Dear Andreas,

We have tried to clarify the stationarity threshold in our manuscript. It is now changed to " Flux was considered non-stationary following Foken and Wichura (1996). In this paper, we used a limit of 0.4 (e.g. 40 % difference between the sub-periods and the total averaging period)."

With kind regards,

Saara Lind

Response to comments of Referee # 1:

The study presents the CO_2 fluxes from a mineral soil in Finland cultivated with reed canary grass, a promising energy crop in northern Europe. The study is topical in the context of increasing interest of bioenergy to combat climate change. However, the study does not compare the energy crop cultivation with current/other land use options, and thus provides only little information for policy intervention. The study uses a state of art method to measure CO_2 flux and describes it well in the manuscript. The results are also well presented but the discussion is not very impressive (see the comments below). I suggest publishing these papers in Biogeoscience but the authors need to address these suggestions and corrections:

We thank Anonymous Referee #1 for helpful comments and suggestions to improve this manuscript. We hope that the revised manuscript is satisfactorily modified. Below you will find the comments from the Referee #1 followed by our responses which are marked in blue.

Major comments/suggestions

1. Finland has been leading country in terms of RCG cultivation for bioenergy production in northern Europe. Please provide the current status (area and cultivation and if it is increasing or decreasing; primary use of biomass eg. Combustion or biogas) of RCG cultivation in Finland.

During the recent years, the reed canary grass production has decreased in Finland due to technical problems associated with the burning process. As a result, the land area under reed canary grass production has decreased to 5839 ha in 2014. Although the current area coverage is low, the potential to produce reed canary grass in Finland still exists as there is an interest on using the biomass on e.g. biogas production. For the future policy making, the knowledge on climatic impacts of reed canary grass cultivation on different soil types is still needed.

Added to introduction "*Cultivation of RCG has been popular in Finland since the mid-1990s and at the peak approximately 19 000 ha (2007 and 2008) were cultivated with RCG. However, owing to technical difficulties with the burning of the RCG biomass in combustion plants, the scope of RCG as a source of biomass bioenergy has declined in the last few years. In 2014, the average cultivation area was around 6000 ha. Nevertheless, the scope for RCG as a source of liquid biofuel, a digestate in biogas plants, oil spill absorption and a buffer crop between terrestrial and aquatic landscape is wide (Pasila and Kymäläinen, 2000; Partala et al., 2001; Powlson et al., 2005; Kandel et al., 2013b)*".

2. In discussion, the paper compares the CO2 fluxes results with many different types of biomass crops cultivated in different ecological zones which I think is not so interesting and useful. For example, comparing CO2 fluxes from RCG cultivation in Finland with hybrid poplar in Canada or Switchgrass in USA is neither useful to validate the results nor for policy intervention. It would be more useful to compare the results with previous studies in Finland which have measured CO2 fluxes from mineral soil with arable crop cultivation. Such comparisons would provide idea for land use change to bioenergy systems from arable cropping systems.

â A c The paper has also particular focus in comparing CO2 fluxes from mineral soil and cutaway peatland. The cutaway peatland is a margin soil and we can expect very small biomass production, and thus GPP and TER from such poor soil. Nevertheless, these types of soil can be useful to cultivate bioenergy crops even the biomass production is small. As oppose to the cutaway peatlands, there are many options to cultivate in the arable mineral soil. Therefore, as mentioned earlier**,** a comparison with current crop cultivation in mineral soil and biomass crop cultivation would be much more interesting. It would be best if the study had also included parallel CO2 flux measurement with arable cropping system but comparing results from previous studies will also be useful to understand environmental impact before changing land use to biomass crop cultivation.

The referee is correct on bringing up challenges with the data comparison. To our knowledge, there are no published data on CO_2 exchange of reed canary grass cultivation on mineral soil site. That is why we compared the results to that of reed canary grass on organic soil. In order to give the reader, and policy makers, a better understanding how our results fit scale of published CO_2 exchange results, we included other CO2 exchange studies done on bioenergy crops/forests to the comparison. The references used in our paper, report annual CO_2 exchange which were obtained using eddy covariance method and the sites were mineral soils. To our understanding, this type of data on crops or grasses in Finland is not available.

We also agree with the referee's suggestion that a concurrent measurements of different crops would have been interesting. However, due to the requirements on the eddy covariance method, we were not able to do it.

3. The maximum crop yield in winter is about 11 and 16 ton DM ha-1 in 2010 and 2011, respectively. However, it seems the senescence and dispersal loss of biomass is quite high as the spring harvest only yielded about 6.2 and 6.6 ton DM ha-1 in 2010 and 2011, respectively. Although the biomass quality can be improved with spring harvest, but it may not be an economically better option as 44 and 58% of total aboveground biomass (the difference between autumn and spring harvests) was lost in spring harvest. It is surprising to see the large dispersal loss as the leaf may have only about 20% of total biomass after the growth season in autumn (Kandel et al., 2013. Bioresource Technology, 130, 659–666). Probably the concentration of minerals in biomass does not change considerably when the growth of the crop stops. If that is the case, harvesting very late in spring may just contribute to reduce harvestable biomass yield. More discussion is needed on autumn and spring harvest time as the difference in biomass removal in autumn and spring harvest is very large which can have large effect in CO2 fluxes. Probably, much higher TER can be expected in coming years if biomass is harvested in spring as major portion of biomass is left in the field.

We agree with the referee with the difference in the autumn and spring harvest. However, the values are not directly comparable as there are difference in the sampling scale and sampling method which have an effect on the results. The autumn collected biomass samples was sampled from a 20 * 20 cm^2 area from three locations within the field. This type of small scale sampling is prone to the variation in the plant growth and density within the field. Also the sampling was done by manually clipping the individual plants as close to the soil surface as possible and collecting them with care. The spring harvested yield is collected with a field scale machinery following the common practice of the reed canary grass biomass harvesting in Finland. A biomass loss between 20 to 30 % has been reported when using field scale harvesting (Pahkala et al 2005. Maa- ja elintarviketalouden tutkimuskeskus, Jokioinen, 2005 (report, in finnish only)). It has been reported earlier that the total dry matter harvested in the spring time has been higher than that in autumn time when same method of harvesting was used (Pahkala and Pihala, 2000, Industrial Crops and Products, 11: 119–128). In our study, the difference between autumn and spring harvest is not 44 to 58 % for 2010 and 2011, respectively, but less than that if the same method would have been applied.

It is true that the leftover biomass at the site will have an effect on the TER. In our study, we did not determine how much of the biomass was left to the field after the harvesting. And based on our study, we cannot draw conclusions whether there would be difference in the leftover biomass if the harvesting was done in the autumn or in the spring.

We think that the timing of the harvesting should be selected based on the use of the biomass. In the spring time harvest the biomass quality will be different when compared to that of autumn harvest and also the ratio of stem to leaves in the harvested biomass will increase in the spring than in the autumn (Pahkala and Pihala, 2000, Industrial Crops and Products, 11: 119–128). In our case, the crop was produced for biomass burning and we followed the cultivation practice that aims to produce biomass with best possible quality for the burning. As we mention in our paper, the spring harvested biomass has been found to be better suited for burning when compared with the autumn harvesting.

The methodological differences of biomass collection and the reason for spring harvesting were clarified accordingly in the manuscript.

4. Although it is mentioned that a detailed LCA is out of the scope of this paper, including biomass removal (calculation of net ecosystem carbon balance) would be interesting to judge the sustainability of the ecosystem. Also, I suggest calculating fossil fuel displacement by the harvested biomass to get a more complete atmospheric impact.

We agree with the referee that these steps would increase the value of the paper. We have chosen to include the CO_2 exchange aspects in this paper as we are also working on a complete LCA analysis of the reed canary grass cultivation on mineral soil in a subsequent paper.

5. There is no mention about energy balance in title, abstract and introduction of the manuscript. It seems the objective of manuscript is nothing to do with energy balance. Therefore, I suggest either to remove energy balance part or to describe more in introduction why it was important to measure. It is used for calculation of water use efficiency of RCG but that is also not a main objective of the paper.

It is true that the energy balance is briefly handled in the manuscript and it is not mentioned in the title, abstract or introduction.

We use the energy components in energy balance closure determination to show how successful the measurements were and also to determine the systematic error in the measurements. It is also important to show the raw data behind the results upon which we based our conclusions. Therefore, we have increased the information on the eddy covariance method in the manuscript.

Minor comments:

Abstract, Line 16. The study period is not clearly defined in abstract. Therefore, either define it clearly or delete that sentence.

The time period in the abstract was defined clearly and the sentence is written now:
"*Throughout the study period from July 2009 until the end of 2011, cumulative NEE was -575 g C* m^{-2}."

Page 2, Line 10: Cutaway peatland probably do not emit large amount of CO2 from when the emission is compared with arable organic and mineral soils. A recent paper by Vanselow-Algan et al. (Biogeosciences, 12, 4361–4371, 2015) has shown very small CO2 emissions from cutaway peatland compared to other types of organic soil. Does the Kasimir-Klemedtsson et al., 1997 cited here mentions high CO2 fluxes from cutaway peatlands? Here, TER in this paper is much higher compared to Shurpali et al. 2009 which was probably contributed by high biomass yield in mineral soil. I wonder if it is possible to do estimate SR from both sites and compare SR results. That would be interesting as a major portion of TER may have come from the plant biomass and diluted the effect of soil types in CO2 fluxes.

In a review by Maljanen et al. 2010 (Biogeosciences, 7: 2711–2738) the average net CO_2 exchange of cutaway peatland in Nordic countries was estimated to be around 200 g C m^{-2} a^{-1}. The findings of Vanselow-Algan et al. 2015 (Biogeosciences, 12: 4361–4371) on the active cut-way peatland were equal with this. The net Co2 exchange of a cultivated organic soils range from 80 to 820 g C m^{-2} a^{-1} and of a previously cultivated but now abandoned sites from 110 to 810 g C m^{-2} a^{-1} (Maljanen et al. 2010). Based on this, the CO_2 emission is lower from the cut-away areas than cultivation sites. The Kasimir-Klemedtsson et al. 1997 (Soil Use and Management, 13: 245-250) are referring to emissions due to drainage of the peatlands and the decomposition of leftover peat.

It is correct, the TER in the present paper is affected by the higher biomass yield in the mineral soil. This is a topic for another paper and thus out of scope of the present one.

Page 2, Life 26: Change quantity to quantify

Quantity changed to "quantify"

Page 4, Line 8: It is not clear why the May-September precipitation was mentioned with focus. In the manuscript, it is not mentioned earlier that it was a growing period of RCG in Finland.

Length of the growing season varies between the years and it is not fixed to May-September period. The lengths of the growing seasons are given in the results section. The precipitation of May-September was given, in addition to the annual value, as it is a fixed time period and allows us to easily compare the long-term mean precipitation to that what we measured during our study.

Page 4, Line 15: It seems there was large difference in C concentration in soil. Was the land in the transition between mineral and organic soil? If so, was there a trend with higher TER fluxes measured from footprint which has higher soil C concentration?

The section in materials and methods considering the soil characteristics has been now properly checked and updated. Also, as the soil sampling did not cover the entire field (only three locations), we would have not be able to divide the flux data based on the soil characteristics.

