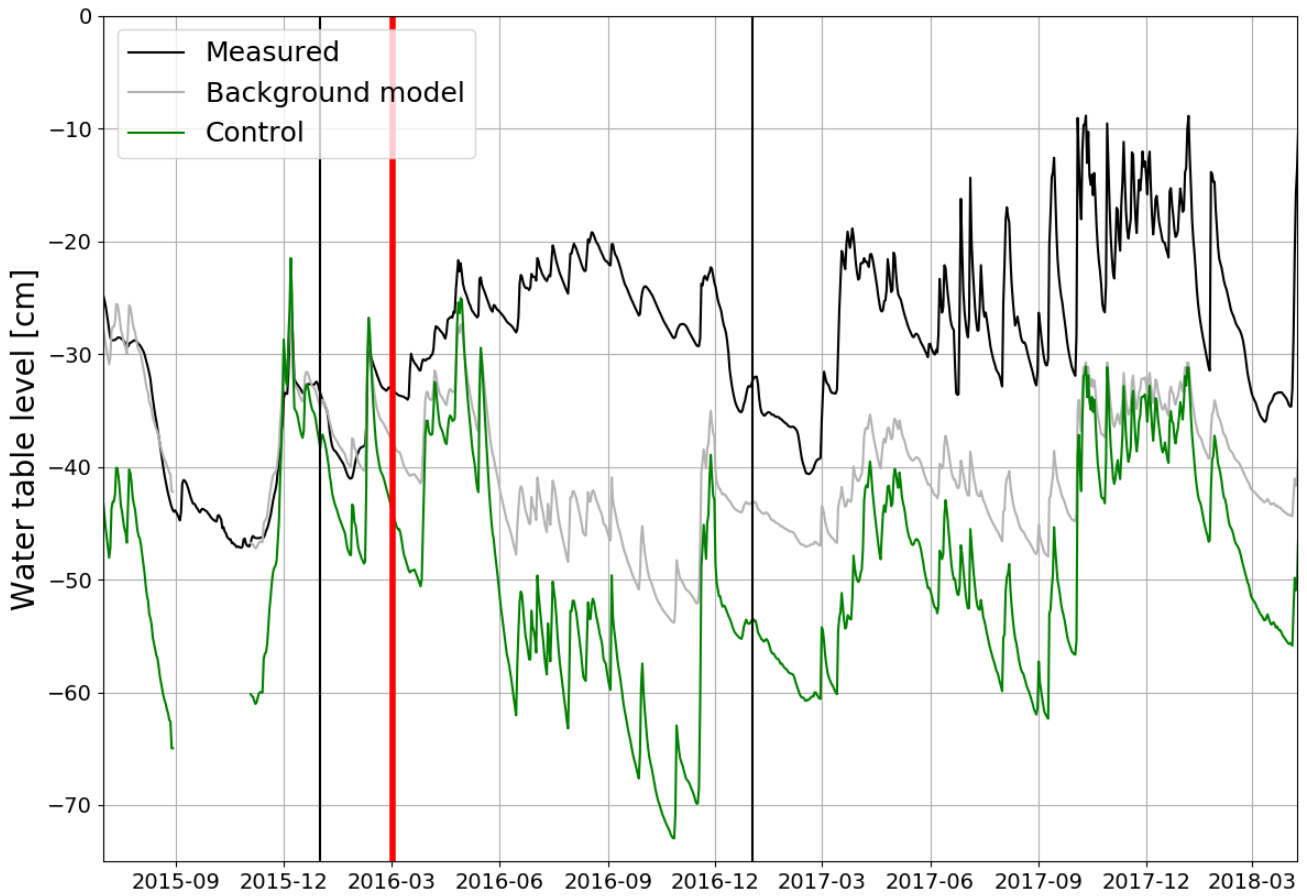


Figure 3. Mean daily water table level at the control site (measured; green) and in the clear-cut site with (measured; black line) and without (estimated; grey line) the harvesting effect averaged over all the measurement points (4, 8, 12 and 22.5 m from the ditch) from June 2015 to October 2017. The clearcutting (red vertical line) was carried out in 5 February–March 2016.

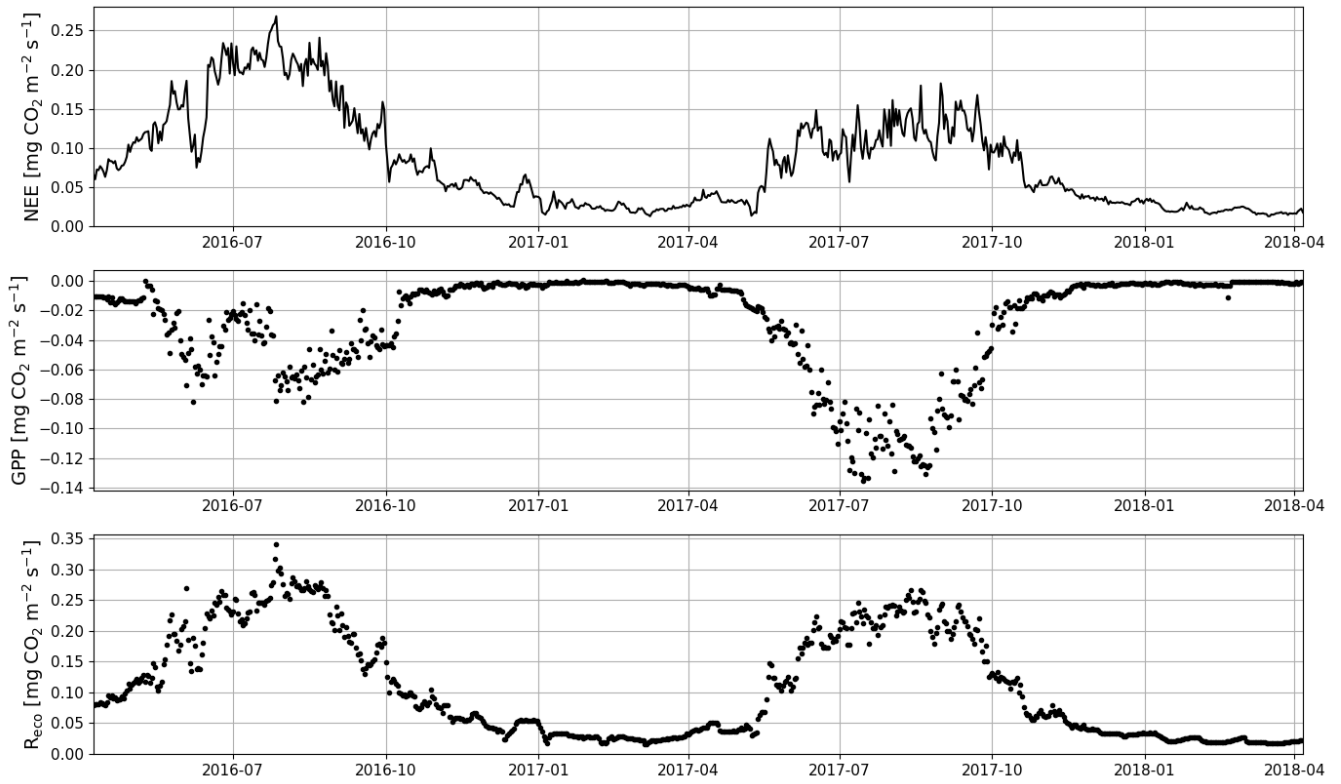


Figure 4. The gap-filled time series of daily mean net ecosystem exchange (NEE, top panel) and the corresponding modelled gross primary production (GPP, middle panel) and ecosystem respiration (R_{eco} , bottom panel) based on Eq. (A2) and Eq. (A3), respectively.