Page 5, Line 14: Why was it discarded? This information is repeated in line 19, page 6

The presence of the cabin interferes the wind in the discarded direction. This part was clarified in the manuscript:

"Except for the wind sector from 85° to 130° downwind of the instrument cabin, all wind directions were acceptable because no other obstacles were present and the sonic anemometer in use had an omnidirectional geometry.".

Repetition of the information in line 19, page 6 was removed.

Page 9, Line 12: The results from fresh weight are not presented later in result section. Therefore, it is better to delete this sentence as fresh weight yield is not so interesting information in this manuscript. If the result is included, then it is important to mention why moisture content is an important quality for biomass conversion especially in spring harvest for combustion.

This sentence was removed from the manuscript.

Page 10, Line 9: Was this temperature relation not fitting well for gap filling purpose?

We have compared the results from this site with those from an earlier study by our group. To allow for a better comparison, and to make the analyses consistent, we used this relationship.

Page 11, Line 6: in the end of the sentence add 'than the long term mean'.

Added "*than the long-term mean*"

Page 11, line 22-26: Probably the relation between GPP and ER and WUE does not fit under this subheading.

ET is related to seasonal climate and plant growth. As WUE is calculated from ET and GPP, it was natural for us to include the WUE results together with ET.

Page 12, Line 4: This sentence seems incomplete. Is it 9 weeks?

Added "weeks"

Page 12 (Fig 3): Some scattered points in winter are showing up to 10 to -10 micromole CO2 m-2 s-1. Probably these points represents spikes as there is very less probability of having such large photosynthesis and respiration in winter in Finland.

The raw data was thoroughly checked and flagged prior to the calculations. In spite of this, some scatter was left in the data. However, there was no reason to remove those data points.

Page 14, Line 11. Place a full stop after respectively.

Added "."

Page 19, line 21. Earlier studies have shown RCG can have maximum yield potential in 2nd to 3rd year of establishment. Therefore, a decline is more likely with ageing stand of RCG.

It is true that the yields during the following years would be similar with the second harvest. In multi-year study carried out in Finland, the spring harvested yields were increasing significantly from first to second harvest after which the yields remained fairly constant for the next six years (Saijonkari-Pahkala, 2001, Non-wood plants as raw material for pulp and paper, PhD Thesis). What is interesting in the present study is that the root biomass was low. We are expecting an increase in the root biomass as the crop ages. In theory, more developed root system should enhance the viability of the crop and, therefore, lead to higher aboveground biomass yields.

Page 20, Line 19-20. Previously it has been mentioned RCG has very shallow roots mainly concentrated on 0-15 cm. Here it is written that the plants can take water from deeper layers to cope drought stress. This is contradictory claim as the short rooted crops can be highly affected by drought.

The shallow root system where 95 % of the roots were concentrated on the 0-15 cm layer was reported for the comparison site on organic soil. In the present study, 70-80 % of the root was in 0-10 layer. In the present study, it is possible that the roots reach deeper layers in the soil. Also the water movement and availability is different between the soil types: water is easier available to the plants in mineral soils. This is one of the strong points of this comparison study showcasing the differences in the two study sites.

Response to comments of Referee # 2:

The manuscript focusses on the potential climate mitigation of reed canary grass (RCG), and is novel in the fact that it deals with a RCG cultivated in a mineral soil, while most of the existing studies reported in the scientific literature concern RCG in organic soils, e.g. for restauration of drained organic soil. The CO2 balance of the RCG is computed combining eddy covariance (EC) methodology and LAI analyses, and then compared with a reference study of a RCG on organic soil. The manuscript is well written and interesting. However, minor revisions are required in my opinion in order to be acceptable for publication on BG, especially in the discussion section that needs to be extended.

We thank Anonymous Referee #2 for helpful comments and suggestions to improve this manuscript. We hope that the revised manuscript is satisfactorily modified. Below you will find the comments from the Referee #2 followed by our responses which are marked in blue.

EC methodology is a well consolidated technique to calculate fluxes of trace gases with the atmosphere, and so to extrapolate budgets of these gases in the studied ecosystems. However, this technique alone cannot provide a fully comprehensive budget, as non-turbulent fluxes escape this computation, like off-site emissions involved in the management and the C exported in biomass. Furthermore the study only focusses on CO2 fluxes: it is well known that other fluxes than CO2 have a high importance in the evaluation of the warming mitigation potential of cultivation. That said, the interest of the manuscript is in the fact that this type of cultivation is not well studied in mineral soils, and that a CO2 balance can provide a clear message on the biological CO2 exchanges of RCG. This is why I found crucial the comparison with a reference study on organic soil, which is a more explored field. Comparing the same factors in the evaluation of the cultivation increases the robustness of the message the authors wish to give. This aspect seems to be treated more accurately in the discussion section, but not having the right importance in the Introduction. The authors declare they aim to characterize the NEE of the site, which would not be enough. I suggest the authors to clearly state and underline in the manuscript that their objectives include the comparison of the study site with a reference study, especially in the introduction and the abstract. All the main passages of the manuscript should deal with this comparison, in particular analogies and differences between the sites should be described not only for what concerns the results, but also about general site characteristics (climate, management, use…)

We are currently describing the comparison between the mineral soil site and the organic soil site in the abstract and introduction. Also, a separate section covering the general background of the organic soil site was added to the materials and methods.

The comparison with other bioenergy crops, and to cropland in general (especially the crop types that used to be cultivated before the installation of RCG) should also be strengthened in the discussion and referred to also in the conclusion section, as the reference site was evaluated not as a bioenergy crop per se, but as a restauration of drained organic soil, with an expected high respiration rate. The studied site of the manuscript was instead installed in cropland, and the simple fact that the CO2 balance is negative in the three years is not enough to evaluate whether or not the RCG plantation is “environmental friendly”, as stated in the conclusions.

We agree with the referee on the limited data comparison. However, to our knowledge, there are no published eddy covariance data on CO_2 exchange of reed canary grass cultivation on mineral soil site. Also, to our knowledge, there are no annual CO_2 exchange data measured using eddy covariance on other crops on mineral soil in Finland nor in other Nordic countries. This limits our options with the data comparison in the discussion.

We have mentioned in the conclusion, that from the CO2 exchange point of view, the RCG cultivation is environmentally friendly and that only through a full LCA (including other GHG emissions and management costs and biomass burning) we are able conclude more on the performance of this crop. Also, we do not try estimate what would be the GHG balance of the site if it was cultivated with another crop and if some of the emissions would be possible to avoid with RCG cultivation.

From a technical viewpoint, the structure of the manuscript sometimes suffers of some lacks, especially in the discussion section: while some aspects are very well detailed, some others seem to have been excluded, while they might have an importance in explaining the observed results. The differences between the study site and the reference site are not always discussed in the proper manner, as it is assumed that they are due only to the different soil type, while it is necessary to add some considerations on other possible reasons. Also, some operations that are correctly reported in the material and method section, and that might have an influence on the studied aspects, are not considered at all in the discussion section (e.g. the fact that the aboveground biomass is left in the field during the first year, or the use of herbicide). I suggest to add some considerations in the discussion section in that. Another weakness of the study concerns the fact that conclusions are sometimes too generalized: the study site cannot be considered representative of all the RCG in mineral sites. Also, differences between the study site and other studies on RCG are sometimes too easily attributed to the difference on the soil type (mineral/organic), while other site characteristics (climate, type of management, etc.) should be taken into account. I suggest deepening the parts of the discussion where differences with other studies are illustrated, including clear statements on other possible reasons that might explain the found differences.

The discussion section was revised accordingly.

As a last general comment I underline the fact that EC methodology is for its complexity subject to several sources of uncertainty. I understand that for the same reason is hard to quantify this uncertainty, and there is not a standard procedure. However, as the manuscript is mainly based on EC, uncertainty quantification is recommended based on existing papers (e.g. Hollinger and Richardson, 2005, Papale et al., 2006). In my opinion, after having implemented the suggested changes and discussion parts, the manuscript will be more robust and adapt for publication in BG.

We agree with the referee that reporting uncertainties with the results is always a good practice. However, it is also important to make a clear distinction between random and systematic uncertainties, since the relative significance of random uncertainties diminishes with integrating, i.e. their effect on the uncertainty of annual balances is most likely negligible, whereas systematic uncertainties are not affected by averaging or integrating processes.

The random uncertainties of EC fluxes stem mainly from one-point sampling of the flux, in other words from the fact that a finite sample of a stochastic process (turbulence) is used to calculate the flux (e.g. Lenschow et al., 1994). The random errors of 30-min averaged EC fluxes are commonly within few tens of percentages of the flux (e.g. Mauder et al., 2013).

The random error in the present study was determined and added "*The random errors of 30-min averaged and quality controlled CO_2 fluxes were determined following Vickers and Mahrt, 1997). The random error was 14%, 16% and 14% during July-September 2009, May-September 2010 and May-September 2011, respectively.*"

The systematic errors are primarily caused by 1) the limitations of the EC measurements (e.g. inadequate high frequency response of instruments) or 2) unmet assumptions and methodological challenges (Richardson et al., 2012). The first source of systematic uncertainty was already minimized by carefully processing the EC data (see Sect. 2.2 in the manuscript). However, the second source of systematic uncertainty is more difficult to assess, since that requires estimation of e.g. advective fluxes. This is a challenging task (e.g. Feigenwinter et al., 2008) and out of the scope of this paper. Nevertheless, the energy balance closure (EBC) can be regarded as an estimate of the flux systematic errors (Mauder et al., 2013) and an analysis of the EBC is already included in the manuscript. The section on EBC was revised and modified accordingly.

Specific comments:

Abstract: the abstract is synthetic and concise; however I suggest adding a sentence on the comparison with the reference study, instead of only reporting the aim of characterising NEE.

Changed to "*Carbon balance and its regulatory factors were compared to the published results of a comparison site on drained organic soil cultivated with RCG in the same climate. On this mineral soil site, the RCG had higher capacity to take up CO_2 from the atmosphere than on the comparison site*."

Introduction: In this section it should be clearly indicated the aim of basing the evaluation of the performance of the RCG cultivation on mineral soil on the comparison with studies performed on organic soil.

Added *"Additionally, we aim to compare our findings from the mineral soil site to the published data on of a RCG cultivation system on a drained organic soil (referred to hereafter as comparison site) in the same climate region."*

Material and methods: this section shortly describes the site and provides some details on the micrometeorological and companion measurements, and also in the formulas used for the data analysis. However, as the CO2 balance is mainly based on the EC technique, a deeper description of the steps used to get calculated fluxes is needed: how did you select the ustar threshold? Which model(s) did you use for footprint calculation? Also other methods should be more carefully described, e.g. soil analyses.

Added

1. paragraph "*2.5 Comparison site characteristics*"
2. for u*star "*We plotted the night-time NEE with u* and found no correlation between the two. Nevertheless, a default u* filter of 0.1 m s^{-1} was used.*"
3. for footprint model "*Footprints were calculated for each 30-min averaging period with the analytical footprint model developed by Kormann and Meixner (2001). The model is valid within the surface layer and it utilizes power law profiles for solving the footprint sizes analytically in a wide range of atmospheric stabilities. Based on the analysis, 80% of the flux was found to originate from within 130 m radius from the mast*."
4. methods for soil analyses

Results: this section is complete and detailed. Results of micrometeorological measurements, climatic pattern, trends and drivers are carefully illustrated, and the CO2 annual budget is reported at last.