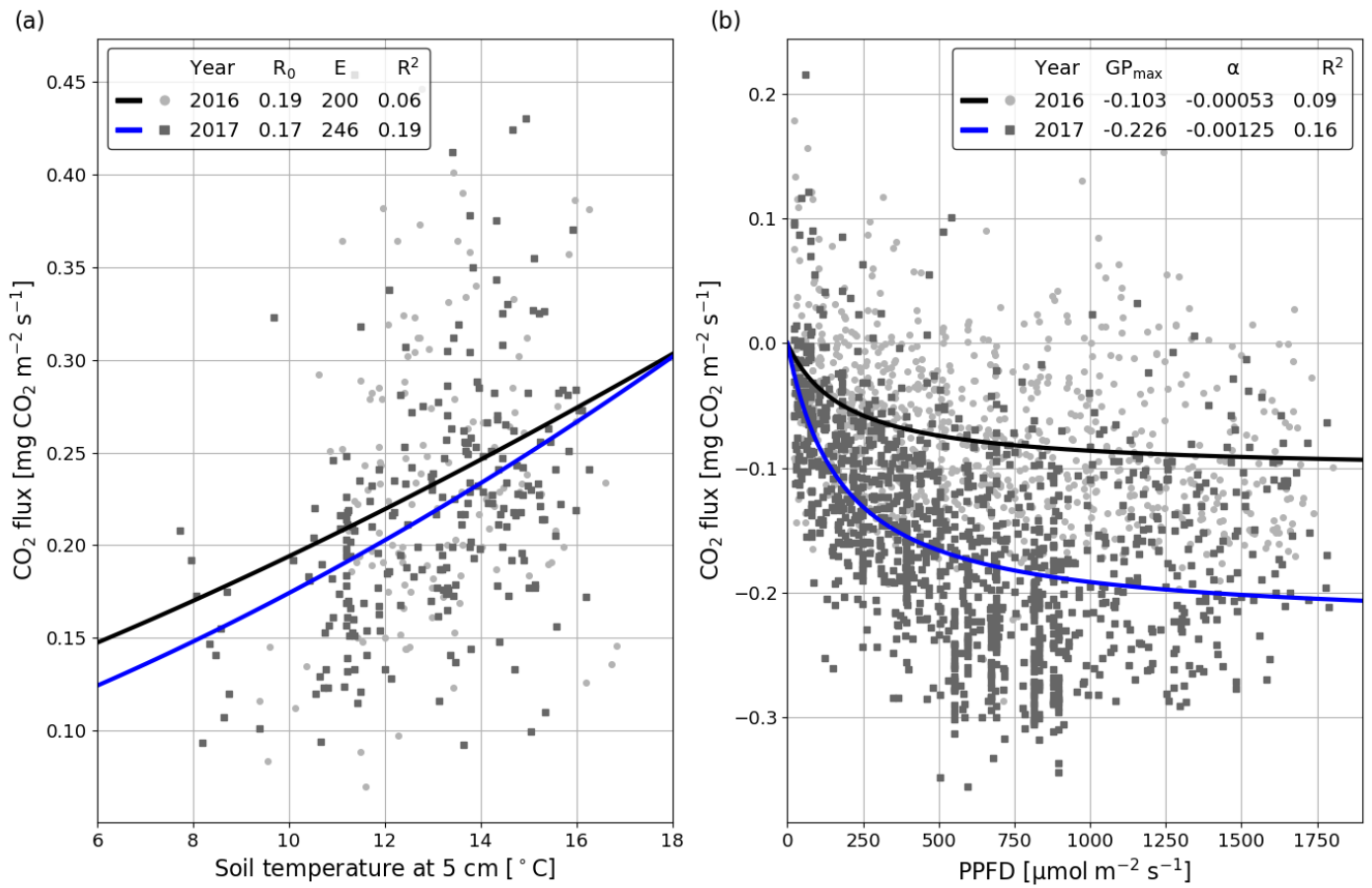


Figure 5. Temperature (a; Eq. A3) and light responses (b; Eq. A2) of 30 min CO₂ fluxes for summers (JJA) 2016 (black) and 2017 (blue). The temperature response equation was fitted to the night-time data (PPFD < 20 μmol m⁻² s⁻¹) and the light response equation to the daytime (PPFD > 20 μmol m⁻² s⁻¹) data.

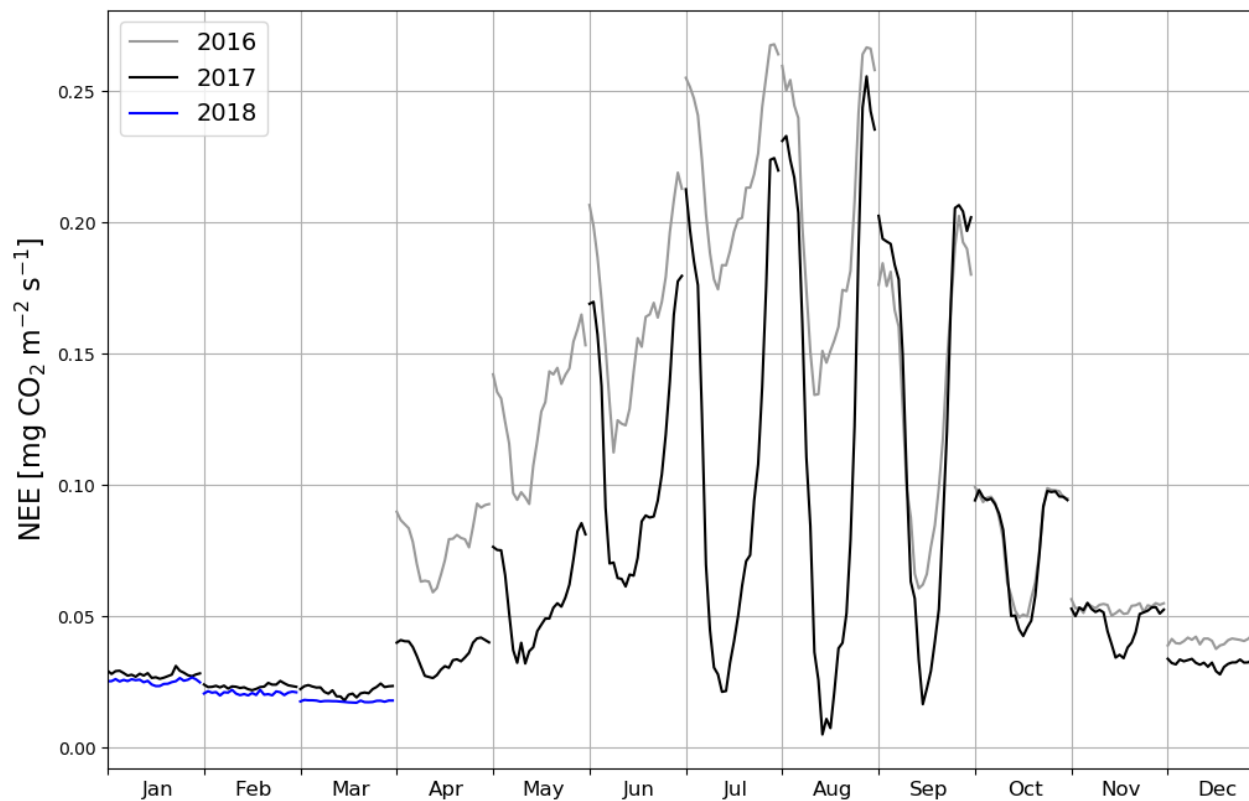


Figure 6. Monthly mean diel cycles of gap-filled net ecosystem exchange (NEE) measurements in the first (2016, grey), second (2017, black) and third (2018, blue) calendar year after the clearcutting.

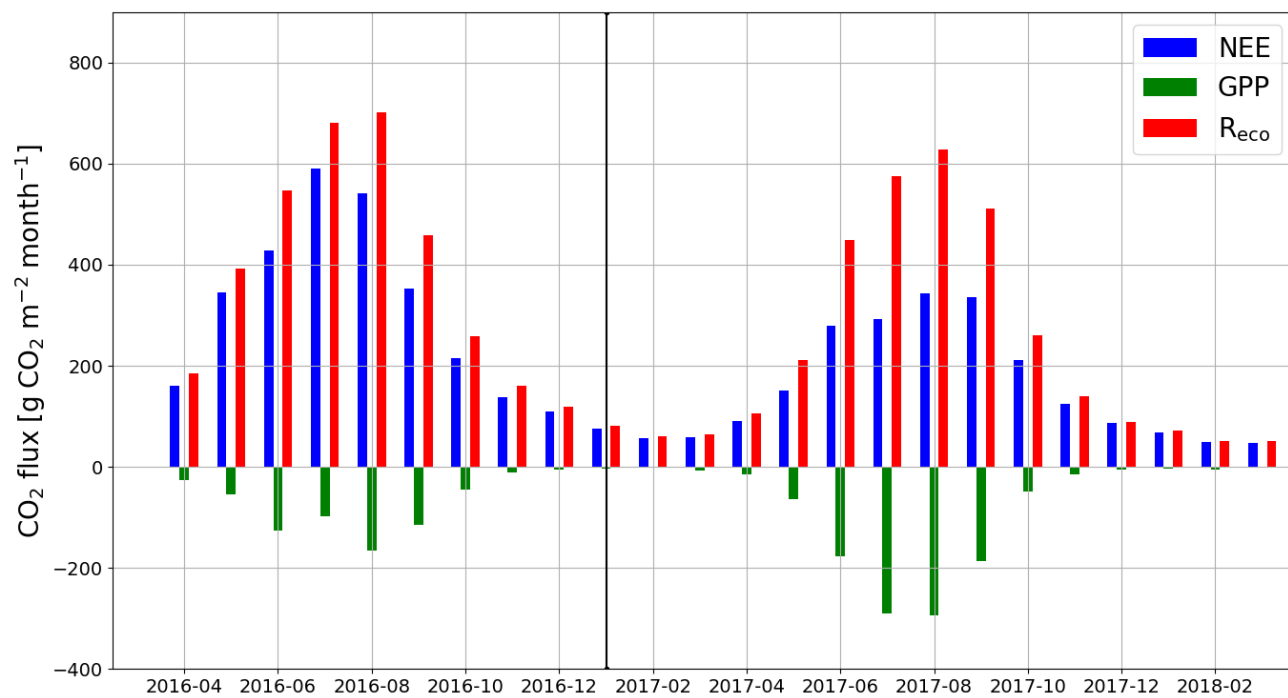


Figure 7. The monthly sums of net ecosystem exchange (NEE), gross primary production (GPP) and ecosystem respiration (R_{eco}) based on EC data in April 2016 – March 2018.