Discussion: This section is well structured. However, some discussions need to be added to reach a higher degree of completeness and robustness of the manuscript. In particular, it would be cited the fact that alternative options exist for peatland restauration, with a brief discussion on expected differences with RCG.

It is true, that there are many after-use options for cutaway peatlands. However, the primary study site the present paper focuses on a mineral soil and thus a discussion on peatland restoration is outside the scope of this manuscript.

Also, authors should keep in mind that a better performance of the studied RCG as compared to the reference study from the CO2 balance view point is not enough to give a positive evaluation of it: this is related to the fact that 1. other fluxes exist that are relevant for climate mitigation (not only CO2 and not only biological fluxes); and 2. to the fact that the reference site substituted a drained organic soil with likely strong positive NEE, while the RCG of this study was installed in a crop area. The discussion on the first point should be extended, and added for the second point, including comparison with CO2 balances of crop systems similar to the ones present at the site before the seeding of the RCG (as found in the scientific literature).

In the present paper, we aim to report the annual NEE of RGC cultivation on mineral soil and to determine the controlling factors of the NEE. Also we aim to compare the findings on mineral soil to that of RCG on organic soil, from a comparative analysis point of view. We do not aim to determine whether CO_2 emissions were substituted while RCG was cultivated on mineral or on organic soil. Currently we are not even able to do that as, to our knowledge, there are no annual CO_2 measurements done with eddy covariance method on crops on mineral soil in Finland or in similar ecosystems. Our original use of the term “reference site” for the organic soil site is wrong in the present paper as it has different meaning on the LCA studies. We have replaced the “reference site” with “*comparison site*” in the manuscript in order to clarify the purpose of the comparison in our work.

Moreover, when discussing the differences between study site and reference site, other reasons than soil type should be discussed: for example, different climatic patterns, or the fact that the biomass was left in the field in the first year of cultivation of the study site, especially when discussing respiration patterns. Please add some comments on that to increase the robustness of this section.

The discussion section was revised accordingly.

Also some discussions are missing related to some statements of material and method: for example, the energy closure balance problem is analysed in details, but no mention is made on the angle of attack issue, which has been reported as one of the possible causes for the imbalance (Nakai et al., 2006). Or the fact that measurements started 3 years after the seeding. At last, some considerations should be added also concerning the results of the first year, not only related to the emissions due to soil preparation, but also making some speculations on the fact that different management operations applied (i.e. use of herbicide after seeding). This might have implications in the patterns of fluxes and in the fact that the study site was a net source of CO2 in the first year.

We agree, it is good to shortly discuss the possibility that better energy balance closure (EBC) could be achieved if the angle-of-attack correction would have been implemented. We opted not to do the correction, since in our opinion, it still lacks a thorough validation in the field. We are aware of the progress made in this regard (Nakai and Shimoyama, 2012), but we still feel that a solid long term validation of the angle-of-attack correction method is needed.

We also agree that there is a difference in the age of the crop stands between the present study site and the comparison site. However, the age of the stand in the comparison site is still far from the end of the life cycle of the crop that lasts 10 to 15 years. Estimation of the other energy inputs, management effects etc. is part of an LCA, which is not in the scope of the present paper. Also, due to the fact that we started the CO_2 measurements after the soil preparation work, we cannot discuss the effect of those on the CO_2 exchange. Also based on our data, it is not to possible to discuss the effect of the herbicides on the CO_2 exchange as the measurements were started only few days before the herbicides were applied and stopped few days after for approximately three weeks.

Technical comments:

L9, P16674: if measurements covered a period of three years, why you report only 2010 and 2011? Please clarify.

Changed to "*To quantify the CO_2 exchange of this RCG cultivation system, and to understand the key factors controlling its CO_2 exchange, the net ecosystem CO_2 exchange (NEE) was measured from June 2009 until the end of 2011 using the eddy covariance (EC) method*."

L15-16, P16674: please try to evaluate the uncertainty related to EC measurements, as it provides info on the reliability of the numbers you use to evaluate the CO2 balance of the cultivation.

Random and systematic errors were estimated and added "*The random errors of 30-min averaged and quality controlled CO_2 fluxes were determined following Vickers and Mahrt (1997). The random error was 14%, 16% and 14% during July-September 2009, May-September 2010 and May-September 2011, respectively.*" and "In this paper, the EBC is regarded as an estimate of the flux systematic errors following Mauder et al. (2013)."

L24, P16674: please specify different sources of respiration (plant, soil, microorganism…)

Added "*(plants and micro-organisms)*"

L15, P16675: Please use SI units: Mg instead of tons. Check for consistency: in the abstract you used kg DW ha-1 for biomass. In addition: is this range global?

Changed all yields to kg DW ha^{-1}.

The range is not global. Changed to "*The annually harvested yield up to 12 000 kg DW ha^{-1} has been reported (Lewandowski et al., 2003).*"

L16-20, P16675: please specify this is a general rule concerning respiration. Another factor that might impact the NEE is the GPP rate (and not only length), while the C balance can be influenced by the biomass use. Please consider rephrasing: here you are considering benefits from a larger perspective (not only GHG), but including only some factors (respiration and not GPP rate)

We aim to larger perspective with this section, as not only GHG balance is different between annual and perennial agriculture. Changed to "*As a perennial crop, it has advantages over the annual cropping systems. The crop growth following the first overwintering starts earlier as the re-establishment of the crop in the spring is not needed. This cultivation style also reduces the use of machinery at the site since e.g. annual tilling is not required.*".

L23, P16675: do you have reference for no studies on that? Or is it your knowledge? Please specify

Added "*to our knowledge*"

L25-27, P16675: As I already said, more relevance in the Intro should be given to the fact that you want to compare it to a reference study on organic soil.

Added "*Additionally, we aim to compare our findings from the mineral soil site to the published data on of a RCG cultivation system on a drained organic soil (referred to hereafter as comparison site) in the same climate region..*"

L26, P16675: Typo: quantify.

Changed "quantity" to "*quantify*"

L9-26, P16676: please provide further information on how soil analysis was performed. How many samples? Which methods? When? This will make more clear some sentences, e.g. if the found variability (reported ranges) was due to spatial or temporal variability

While checking the data, we noticed a mistake with the data processing. The values were updated and details on sampling and methods were added.

L6-8, P16677: does it mean it was not harvested after the first year? Please specify as it might be relevant in the analysis of patterns

It is a common practice to harvest the crop for the first time after the second growing season.

Changed to "*The biomass produced during the first growing season was not harvested but left on the site. During the following years, the harvesting was done in the spring after the growing season (April 28 in 2011 and May 9 in 2012). Thus, the spring 2011 was the first time when the crop was harvested after its establishment in the summer of 2009.*"

L14-15, P16677: please provide justification to this sentence, e.g.: "because no other obstacles were present and the sonic anemometer in use had an omnidirectional geometry". Please consider moving this sentence at the end of the paragraph (i.e. L20, after "vegetation height")

Changed to "*Except for the wind sector from 85° to 130° downwind of the instrument cabin, all wind directions were acceptable because no other obstacles were present and the sonic anemometer in use had an omnidirectional geometry.*".

Sentence was moved at the end of the paragraph.

L21, P16677: please explain acronyms: inner diameter, Polytetrafluoroethylene. And specify that reported values are lengths.

Changed to "*A heated gas sampling line (inner diameter 4 mm, length 8 m polytetrafluoroethylene (PTFE) + 0.5 m metal) with 2 filters (pore size 1.0 µm, PTFE, Gelman® or Millipore®) was used to draw air with a flow rate of initially 6 l min*$^{-1}$ *(until 31 March 2011).*".

L6-8, P16678: does it mean the de-spiking procedure was applied only to CO2 and H2O concentrations? Please specify

The de-spiking procedure was also applied to wind components (u = 10 m s^{-1}, v = 10 m s^{-1} and w = 5 m s^{-1}) and temperature (5°C). This was added to the manuscript.

L8-9, P 16678: the previous or next one? Please clarify

The previous one. Corrected accordingly in the manuscript.

L11, P 16678: can you justify this sentence on angle of attack? This might have consequences in the energy balance closure problem

We opted not to do the correction, since in our opinion, it still lacks a thorough validation in the field. We are aware of the progress made in this regard (Nakai and Shimoyama, 2012), but we still feel that a solid long term validation of the angle-of-attack correction method is needed.

L17, P 16678: reference needed

The sentence was corrected as the point-by-point dilution correction was applied after the de-spiking, not after the spectral corrections as was incorrectly written in the previous version of the manuscript. We do not have a good reference for this.

L21, P 16678: the selection of a ustar thresholds should be carefully applied. Please provide details on how you chose the indicated threshold.

Added "*We plotted the night-time NEE with u* and found no correlation between the two. Nevertheless, a default u* filter of 0.1 m s^{-1} was used.*"

L22-23, P16678: what do you mean here with "stationarity"? Foken and Wichura,1996 use the difference between the dispersion of an averaging period and those of sub-periods, and suggest non-stationarity is found when the difference is above 30%. If you use a different threshold, please specify. Please consider a different name for this indicator, as to avoid to state that if the "stationarity" is higher than a threshold, then the flux is non-stationary.

Changed to "*Flux was considered non-stationary following Foken and Wichura (1996). Generally, a threshold value of 0.3 is used. However in the present study, using this value would have caused a rejection of a lot of good quality data. Therefore, we used a limit of 0.4 (e.g. 40 % difference between the sub-periods and the total averaging period).*"

L27, P16678: which model or models did you use for footprint calculation? Please specify

Added "*Footprints were calculated for each 30-min averaging period with the analytical footprint model developed by Kormann and Meixner (2001). The model is valid within the surface layer and it utilizes power law profiles for solving the footprint sizes analytically in a wide range of atmospheric stabilities. Based on the analysis, 80% of the flux was found to originate from within 130 m radius from the mast*."

L5, P16679: please consider rephrasing in "excluding gap filled data"

Corrected accordingly.

L16-20, P16679: Please reformulate this part. EBC as expressed here is a simplified formula valid for ideal surfaces (i.e. with no mass and heat capacity). more precise formula would include energy storage of the layer considered (as you indicated below). I suggest adding references for eq. (2) (e.g. Arya 1988), and then clarify that the addition of the stored energy is expected to give a more precise estimation of energy balance. However incomplete closure is common also for other reasons: large scale eddies (which is Foken 2008 hypothesis) and angle of attack issue (see Nakai et al., 2006). Please consider rephrasing and discuss this issue in the discussion section, including considerations on angle of attack problem (which you did not correct)

The section was reformulated as follows "*The EBC is expressed in the following formulation (Arya, 1988) and it is a simplified formula which is valid for ideal surfaces, i.e. with no mass and heat capacity:*

$$Rn = LE + H + G \qquad (2)$$

The EBC was determined using data from only those 30 minute time periods when all of the energy components were available. The slope of the regression was 0.70 in May–September period 2010 and 2011. Incomplete closure is a common problem due to e.g. large eddies (Foken, 2008), angle of attack issues (Nakai et al., 2006) and also because part of the available energy is also stored in different parts of the ecosystem (Foken, 2008). Therefore, EBC was calculated so that it include different storage terms, i.e. heat in the soil, crop canopy, amount of energy used in photosynthesis, sensible and latent heat below the EC mast (following Meyers and Hollinger, 2004 and Lindroth et al., 2010) to give a more precise estimation of the EBC. With this approach, the slope increased to 0.75."