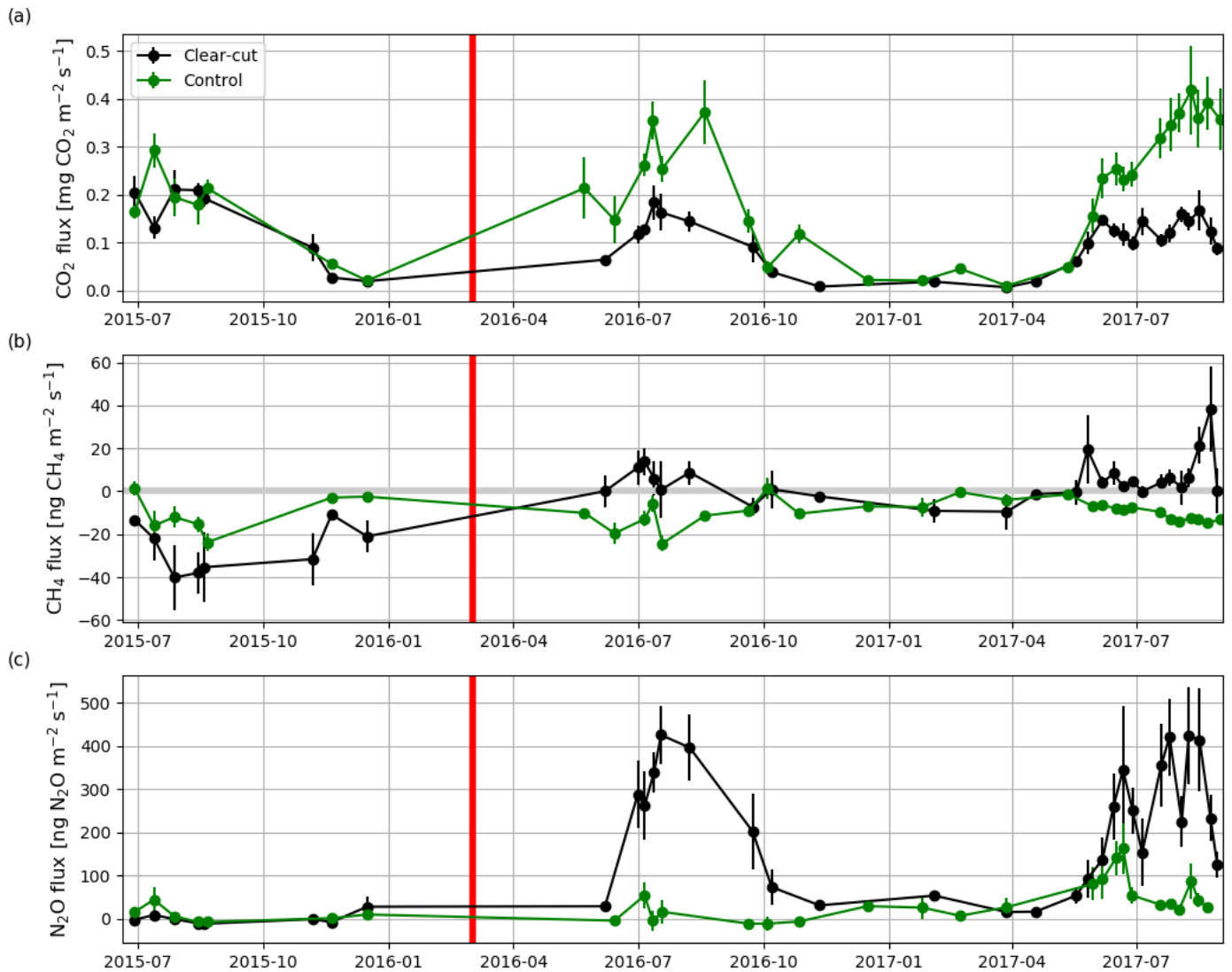


Figure 8. Hourly mean fluxes measured with manual chambers of (a) CO₂, (b) CH₄ and (c) N₂O averaged over all measurement points (4, 8, 12 and 22.5 m from the ditch) at the clear-cut (black) and control (green) sites from June 2015 to August 2017. The error bars show the standard error of the mean. The clearcutting (red vertical line) was carried out in February–March 2016.

5

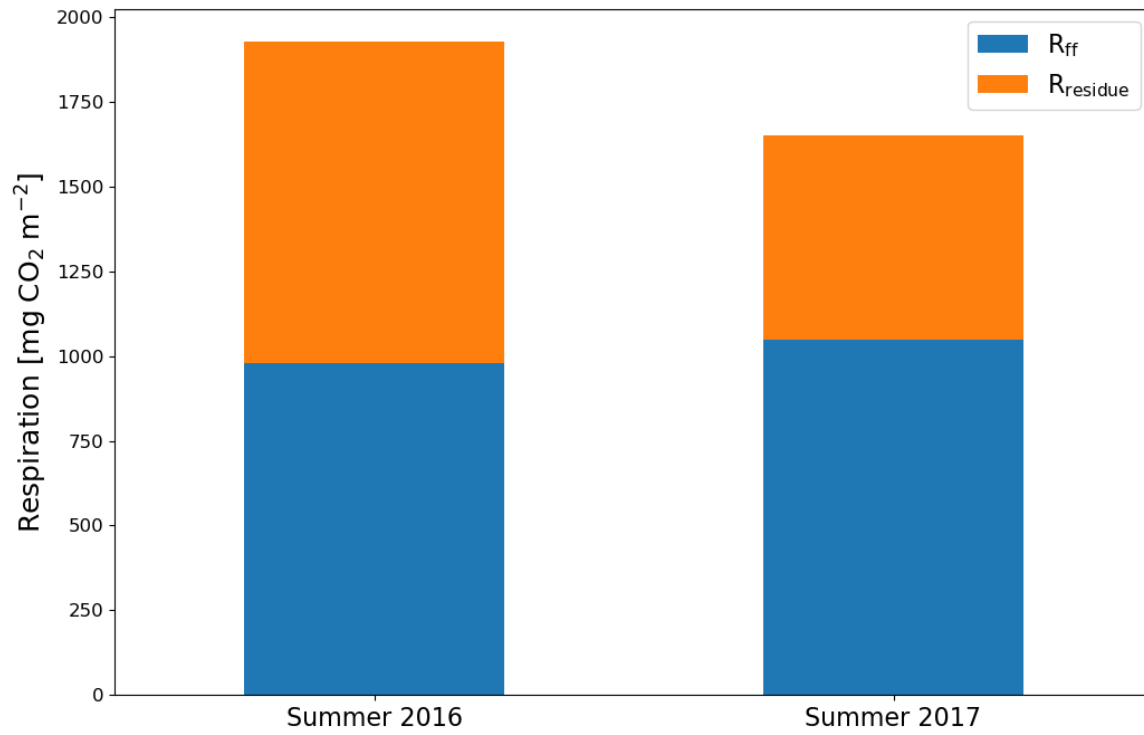


Figure 9. The division of ecosystem respiration (R_{eco} , based on EC measurements) to forest floor respiration R_{ff} (chamber measurements) and respiration of logging residues ($R_{residue} = R_{eco} - R_{ff}$) for summers 2016 and 2017.