L19, P16679: please insert a colon before formula

Added ":"

L23, P16679: missing term or 'a' not needed before common? Please check

"a" is needed before common.

L18, P16680: are you referring to incoming radiation here? Please clarify which is the variable affected by this issue. L19-21, P16680: I suggest to check PAR data with short wave incoming data (if this is the variable you are talking about): such a big underestimation should be evident from that comparison. It is crucial to be certain the instrument is underestimating before correcting, as this potentially affects ECB considerations. In the case that shortwave incoming radiation is actually biased, can you state that other related variables (e.g. shortwave outgoing) are not involved? Please specify. Please also indicate how you corrected data: by adding 35% to all data or taking FMI data for the short wave incoming radiation?

This section is now removed from the manuscript as it is not valid in the present situation.

L1, P16681: please insert a colon before formula

Added ":"

L6-7, P16681: what are you referring to with "belowground"? Please clarify

Changed "*below ground*" to "*below vegetation*".

L10, P16681: is there a reason for excluding 2011 from root sampling strategy?

All root samples collected in 2011 were lost prior to the analysis.

L11, P16681: was this time period enough for a complete drying? If you test it, please clearly state. Otherwise can you provide references that such a short period at 65 C was found to be enough to dry this type of matter?

The weight was checked few times when drying. When the sample weight did not change anymore, it was considered dry. Changed to *"Samples were drying in the oven (+65°C) until the weight of the samples did not change anymore (approximately 24 hours) and dry weight (DW) was measured."*

L2, P16682: please add reference for equation 4

Added Thornley and Johnson, 1990.

L17, P16682: please add reference for equation 5

Added Shurpali et al., 2009.

L22, P16682: TER was obtained by subtracting estimated GPP to NEE, so I would clearly expect a relationship between TER and GPP. Please consider rephrasing, e.g. "to test if the answers of TER and GPP to climatic patterns was the same,…"

It is true that GPP and TER are always connected. This sentence was not changed.

L3-4, P16684: following 2009? Please clarify this sentence, also concerning what "9" is referring to

Added "*weeks*".

L16, P16684: if you gap-filled data, why does Fig. 3 contain gaps? Please clarify

Added "*Measured 30 min values of NEE, H and LE during 2009, 2010 and 2011 prior to the gap filling are shown in Fig. 3.*"

L8-9, P16685: please consider rephrasing: "June presented conditions of high CO2 uptake during the day and of CO2 loss from the RCG cultivation system in night-time"

Changed to "*In both years, June presented conditions of high CO_2 uptake during the day and of CO_2 loss at night.*"

L24-26, P16685: please add in the discussion some consideration on the fact that you are comparing two variables that are related between them from the beginning, as they are estimated from the same main variable (NEE)

This is mentioned in the discussion that NEE is the balance between GPP and TER.

L11, P16686: dot missing

Added "."

L5, P16688: shown

Changed "given" to "*shown*"

L7-19, P16688: what about the biomass that was burnt? This is CO2 that returns fast to the atmosphere. This is good to exclude from the comparison if in the reference study this is also not included; however, this sentence is not correct, please consider rephrasing

We believe that our statement is correct. In the earlier studies, it has been shown, that while cultivated on cut-away peatland, the RG cultivation was a CO_2 sink (Shurpali et al., 2009). In a life cycle assessment at that site, LCA was negative during wet years and still better that the coal during dry years (Shurpali et al., 2010).

L16-19, P16689: consider rephrasing, it is redundant to repeat citations. I suggest to put a dot after "bioenergy crops", deleting anything else up to the next dot and then moving the next sentence ("compared...range") after citation of Grelle et al., 2007. Also, are these values averages on a long term or relative to one year? Please clarify.

Changed to "*During a four year study in Finland, an annual NEE ranging from -8.7 to -210 g C m^{-2} has been reported for a cut-away peatland with RCG cultivation in Finland (Shurpali et al., 2009) and during a one year study in Denmark, an annual NEE of +69 g C m^{-2} was reported for an organic agricultural site (Kandel et al., 2013a). Measurements of CO_2 exchange have been carried out also on other bioenergy crops. On average, annual NEE of switchgrass cultivation was -150 g C m^{-2} during a four year study in USA (Skinner and Adler, 2010). Annual NEE for miscanthus was -420 g C m^{-2} during a two year* *study in USA (; Zeri et al., 2011). Annual NEE of young hybrid poplar stand in Canada was +37 g C m^{-2} in a two year study (Jassal et al., 2013). Willow stands have been studied in Sweden with an annual NEE value of -510 g C m^{-2} in a three year study (Grelle et al., 2007). Compared to these studies, the annual NEE of the present study is within the range of these previously reposted values from various bioenergy systems."*

L25-26, P16689: A bit too strong. Consider rephrasing in "the RCG of the present study showed a higher capacity..." This happens often in the manuscript to generalize the results from the RCG of this study, and I suggest to avoid it.

Changed to "*So, RCG in the present study has a higher capacity for carbon uptake than Scots pine on mineral soils under boreal environmental conditions*." Also, we checked the way the results were generalized.

L4-6, P16690: please move this sentence to material and method section

Paragraph from P16689 L27 to P16690 L6 was moved to materials and methods under the new section 2.5 Comparison site characteristics.

L12-15, P16690: do these studies refer to the same sites? Please clarify

Changed to "The differences in the nutrient status of the soil types is further borne out by the fact that the mineral soil in the present study had a seasonal N_2O emission from this RCG cultivation system of the order of 2.4 kg ha^{-1} (Rannik et al., 2015), while the comparison site had negligible emissions (Hyvönen et al., 2009). "

L15-18, P16690: please split this sentence

Done.

L11-13, P16691: please report reference values

Values are given in materials and methods under a new section (2.5 Comparison site characteristics).

L24, P16691: please report them

Added values.

L13-15, P16692: are the ref site and the site of this study at the same latitude? Please add discussion on that (different latitudes would mean different PAR levels

They are more or less at the same latitude (63.2°N present site, 62.5°N comparison site). Location information of the comparison site was added to the materials and methods section.

L16-18, P16692: is it a difference with the ref site? Please add some thoughts on that

At the comparison site, the ET was higher than precipitation during the dry years. However, NEE was lower on the dry years.

L4-7, P16693: please discuss also climatic differences (respiration is driven by soil temperature as you say below: are soil temperature levels of the ref site the same?)

The mean temperatures (May-September) at the topsoil were similar between the sites. This aspect was added to the discussion.

L9-10, P16693: please add “in 2010 and 2011, respectively” in the brackets. Also please check units are always reported in the manuscript

Added. Also check the consistency in the units throughout the manuscript.

L23, P16693: please change “same crop” in "same crop type"

Changed “same crop” to “same crop variety” as it has been used throughout the manuscript.

L28-29, P16693: For that reason I think you must focus on the comparison with the organic soil type, and add conclusions on this sense

We agree that the comparison to organic soil site is important in this paper. However, there are limitations how far it can be taken. As we are only reporting the CO_2 exchange on mineral soil in the manuscript, we are not able to conclude more in relative to the life cycle of the RCG based on the findings on organic soil. For example, the N_2O exchange patters are most likely different between the two sites.

Conclusion was revised.

Table 1: In caption please add reference to Fig. 6

Added “*See Fig. 6 for the relationship of GPP to PAR*.”

Table 2: What is the reason to report data in two units? Please consider modifying this table: as the 2009 is not a full year, its relevance is due to the fact that it follows seeding activity. Please consider excluding it from Table 2 as it cannot be compared to full years (2010 and 2011), but use it to show the relevant release of CO2 to the atmosphere following seeding activities. Otherwise you might consider of splitting data in Tab. 2 in periods (e.g. Oct to Apr and May to Sep, approximately corresponding to dormant and growing seasons), which would allow to leave also 2009 data.

The CO_2 flux results are reported in varying units in papers. We believe that a results table with different units would give the reader easily the idea of the range of the results in relative to the units that the reader is most comfortable with. Removed the other unit (g CO_2 m^{-2}) from the table.

Year 2009 was left in the table, as it shows the CO_2 exchange of RCG during the first season. We are missing January to end of June in 2009 when most of the time the site was not even cultivated with RCG.

Fig. 5: what are the open grey circles for? Please clarify

There are no open grey circles in the figure.

Fig. 7, (b): may this poor relationship be due to the fact that after the first year cultivation, the biomass was left on the field? Please consider touching this aspect in the discussion

It is true that the biomass produced in 2009 was left at the site and most likely contributing to the respiration in 2010. However, the respiration rate was increasing from 2010 to 2011 even though there was no extra biomass at the site in 2011. The yield of 2010 to 2011 increased also, so it is not possible to determine, based on our data, how much the extra biomass effect the TER in 2010.

Added “*The lack of GA correlation in 2010 could be attributed to the unharvested biomass from the 2009 season. The biomass left at the site may have affected the soil respiration rates in 2010.”*.

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List of relevant changes:

1. Added paragraph to introduction
2. Revised “Study site and agricultural practices” under Materials and Methods
3. Revised “Micrometeorological measurements” under Materials and Methods
4. Added new section “Comparison site characteristics” under Materials and Methods
5. Large parts of discussion have been re-written
6. Table 2 was updated. Data in unit of g CO_2 m^{-2} was removed.

Carbon dioxide exchange of a perennial bioenergy crop cultivation on a mineral soil

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Abstract

One of the strategies to reduce carbon dioxide (CO_2) emissions from the energy sector is to increase the use of renewable energy sources such as bioenergy crops. Bioenergy is not necessarily carbon neutral because of greenhouse gas (GHG) emissions during biomass production, field management and transportation. The present study focuses on the cultivation of reed canary grass (RCG, *Phalaris arundinaceae L.*), a perennial bioenergy crop, on a mineral soil. To quantify the CO_2 exchange of this RCG cultivation system, and to understand the key factors controlling its CO_2 exchange, the net ecosystem CO_2 exchange (NEE) was measured from July 2009 until the end of 2011~~during three years~~ using the eddy covariance (EC) method. The RCG cultivation thrived well producing yields of 6200 and 6700 kg DW ha^{-1} in 2010 and 2011, respectively. Gross photosynthesis (GPP) was controlled mainly by radiation from June to September. Vapour pressure deficit (VPD), air temperature or soil moisture did not limit photosynthesis during the growing season. Total ecosystem respiration (TER) increased with soil temperature, green area index and GPP. Annual NEE was -262 and -256 g C m^{-2} in 2010 and 2011, respectively. Throughout the study period from July 2009 until the end of 2011~~Throughout the studied period~~, cumulative NEE was -575 g C m^{-2}. Carbon balance and its regulatory factors were compared to the published results of a comparison site on drained

organic soil cultivated with RCG in the same climate. On this mineral soil site, the RCG ~~When compared to the published data for RCG on an organic soil, the cultivation of this crop on a mineral soil~~ had higher capacity to take up CO_2 from the atmosphere than on the comparison site.