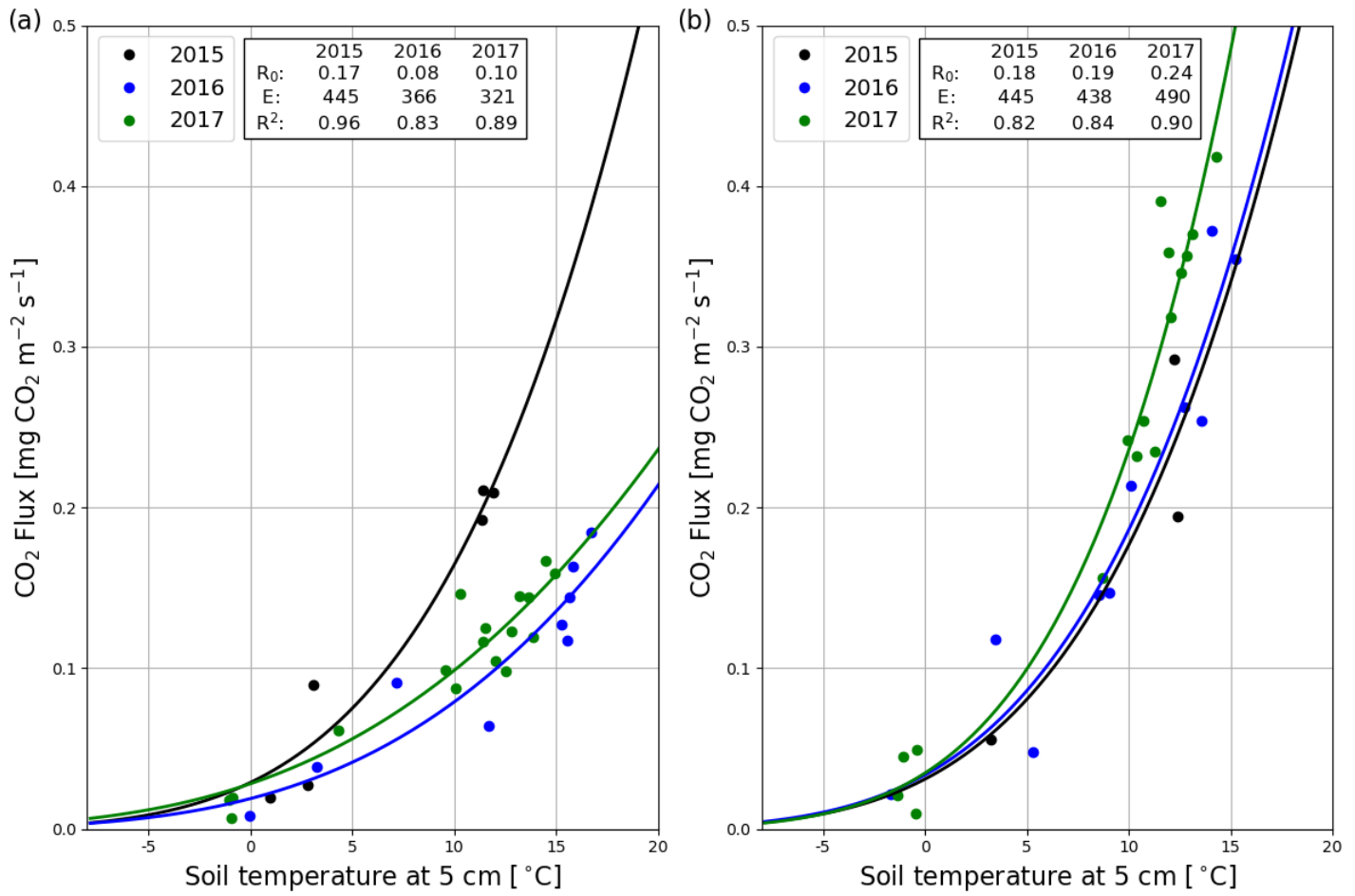


Figure 910. Temperature response (Eq. A3) of the hourly mean CO₂ fluxes measured with manual chambers at the clear-cut (a) and control (b) site in 2015 (black), 2016 (blue) and 2017 (green).

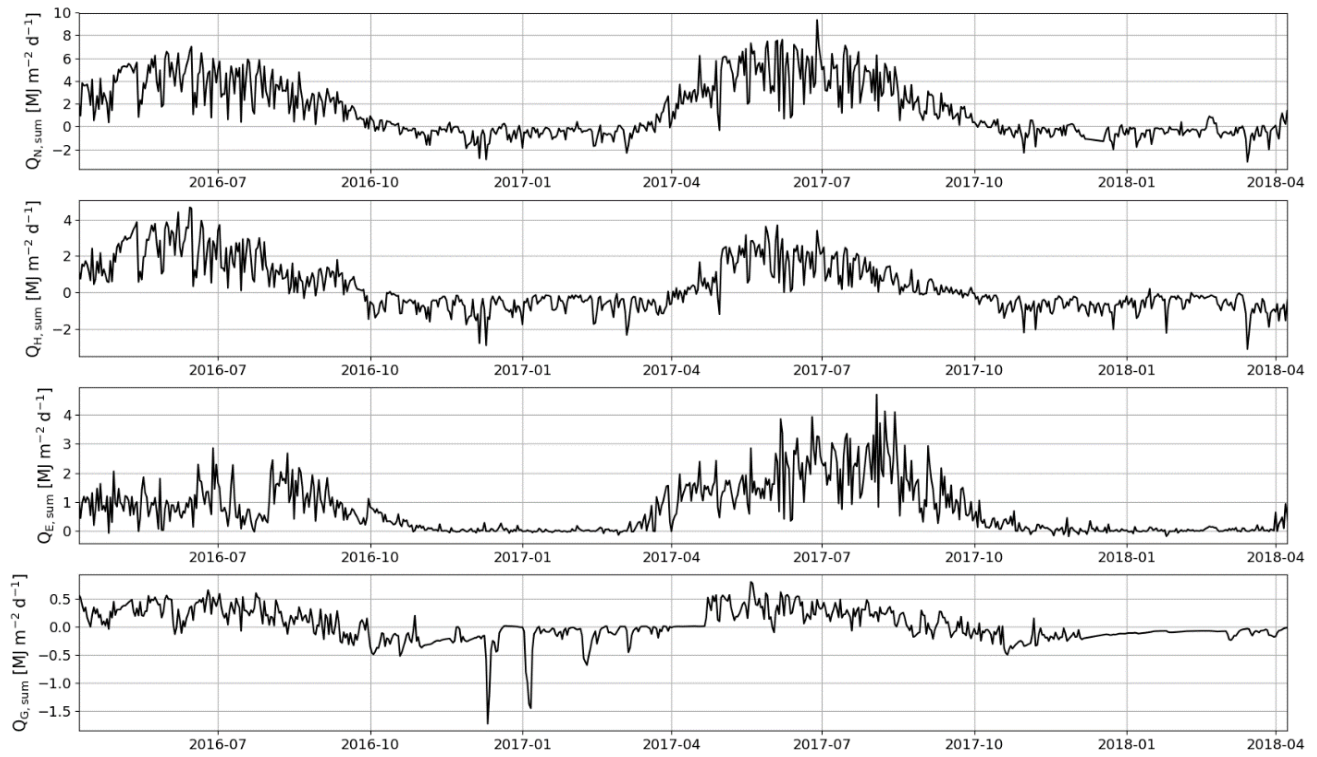
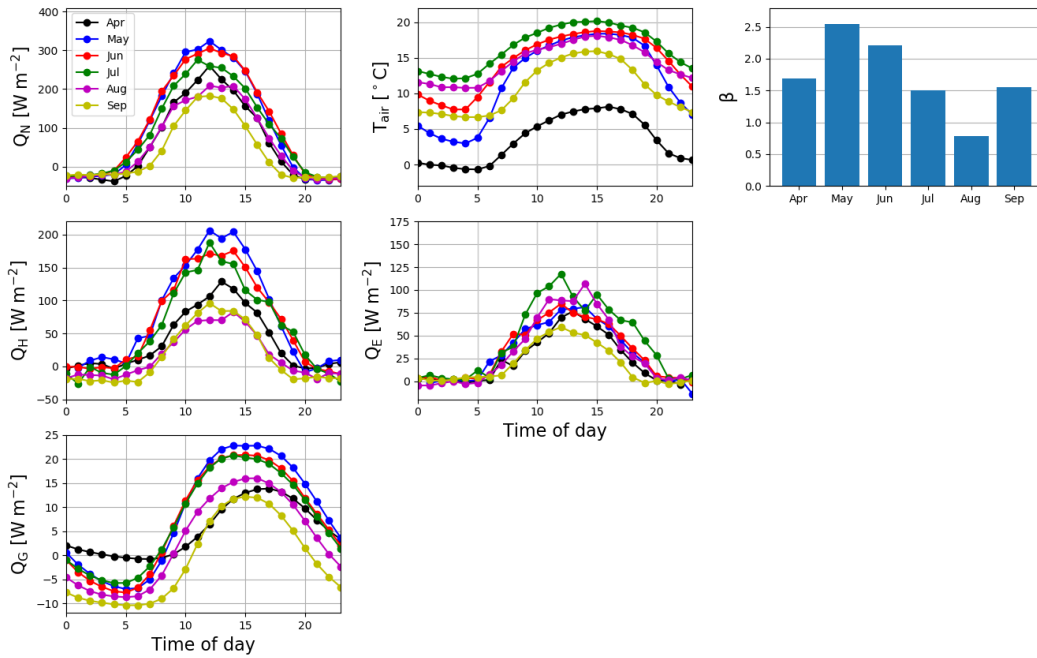


Figure 1011. Daily sums of net radiation (Q_N), sensible heat flux (Q_H), latent heat flux (Q_E) and ground heat flux (Q_G).

(a)



(b)

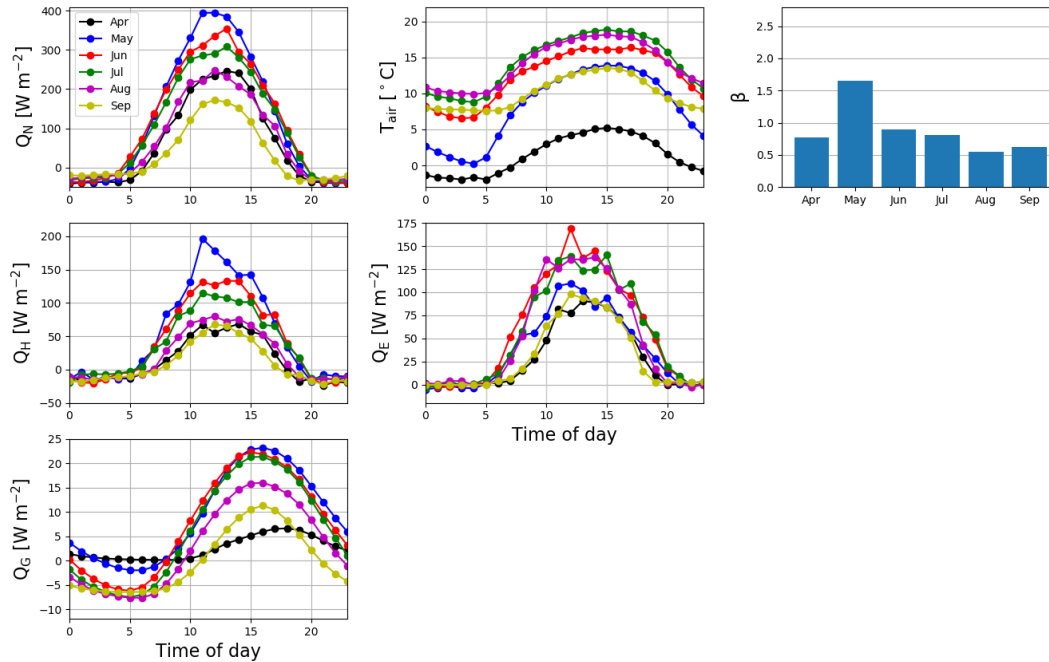


Figure 14.12. Monthly mean diel cycles of net radiation (Q_N), air temperature (T_{air}), sensible heat flux (Q_H), latent heat flux (Q_E) and ground heat flux (Q_G) and the monthly mean daytime (10:00–16:00, UTC+2) Bowen ratios (β) from April to September in 2016 (a) and 2017 (b).