1 Introduction

Anthropogenic increase in the atmospheric concentration of greenhouse gases (GHG) has been considered as the major reason for the global climate warming (IPCC, 2013). The carbon dioxide (CO_2) concentration in the atmosphere has increased from 278 to 391 ppm between 1750 and 2011 and is still increasing (IPCC, 2013). Carbon dioxide emitted to the atmosphere originates mainly from respiration (plants and micro-organisms) and fossil fuel combustion with the main sinks being photosynthesis and oceans (IPCC, 2013). In Finland the energy sector and agriculture are the most important in the total national GHG emissions (Statistics Finland, 2014).

One of the strategies to reduce CO_2 emissions from the energy sector is to increase the use of renewable energy sources, e.g. using biomass. Bioenergy produced from biomass is not necessarily carbon neutral because of GHG emissions during biomass production, field management and transportation. Life-cycle assessment (LCA) results have been recently reported for reed canary grass (RCG, *Phalaris arundinaceae L.*) cultivation on cut-away peatlands in Finland (Shurpali et al., 2010) and Estonia (Järveoja et al., 2013). In these studies, the RCG sites were net sinks for CO_2 and hence, RCG is suggested to be a good after use option for such marginal soils which are known to release large amount of CO_2 as a result of decomposition of residual peat, when left abandoned (Kasimir-Klemedtsson et al., 1997).

Cultivation of RCG has been popular in Finland since the mid-1990s and at the peak approximately 19 000 ha (2007 and 2008) were cultivated with RCG. However, owing to technical difficulties with the burning of the RCG biomass in combustion plants, the scope of RCG as a source of biomass bioenergy has declined in the last few years. In 2014, the average cultivation area was around 6000 ha. Nevertheless, the scope for RCG as a source of liquid biofuel, a digestate in biogas plants, oil spill absorption and a buffer crop between terrestrial and aquatic landscape is wide (Pasila and Kymäläinen, 2000; Partala et al., 2001; Powlson et al., 2005; Kandel et al., 2013b).

RCG is a perennial crop which is well adapted to the northern climatic conditions. It has a rotation time of up to 15 years. The annually harvested yield up to 12 000 ~~harvestable above-ground RCG biomass ranges from 6000 to 12000 tons~~ kg ~~dry matter~~ DW ha^{-1} has~~ve~~ been reported (~~Saijonkari-Pahkala, 2001;~~ Lewandowski et al., 2003). As a perennial crop, it has ~~many benefits when compared~~ advantages over ~~with~~ the annual cropping systems. The crop growth following the first overwintering starts earlier as the re-establishment of the crop in the spring is not needed. This cultivation style also reduces the use of machinery at the site since e.g. annual tilling is not required. ~~There is no annual tilling which reduces the CO_2 emissions from soil (e.g. Chatskikh and Olesen, 2007). Additionally, the continuous plant cover on the soil reduces leaching of nutrients (Saarijärvi et al., 2004).~~

While continuous and long-term measurements of GHG balance from bioenergy crops are needed to evaluate the atmospheric impact of the whole production chain, to our knowledge, there are no GHG flux measurements from RCG cultivation on mineral soils. With this in view, we measured the CO_2 balance of RCG crop cultivation (2009–2011) on a mineral soil by the eddy covariance (EC) technique. Our objectives in this paper are to quanti~~t~~fy and characterise the NEE of a perennial crop cultivated on a mineral soil and to investigate the factors controlling its CO_2 balance. Additionally, we aim to compare our findings from the mineral soil site to the published data on of a RCG cultivation system on a drained organic soil (referred to hereafter as comparison site) in the same climate region.

2 Materials and methods

2.1 Study site and agricultural practices

The study site is located in Maaninka (63˚09'49"N, 27˚14'3"E, 89 m above the mean sea level) in eastern Finland. Long-term (30 years, reference period 1981-2010; Pirinen et al., 2012) annual air temperature in the region is 3.2°C with February being the coldest (-9.4°C) and July the warmest (17.0°C) month. The annual precipitation in the region is 612 mm~~.~~ with a seasonal ~~The~~ amount of 322 mm ~~precipitation~~ during the May-September period ~~is 322 mm~~.

The experimental site is a 6.3 ha (280 x 220 m) agricultural field cultivated with RCG (cv. 'Palaton'). During the last ten years prior to planting of RCG, the field was cultivated with grass

(*Phleum pratense* L.; *Festuca pratensis* Huds), barley (*Hordeum vulgare* L.) or oat (*Avena sativa* L.). For a detailed soil analysis three 100 cm deep soil pits were excavated and eight 6 cm deep horizons between 0 and 93 cm were sampled in July 2010. Three undisturbed soil samples from each horizon were taken with steel cylinders (height 6.0 cm, diameter 5.7 cm). Two soil samples were used for determination of soil physical properties and one for the chemical properties. To characterize properties of top soil (0 – 18 cm) in general, soil samples taken at depths of 0–6, 6–12, 12–18 cm were analysed separately, and mean values over the horizons were calculated for each pit. The results shown here are means (± standard deviation) over the three pits. The soil samples were oven dried at 35°C and ground to pass through a 2 mm sieve. The particle-size distribution was determined with the pipette method (Elonen, 1971). Total organic C and total N contents were determined by dry combustion using a Leco® analyser, the soil particle density with a stoppered bottle pycnometer method and bulk density was calculated as a ratio of the dry weight (oven dried at 105 °C) and sampling volume of the soil. Soil pH and electrical conductivity were measured in soil-water suspension (1:2.5 v/v). The easily soluble P and exchangeable K were extracted with acid ammonium acetate at pH 4.7, as described by Vuorinen and Mäkitie (1955).

The soil was classified as a Haplic Cambisol/Regosol (Hypereutric, Siltic) (IUSS Working Group WRB, 2007), the topsoil being generally silt loam (clay mean 25 ± 5.6%, silt 53 ± 9.0% and sand 22 ± 7.8%) based on the U. S. Department of Agriculture (USDA) textural classification system. The average soil characteristics in the topsoil were as follows: pH (H_2O) 5.8 ± 0.19, electrical conductivity 14 ± 2.4 mS m^{-1}, soil organic matter 5.2 ± 0.90 %, organic carbon 3.0 ± 0.52 %, total nitrogen 0.2 ± 0.03 %, C:N ratio 15 ± 0.4, the acid ammonium acetate extractable K 104 ± 12.9 mg l^{-1} soil, P 5.4 ± 1.28 mg l^{-1} soil, particle density 2.65 ± 0.014 g cm^{-3} and bulk density 1.1 ± 0.11 g cm^{-3}. Based the soil moisture retention curve field capacity was 39.7 ± 1.2 % (soil moisture (v/v)) and wilting point was 21.6 ± 0.8 % (soil moisture (v/v)).

~~The soil is classified as a Haplic Cambisol/Regosol (Hypereutric, Siltic) (IUSS Working Group WRB, 2007) and the texture of the topsoil (0–28cm) varied from clay loam to loam (clay 22–34%, silt 46–64% and sand 14–30%) based on the U. S. Department of Agriculture (USDA) textural classification system. In the topsoil, pH (H_2O) varied from 5.4 to 6.1, electrical conductivity from 960 to 3060 µS cm^{-1} and soil organic matter content from 3 to 11%. The average C:N ratio of the topsoil was 14.9. The exchangeable K and easily soluble P concentrations (Vuorinen and Mäkitie, 1955) ranged from 67.3 to 153 mg l^{-1} soil and from 3.3~~

to 12.9 mg l^{-1} soil, respectively. Particle density (0–18cm) varied from 2.6 to 2.7 g cm^{-3}. Based on the soil moisture retention curve (0–18cm), mean (± standard error) field capacity was 39.7 ± 1.2% (soil moisture (v/v)) and wilting point was 21.6 ± 0.8% (soil moisture (v/v)). The soil bulk density (0–7 cm) was calculated as a ratio of the dry weight of the soil and the sampling volume in in August 2010 (0.76 g cm^{-3}) and October 2011 (0.89 g cm^{-3}). For this, six soil samples were collected from the field and oven dried (+60˚C) after which the weight of the soil was measured.

In the beginning of June 2009, the sowing of RCG was done with a seed rate of 10.5 kg ha^{-1} together with the application of a mineral fertilizer (60 kg N ha^{-1}, 30 kg P ha^{-1} and 45 kg K ha^{-1})). The field was rolled prior to and after sowing. Additional sowing was done to fill the seedling gaps in June and July. Herbicide (mixture of MPCA 200 g l^{-1}, clopyralid 20 g l^{-1} and fluroxypyr 40 g l^{-1}, 2 l in 200 l of water ha^{-1}) was applied by the end of July 2009 to control the weeds. Mineral fertilizer was applied as surface application in spring 2010 (70 kg N ha^{-1}, 11 kg P ha^{-1} and 18 kg K ha^{-1}) and spring 2011 (76 kg N ha^{-1}, 11 kg P ha^{-1} and 19 kg K ha^{-1}). The biomass produced during the first growing season was not harvested but left on the site. During the following years, the harvesting was done in the spring after the growing season (April 28 in 2011 and May 9 in 2012). Thus, the spring 2011 was the first time when the crop was harvested after its establishment in the summer of 2009. As produced biomass was used for burning, keeping the crop at the site to over winter is a standard RCG cultivation practise in the Nordic countries, as the spring harvest has been shown to improves the quality of the biomass for burning (Burvall, 1997). The biomass was harvested using a farm scale machinery. The naturally dried vegetation was cut with conventional disk mover (without conditioner) to approx. 5 cm stubble height, swathed and baled for round bales 1 – 2 days after cutting. In order to enhance the quality of the biomass for burning, the crop was kept at the site over winter (Burvall, 1997) and was harvested in the following spring (April 28 in 2011 and May 9 in 2012).

2.2 Micrometeorological measurements

Measurements of CO_2, latent heat (LE) and sensible heat (H) fluxes were carried out from July 2009 until the end of 2011 using the closed-path eddy covariance (EC) method (Baldocchi, 2003). Measurement mast was installed approximately in the middle of the field and the instrument cabin was located about 10 m east of the EC mast. ~~Except for the wind sector from 85° to 130° downwind of the instrument cabin, all wind directions were acceptable.~~ The prevailing wind direction was northerly with a 24% occurrence during the study period. The EC instrumentation consisted of an infra-red gas analyser (IRGA) for CO_2 and water vapour (H_2O) concentrations (model: Li-7000 (primary) or Li-6262 (backup), LiCor) and a sonic anemometer (model: R3-50, Gill Instruments Ltd, UK) for wind velocity components and sonic temperature. The mast height was 2, 2.4 or 2.5m, adjusted according to the vegetation height. Except for the wind sector from 85° to 130° downwind of the instrument cabin, all wind directions were acceptable because no other obstacles were present and the sonic anemometer in use had an omnidirectional geometry.

A heated gas sampling line (inner diameter ~~i.d.~~ 4 mm, length 8 m polytetrafluoroethylene (PTFE) + 0.5 m metal) with 2 filters (pore size 1.0 µm, PTFE, Gelman® or Millipore®) was used to draw air with a flow rate of initially 6 l min^{-1} (until 31 March 2011). Subsequently, a flow rate of 9 l min^{-1} was used. The IRGA was housed in a climate controlled cabin. Reference gas flow, created using sodalime and anhydrone, also fitted with a Gelman® filter, was 0.3 l min^{-1}. The IRGA was calibrated approximately every second week with a two-point calibration (0 and 399 µl l^{-1} of CO_2, AGA Oy, Finland) and additionally with a dew point generator (model: LI-610, LiCor) for H_2O mixing ratio during conditions when air temperature was above +5˚C.

Data collection was done at 10 Hz using the Edisol program (Moncrieff et al., 1997). The 30 min EC flux values were calculated from the covariance of the scalars and vertical wind velocity (e.g. Aubinet et al., 2000). Data processing was done using EddyUH post-processing software (~~http://www.atm.helsinki.fi/Eddy_Covariance/index.php~~Mammarella et al., 2016). Despiking was done by defining a limit for the difference in subsequent data points for CO_2 (15 µl l^{-1}) and H_2O (20 mmol mol^{-1}) concentrations, wind components (u = 10 m s^{-1}, v = 10 m s^{-1} and w = 5 m s^{-1}) and temperature (5°C). A data point defined as a spike was replaced with the ~~adjacent~~ previous value. Point by point dilution correction was applied after the despiking. Two dimensional-coordinate rotation (mean lateral and vertical wind equal to zero) was done on the sonic anemometer wind components. Angle of attack correction was not applied. Detrending was done using block-averaging. Lag time due to the gas sampling line was calculated by maximizing the covariance. Low frequency spectral corrections were implemented according to Rannik and Vesala~~,~~ (1999). For high frequency spectral corrections, empirical transfer function calculations were done based on the procedure introduced by Aubinet et al. (2000).

Humidity effects on sonic heat fluxes were corrected according to Schotanus et al. (1993). Point by point dilution correction was applied after the spectral corrections. From the processed data, flux values measured when winds were from behind the instrument cabin (between 85° and 130°) and those during rain events were removed. The available flux data was further quality controlled using filters as follows. We plotted the night-time NEE with u* and found no correlation between the two. Nevertheless, The night-time NEE did not correlate with u*, nevertheless, a default u* filter of 0.1 m s^{-1} was used. Flux was considered non-stationary following and rejected when stationarity (according to Foken and Wichura (1996Foken and Wichura, 1996). In this paper, we used a limit of 0.4 (e.g. 40 % difference between the sub-periods and the total averaging period).) was higher than 0.4. Both skewness and kurtosis of the data were checked and the acceptable skewness range was set from -3 to 3 and kurtosis from 1 to 14. Overall flags (according to Foken et al., 2004) higher than 7 were removed. Finally, the data was visually inspected. From the available data, approximately 30% of the CO_2 and H flux data and 40% of the LE flux data were rejected. The random errors of 30-min averaged and quality controlled CO_2 fluxes were determined following Vickers and Mahrt (1997). The random error was 13%, 12% and 14% during July-September 2009, May-September 2010 and May-September 2011, respectively. Footprints were calculated for each 30-min averaging period with the analytical footprint model developed by Kormann and Meixner (2001). The model is valid within the surface layer and it utilizes power law profiles for solving the footprint sizes analytically in a wide range of atmospheric stabilities. Based on a footprint the analysis, 80% of the flux was found to originate from within 130 m radius from the mast.

The data gap filling and flux partitioning was done using the online tool (http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/index.php). This gap filling method considers both the co-variation of the fluxes with global radiation, temperature and vapour pressure deficit (VPD) and temporal auto-correlation of the fluxes (Reichstein et al., 2005). Flux partitioning was done excluding gap filled data. using only the measured data points. Total ecosystem respiration (TER) was defined as the night-time measured net ecosystem CO_2 exchange (NEE). The regression between night-time NEE and air temperature (T) was calculated using an exponential regression model (Lloyd and Taylor, 1994) of the form:

$$R(T) = R_{ref}\, e^{E_0 \left(\frac{1}{T_{ref}-T_0} - \frac{1}{T-T_0}\right)} \qquad (1)$$

where T_0 = -46.021 °C, T_{ref} = 10 °C and fitted parameters were R_{ref} (the temperature independent respiration rate) and E_0 (temperature sensitivity). Using the model outputs for R_{ref} and E_0, the half-hour TER was estimated using the measured air temperature. Finally, gross photosynthesis (GPP) was calculated as a difference between NEE and TER. In this paper, CO_2 released to the atmosphere is defined as a positive value and uptake from the atmosphere as negative.

As a final step, the EC measurements were validated using the energy balance closure (EBC) determined as the slope of the regression between net radiation (Rn) and latent heat (LE), sensible heat (H) and the ground heat flux (G). The EBC is expressed in the following formulation (Arya, 1988) and it is a simplified formula which is valid for ideal surfaces, i.e. with no mass and heat capacity:~~;~~

$$Rn = LE + H + G \tag{2}$$

The EBC was determined using data from only those 30 minute time periods when all of the energy components were available. The slope of the regression was 0.70 in May–September period 2010 and 2011. Incomplete closure is a common problem due to e.g. large eddies (Foken, 2008), angle of attack issues (Nakai et al., 2006) and also because ~~as~~ part of the available energy is also stored in different parts ~~on~~ of the ecosystem (Foken, 2008). Therefore, EBC was calculated so that it includes different storage terms~~Different storage terms were included~~, i.e. heat in the soil, crop canopy, amount of energy used in photosynthesis, sensible and latent heat below the EC mast (following Meyers and Hollinger, 2004 and Lindroth et al., 2010) to give a more precise estimation of the EBC.~~,~~ With this approach, the ~~and the~~ slope increased to 0.75. The obtained EBC is well within the range of EBCs reported for several FLUXNET sites by Wilson et al. (2002). Mauder et al. (2013) suggested that the EBC could be used as a metric for systematic uncertainty in EC fluxes. Based on this approach the systematic uncertainties of the EC fluxes reported in this study were similar to those published in other studies.

2.3 Supporting measurements

A weather station was set up close to the EC mast. Height of the weather station mast was adjusted according to the EC mast height. Supporting climatic variables, i.e., net radiation (model: CNR1, Kipp&Zonen B.V.), air temperature and relative humidity (model: HMP45C, Vaisala Inc), photosynthetically active radiation (PAR, model: SKP215, Skye instruments

Ltd.), amount of rainfall at 1 m height (model: 52203, R.M. Young Company), soil temperature at 5, 10 and 30 cm depths (model: 107, Campbell Scientific Inc.), soil moisture at depths of 5, 10 and 30 cm (model: CS616, Campbell Scientific Inc.), soil heat flux at 7.5 cm depth (model: HPF01SC, Hukseflux) and air pressure (model: CS106 Vaisala PTB110 Barometer) were measured. Data was collected using a datalogger (model: CR 3000, Campbell Scientific Inc.). All meteorological data were collected as 30 minute mean values (precipitation as 30 minute sum), except air pressure which was recorded as an hourly mean. Supporting data collection began since August 14, 2009. Short gaps in the data were filled using linear interpolation. If air temperature, relative humidity, pressure or rainfall data were missing for long periods, data from Maaninka weather station, located about 6 km to South-East from the site and operated by the Finnish Meteorological Institute (FMI), was used. ~~At the end of the study period, the measured shortwave radiation data when compared with the radiation data available from FMI were found to be approximately 35% higher. Based on this analysis, the overestimation in the measurements of the available energy was corrected before the EBC calculations were made.~~

The RCG green area index (GA) was estimated following Wilson et al., 2007). Measurements were done approximately on a weekly basis during the main growing period and less frequently in the autumn. Three locations (1 x 1 m^2) were selected and within those, three spots (8 x 8 cm^2) were used to count the number of green stems (Sn) and leaves (Ln) per unit area. Three plants adjacent to small spots were selected for measurements of green area of leaves (La) and stems (Sa). Following equation was used to calculate GA (m^2 m^{-2}):~~;~~

$$GA = (Sn \cdot Sa) + (Ln \cdot La) \tag{3}$$

Leaf area index (LAI) was measured using plant canopy analyser (model: LAI-2000, LiCor) with ~~an~~a 180˚ view cap. The LAI was measured close to GA plots at the same interval and at the same day as GA was estimated. A measurement was accepted when the standard error of LAI was less than 0.3 and the number of above and below ~~ground~~ vegetation observation pairs was more than three.

Above-ground biomass samples were collected approximately on a monthly basis from three locations in the field during the snow-free season in 2009, 2010 and 2011 and root samples in 2009 and 2010. Above-ground biomass was collected from a 20 x 20 cm^2 area. Samples were dried in the oven until (+65°C) the weight of the samples did not change anymore (approximately 24 hours)~~After drying (+65°C) for 24 hours,~~ and dry weight (DW) was measured. ~~In 2011, the fresh weight (FW) was also recorded.~~ Root biomass (0–25 cm) was sampled from the same areas as the above-ground biomass using a soil corer (diameter 7 cm). Living roots (fine and coarse roots) were picked and washed. After drying (+65°C) for 24 hours, DW was measured.

To analyse the performance of the crop, water use efficiency (WUE) was determined following Law et al. (2002). For this purpose, evapotranspiration (ET) was determined by dividing LE with the latent heat of vaporization (L = 2500 kJ kg^{-1}). Monthly sums of GPP and ET from May to September period were obtained and WUE was determined as the slope of the linear regression between monthly GPP and ET. Bowen ratio was calculated from daytime (PAR > 20 µmol m^{-2} s^{-1}) measured H and LE fluxes.

2.4 Analysis of environmental factors governing CO_2 exchange

The relationship between GPP and PAR was examined on a monthly basis from mid-May to September separately for 2010 and 2011. Prior to the analysis, PAR data were binned at an interval of 10 µmol m^{-2} s^{-1}. The bin averaged values of GPP were plotted against PAR and the data were fitted with a rectangular hyperbolic model of the form (e.g. Thornley and Johnson, 1990):~~;~~

$$GPP = \frac{GP_{max} \cdot PAR \cdot \alpha}{GP_{max} + PAR \cdot \alpha} \quad (4)$$

where GP_{max} (µmol m^{-2} s^{-1}) is the theoretical maximum rate of photosynthesis at infinite PAR and α is the apparent quantum yield. Additionally, data with PAR levels greater than 1000 µmol m^{-2} s^{-1} were used to study the relationship between GPP and air temperature, VPD and soil moisture. To analyse the relationship between GPP and GA and also LAI, a weekly averaged GPP was constructed for those weeks when the plant variables were available. These data were fitted with a linear regression.

To be able to compare the results in detail with the earlier findings on RCG on organic soil site in Finland (Shurpali et al., 2010) another regression model was used to assess the relationship between TER and soil temperature, night-time measured NEE (PAR < 5 µmol m^{-2} s^{-1}) from May to September separately for 2010 and 2011 was used. Prior to the analysis, the data were binned with soil temperature at 2.5 cm depth (from 0 to 21.5 °C with a 0.5°C interval). The bin averaged values of TER were plotted against soil temperature and the data were fitted with an exponential regression model of the form ~~;~~(e.g. Shurpali et al., 2009):

$$TER = R_{10} \cdot Q_{10}^{(T_s / T_{10})} \quad (5)$$

where T_s is the measured soil temperature (°C) at 2.5 depth, T_{10} = 10 °C and the fitted parameters are R_{10} (base respiration, µmol m^{-2} s^{-1}, at 10°C) and Q_{10} (the temperature sensitivity coefficient). To analyse the relationship between TER and vegetation, we constructed weekly means from daily TER values for the weeks during which GA was estimated for 2010 and 2011. To assess the relationship between GPP and TER, daily sums of TER and GPP from May to September separately for 2010 and 2011 were used in the linear regression analysis.

2.5 Comparison site characteristics

The comparison site with organic soil is intensively studied and several papers reports results from it (e.g. Shurpali et al., 2008; Hyvönen et al., 2009; Shurpali et al., 2009, 2010, 2013; Gong et al., 2013). The comparison site is located in eastern Finland (62°30'N, 30°30'E, 110 m above the mean sea level). Long-term (30 years, reference period 1981-2010) annual air temperature in the region is 3.0°C and the annual precipitation in the region is 613 mm. The area was originally an ombrotrophic *Sphagnum fuscum* pine bog (for more details, see Biasi et al., 2008). From 1976 onwards the site was prepared for peat extraction i.e. it was drained and the vegetation was removed. Peat extraction was started in 1978. In 2001, when the peat depths wereas between 20 and 85 cm, a 15 ha area was sown with RCG (cv. Palaton). Since then, the site was annually fertilized with 50 kg N ha^{-1}, 14 kg P ha^{-1} and 46 kg K ha^{-1}. Lime was added as dolomite limestone ($CaMg(CO_3)_2$) with rate of 7.8 t ha^{-1} in 2001 and 2006.

The average surface peat characteristics were as follows: pH 5.4, bulk density 0.42 g m^{-3} and C:N ratio 40.3 (Shurpali et al., 2008). The climatic conditions during the years 2004-2007 at the site were such that the annual air temperature was 2.7, 3.7, 3.1 and 3.2°C and annual precipitation was 862, 544, 591, 700 mm in 2004, 2005, 2006 and 2007, respectively (Hyvönen et al., 2009). During May-September period, the precipitation was 554, 246, 249 and 423 mm in 2004, 2005, 2006 and 2007, respectively. The difference to the long-term mean (312 mm) was approximately 20% during the dry years (2005 and 2006) and 36 and 78% during the wet years (2004 and 2007, respectively). Water table level was on average 0.65 m, varying from 0.4 to 0.7 m during the years (Hyvönen et al., 2009). The VWC at 30 cm depth was always high and did not vary between the years. The VWC at surface layers (2.5 and 10 cm depths) was fluctuating in response to the precipitation events and ranged from 0.1 to 0.8 m^3 m^{-3}. The biomass at the site was used for burning purpose and, therefore, it was harvested in the spring. The spring harvested yields were 3700, 2000, 3600 and 4700 kg ha^{-1} in 2004, 2005, 2006 and 2007, respectively (Shurpali et al., 2009). The CO_2 exchange was measured using open path EC system and the details for the measurements and data processing can be found from Shurpali et al. (2009).

3 Results

3.1 Seasonal climate and crop growth

The mean annual air temperature at the study site was 3.5, 2.2 and 4.5 °C in 2009, 2010 and 2011, respectively, with the daily means varying from -30.0 to +27.1 °C (Fig. 1a). Annual precipitation was 421, 521 and 670 mm in 2009, 2010 and 2011, respectively. In May–September period the precipitation was 40% and 28% lower in 2009 (192 mm) and 2010 (228 mm) than the long-term mean. Precipitation was about the same as the long-term mean in 2011 (327 mm, Fig. 1b). The growing season is defined to have commenced when the mean daily air temperature exceeds 5 °C for five consecutive days with no snow and ended when the mean daily air temperature is below 5 °C five consecutive days. Growing season commenced on May 1 in 2009, May 9 in 2010 and April 23 in 2011 and lasted 152, 156 and 182 days in the three consecutive years.

The daily averaged VWC ranged from 0.12 to 0.54 m^3 m^{-3}, from 0.09 to 0.37 m^3 m^{-3} and from 0.11 to 0.45 m^3 m^{-3} in 2009, 2010 and 2011, respectively (Fig. 1c). The summer maximums were recorded at 2.5 cm depth in July 2010 (20.9°C) and 2011 (19.1°C) (Fig. 1d). During the winter 2009–2010 and 2010–2011 the soil temperatures were close to zero. The lowest soil temperatures were recorded at 2.5 cm depth in December 2009 (-7.5°C) and November 2010 (-3.4°C).

The estimated evapotranspiration (ET), was 110, 330 and 370 mm in August – September 2009, May – September 2010 and May – September 2011, respectively. During those time periods, ecosystem used more water than was received through rainfall as the corresponding precipitation amounts were 80, 220 and 320 mm in 2009, 2010 and 2011, respectively. Clear linear relationship was found between GPP and ET (adjusted $R^2 = 0.73$, $p < 0.01$, $n = 12$) during May–September period in 2010 and 2011. The water use efficiency (WUE) of the RCG cultivation determined from this relationship was 12 g CO_2 per kg H_2O. Averaged daytime

Bowen ratio was 0.18 and 0.28 during the May–September period in 2010 and 2011, respectively.

During the first growing season (2009), the vegetation development was slow and the maximum plant height was low when compared to the subsequent years (0.6, 1.7 and 1.8 m in 2009, 2010 and 2011, respectively). –In the following years, the initial sprouting in early spring was followed by vigorous plant growth which lasted about 9 weeks. The rapid plant growth resulted in a steep increase in green area (GA) and leaf area indices (LAI) in 2010 and 2011 (Fig. 2b, c). Both GA and LAI levelled off in the beginning of June. The maximum above-ground biomass was recorded at the end of the season (560, 1100 and 1600 g DW m^{-2} in 2009, 2010 and 2011, respectively) (Fig. 2a, b and c). The maximum root biomass was 480 g DW m^{-2} in 2010 (Fig. 2b). Depending on the sampling occasion, 70 to 80% of the roots were distributed within the 0–10 cm depth. The crop yield was 6200 kg DW ha^{-1} and 6700 kg DW ha^{-1} in for 2010 and 2011, respectively.

3.2 CO_2 exchange patterns

3.2.1 Measured net ecosystem CO_2 and energy exchange

Measured 30 min values of NEE, H and LE during 2009, 2010 and 2011 prior to the gap filling are shown in Fig. 3. In 2009, the NEE measurements began 45 days after the sowing in mid-June. The maximum amplitude of the diurnal NEE cycle varied from -26 to 20 µmol m^{-2} s^{-1} during the growing season in 2009. The amplitude of the diurnal NEE cycle was noticeable around mid-May onwards until November in 2010 and 2011. The maximum amplitude of diurnal NEE cycle varied from -31 to 18 µmol m^{-2} s^{-1} and from -37 to 20 µmol m^{-2} s^{-1} during the growing seasons in 2010 and 2011, respectively (Fig. 3a). Outside the growing seasons, respiratory losses dominated the net CO_2 balance. The ecosystem CO_2 loss was 0.62 µmol m^{-2} s^{-1} from October 2009 to mid-May 2010, 0.76 µmol m^{-2} s^{-1} during a similar period in 2010-2011 and 1.1 µmol m^{-2} s^{-1} for a shorter time period in 2011 (November and December). The diurnal LE cycle had the maximum amplitude during the summer months and ranged from -30 to 400, from 0 to 400 and from 0 to 600 W m^{-2} in 2009, 2010 and 2011, respectively. LE was close to zero during the non-growing season. The amplitude of diurnal H cycle was at the maximum during the summer months and ranged from -50 to 130, from -100 to 210 and from -100 to 190

W m^{-2} in 2009, 2010 and 2011, respectively. H ranged from -60 to 20 W m^{-2} during the non-growing seasons.

3.2.2 Diurnal trends

To examine the diurnal trends, the data on air temperature, VPD, PAR and NEE in June 2010 and 2011 were averaged to generate half-hour diurnal means (Fig. 4). In both years, June presented conditions of high CO_2 uptake during the day and of CO_2 loss at nightIn both years, June represented a period with both high CO_2 uptake and loss from the RCG cultivation system. Air temperature was lower in 2010 than in 2011 but both years showed typical diurnal patterns with minimum values during early morning hours and maximum values late in the afternoon (Fig. 4a). Similarly, the VPD was lower in 2010 than 2011 (Fig. 4b). The maximum in VPD (0.96 kPa) occurred late afternoon in 2010 whereas in 2011 the maximum (0.89 kPa) occurred around noon. In both years, the amplitude of diurnal mean of temperature and VPD was moderate. The mean diurnal pattern of NEE was similar between 2010 and 2011 and the patterns were fairly symmetrical (Fig. 4d). During the night time, from 22:00 to about 02:00 hours, CO_2 exchange between the ecosystem and atmosphere was constant and dominated by respiration. Mean NEE during this time was 4.5 µmol m^{-2} s^{-1} in 2010 and 6.6 µmol m^{-2} s^{-1} in 2011. In the morning hours, with increasing PAR (Fig. 4c), NEE began to decline and the light compensation point occurred at a PAR level of about 200 µmol m^{-2} s^{-1} at around 05:00 hours. After this, the uptake dominated the CO_2 balance. The peaks in mean NEE occurred around 12:00 hours at the same time as the peaks in the mean PAR. The maximum mean NEE in June was -21 and -23 µmol m^{-2} s^{-1} 2010 and 2011, respectively. With declining PAR levels, the plant CO_2 uptake also declined. The secondary light compensation point occurred at around 20:00 hours.

3.2.3 Daily patterns

Seasonal patterns of daily sums of GPP, TER and NEE are shown in Fig. 5. From the start of NEE measurements in late July to mid-August in 2009, the site was a net source of CO_2 to the atmosphere. By mid-August, GPP began to overwhelm TER turning the site into a CO_2 sink. During the growing season, the maximum daily values of NEE, TER and GPP were -5.8, 9.7

and -10.5 g C m^{-2} d^{-1}, respectively. The uptake of CO_2 ended by late October. Respiration levelled off by mid-December. From mid-December 2009 until May 2010, TER remained low at an average rate of 0.46 g C m^{-2} d^{-1}. In May 2010 and 2011, the daily GPP and TER were clearly distinguishable. During the growing season, the maximum daily values of NEE, TER and GPP were -9.4, 11.5 and -18.0 g C m^{-2} d^{-1}, respectively. Respiration levelled off at the end of November and TER remained low during the winter time until beginning of May in 2011. Winter time TER averaged to 0.51 g C m^{-2} d^{-1}. During the growing season in 2011, the maximum daily values of NEE, TER and GPP were similar to that in 2010. Respiration levelled off by the beginning of December, with an average value of 0.76 g C m^{-2} d^{-1} for December 2011.

3.3 Factors controlling CO_2 exchange

3.3.1 Gross photosynthesis

The strong relationships between bin-averaged GPP and PAR from May to September in 2010 and 2011 can be seen in Fig. 6a–e. The rectangular hyperbolic model provided good fits to the data (adjusted R^2 > 0.90, Table 1) except in May 2010 and 2011 (adjusted R^2 0.52 and 0.76, respectively) and all relationships were statistically significant ($p < 0.01$). There was no clear indication of GPP saturation even at PAR levels close to 1800 µmol m^{-2} s^{-1} during June and July (Fig. 6a–e). The estimated monthly GP_{max} values are shown in Table 1. There were no differences in the GP_{max} values for May, June and July during 2010 and 2011, whereas in August and especially in September, the monthly average GP_{max} was higher in 2011 than in 2010. The seasonal variation in monthly GP_{max} values was clear (Table 1) and in May, September and August, the monthly averaged GP_{max} were low while the maximum values were observed in June and July. The range of the monthly α -values (quantum yield) varied from -0.04 to -0.06 in 2010 and from -0.05 to -0.07 in 2011. Further analysis under conditions with PAR level greater than 1000 µmol m^{-2} s^{-1} revealed that effect of other climatic variables such as air temperature, VPD and soil moisture on GPP was masked by the dominant role of PAR.

We studied the relationships between weekly averaged GPP, GA and LAI. GPP increased with an increasing GA implying a positive linear relationship between these variables, the adjusted R^2 value of the regression was 0.28 in 2010 ($p = 0.011$) and 0.45 in 2011 ($p < 0.01$). Relationship between GPP and LAI was not evident in 2010; however, they were better correlated in 2011 with an adjusted R^2 value of 0.42 ($p < 0.01$).

3.3.2 Ecosystem respiration

There was a clear relationship between bin-averaged night-time TER and soil temperature from May to September in 2010 and 2011 (Fig. 7a). The exponential regression model provided good fits to the data (adjusted R^2 0.71 and 0.69 for 2010 and 2011, respectively) and the relationships were statistically significant ($p < 0.01$). The Q_{10} values were similar between the two years (2.17 and 2.35). The R_{10} values were 1.75 and 1.66 µmol m^{-2} s^{-1} in 2010 and 2011, respectively. Additionally, TER increased with the increasing GA in 2010 (Fig. 7b), however, the linear correlation was not statistically significant (adjusted $R^2 = 0.16$, $p = 0.053$). TER and GA were better correlated in 2011 (adjusted $R^2 = 0.51$, $p < 0.01$). There was a strong positive linear relationship between TER and GPP ($p < 0.01$) in both years (Fig. 7c). GPP explained 82% and 75% of the variation in the TER in 2010 and 2011, respectively.

3.4 Annual balance

The estimated annual balances of TER, GPP and NEE are ~~given~~ shown in Table 2. The site acted as a CO_2 sink during the studied years and the annual NEE was -56.7, -262 and -256 g C m^{-2} in 2009 (23 July – 31 December), 2010 and 2011, respectively. The pattern in NEE accumulation is show in Fig 8. During the three week time period from late July to mid-August 2009, the site acted as a source of atmospheric CO_2. After the transition from a source to a sink in mid-August 2009, the site sequestered atmosphere CO_2 for about 60 days leading to a negative cumulative NEE of -160 g C m^{-2}. During the winter dormancy period (from late October 2009 to May 2010) the site lost 183 g C m^{-2} and the cumulative NEE was 23 g C m^{-2}. After this, the site was an annual CO_2 sink, since the summer time uptake was higher than the winter time CO_2 loss. In 2010, CO_2 uptake period lasted approximately 120 days (May to mid-September) and in mid-September the cumulative NEE was -403 g C m^{-2}. During the second winter dormancy, from Mid-September 2010 to mid-May 2011, the site lost approximately 168 g C m^{-2}. In 2011, the CO_2 uptake period lasted about 135 days (from mid-May to early October) with a cumulative NEE of -679 g C m^{-2} by the end of this season. By the end of 2011, the cumulative NEE was -575 g C m^{-2}. This final cumulative value of CO_2-C represents the amount of carbon the site accumulated from the start of the measurements in July 2009 until the end of 2011.

4 Discussion

The use of renewable energy sources such as perennial bioenergy crops has been suggested as one of the options for mitigating CO_2 emissions. Cultivation of RCG, a perennial bioenergy crop, has been shown to be a promising after-use option on a cutaway peatland (a drained organic soil) in Finland (Shurpali et al., 2009, 2010). In the present study we explore further if the benefits of RCG cultivation were limited to the organic soils only. For the purpose, we measured CO_2 exchange during three years from the start of the crop rotation cycle on a mineral soil from the same variety of RCG crop as was used on a drained organic soil, in eastern Finland. Generating such knowledge from different soil types is useful in developing scientifically based bioenergy policies.

The studied RCG site on mineral soil was an annual sink for atmospheric CO_2 with an average NEE of -260 g C m^{-2} for 2010 and 2011 (Table 2). This net uptake rate of CO_2 is higher than what has been reported previously for RCG cultivation. During a four year study in Finland, an a~~A~~nnual NEE ranging from -8.7 to -210 g C m^{-2} has been reported for a cut-away peatland with RCG cultivation in Finland (Shurpali et al., 2009) and during a one year study in Denmark, an annual NEE of +69 g C m^{-2} was reported for an organic agricultural site~~ in Denmark ~~ (Kandel et al., 2013a). Measurements of CO_2 exchange have been carried out also on other bioenergy crops. ~~such as switchgrass (*Panicum virgatum* L.), miscanthus (*Miscanthus×giganteus*), hybrid poplar (*Populus deltoides x Populus petrowskyana*) and willow (*Salix* spp) (Grelle et al., 2007; Skinner and Adler, 2010; Zeri et al., 2011; Jassal et al., 2013). Compared to these studies, the annual NEE of the present study is in the middle range.~~ On average, ~~A~~annual NEE of switchgrass cultivation ~~ranged~~ was ~~from~~ -150 ~~to -470~~ g C m^{-2} during a four year study in USA (Skinner and Adler, 2010). Annual NEE for ~~and for~~ miscanthus ~~cultivation in USA, it~~ was -420 g C m^{-2} during a two year study in USA (~~Skinner and Adler, 2010~~; Zeri et al., 2011). Annual NEE of young hybrid poplar stand in Canada was +37 g C m^{-2} in a two year study (Jassal et al., 2013). Willow stands have been studied in Sweden with an annual NEE value of -510 g C m^{-2} in a three year study (Grelle et al., 2007). Compared to these studies, the annual NEE of the present study is within the ~~in the middle~~ range of these previously reposted values from various bioenergy systems. Forests are an important source of bioenergy in the boreal region and long-term CO_2 exchange studies have been carried out on Scots pine stands on mineral soils. Annual NEE of an approximately 40 year old stand in southern Finland was -210 g C m^{-2} during the six year study ~~period~~ (~~2002–2007~~, Kolari et al., 2009). Average NEE of a 50 year old stand measured during a 10 year study ~~period (1999–2008)~~ in eastern Finland was estimated to be -190 g C m^{-2} (Ge et al., 2011). So, RCG in the present study has a higher capacity for carbon uptake than Scots pine on mineral soils under boreal environmental conditions.

The mineral soil site in the present study had stronger capacity to withdraw atmospheric CO_2 than the same variety of RCG crop cultivated on a comparison site ~~on~~ (a drained organic soil) in Finland (Shurpali et al., 2009). The organic site and the mineral site under investigation in this study are located approximately at the same latitude. The long-term climatic conditions between the sites are similar. Also, the variety of RCG crop planted on the study site is the same as the one cultivated on the organic soil site. ~~In the following,~~ Therefore, it is intuitive to ~~we will~~ compare the results from ~~differences between the mineral soil site in~~ the present study with the already published results from the comparison site ~~and the published results of a drained organic soil site~~ (~~a reference site,~~ Shurpali et al., 2008; Hyvönen et al., 2009; Shurpali et al., 2009, 2010, 2013; Gong et al., 2013). ~~In brief, this reference site was originally an ombrotrophic pine bog (Biasi et al., 2008). It was drained for peat mining in 1976 and the cultivation of RCG started in 2001. Flux studies on RCG were carried out from 2004–07.~~

The main differences between the two sites lie in the soil type, nutrient status and water retention characteristics of the soil. Mineral soil site studied here is an agricultural field with soil texture of silt loam. ~~ranging from clay loam to loam.~~ Also the soil was rich with nutrients indicated by the low C:N ratio. While the mineral soil site investigated here had a C:N ratio of 14.9, the ~~reference~~ comparison site had a C:N ratio of 40.3 (Shurpali et al., 2008). The differences in the nutrient status of the soil types is further borne out by the fact that the mineral soil in the present study had a seasonal N_2O emission from this RCG cultivation system of the order of 2.4 kg ha^{-1} (Rannik et al., 2015), while the ~~reference~~comparison site had negligible emissions (Hyvönen et al., 2009). Higher N_2O emissions imply~~ing~~ that the enhanced rates of soil N transformations in the mineral soil~~,~~ support active soil C cycling and associated high release of soil nutrients. The soil nutrients are available for the plant roots ~~to exploit~~ so that a vigorous plant growth can be sustained. Additionally, the soil moisture conditions during the study period at the mineral site under investigation were conducive for prolific rates of belowground and above-ground RCG biomass growth. Based on the results presented here, it seems that the soil water movement at the mineral site was coupled with the energy load on the surface. The daily variations in soil profile moisture content (Fig. 1c) reveal that soil moisture at 30 cm depth also varies in phase with the surface soil moisture content at this site hinting at a coupled soil hydrological system. The soil water and heat exchange monitored in this study is thus influenced by the surface energy exchange. This is contrary to what has been reported for the ~~reference~~ comparison site. The ~~organic~~ soil moisture content at 30 cm depth in the comparison site was found to be rather constant and saturated throughout the growing seasons (Shurpali et al., 2009), while only the near surface soil layers exhibited variations in soil moisture content as affected by the radiation load on the soil surface and seasonal precipitation events. These observations hint at a decoupled hydrological system in the ~~reference~~ comparison site (Gong et al., 2013). This is further supported by the shallow rooting pattern reported in Shurpali et al., 2009) where 95% of the RCG roots were concentrated in the first 15 cm of the drained organic soil profile. Owing to a coupled soil hydrology, the rooting depth of RCG plants in this~~e~~ mineral soil, however, appears to be not constrained by hydrological limitations as opposed to the restrictions laid on the RCG root development in a cutover peatland.

Typical rotation cycle of the RCG cropping system grown for bioenergy in eastern Finland varies from 10–15 years. The RCG stand at the mineral site studied here was young, 0–3 year old stand. At the ~~reference~~ comparison site the RCG stand was a matured, 4–7 year old stand. Compared to the published yield from RCG on the ~~reference~~ comparison site, the crop yield from the study site was approximately 3.5 times higher (Shurpali et al., 2009). This difference in the above-ground biomass was visible also in the seasonal LAI with higher maximum values measured at the mineral soil site (5.4) than at the ~~reference~~ comparison site (3.5, Shurpali et al., 2013). However, the timing of the peak LAI (Fig. 2) was similar between the sites. Despite the young age of the crop on the mineral soil, RCG has a capacity to produce more biomass than the same variety of the older RCG crop on the ~~reference~~ comparison site. The average spring harvested RCG yield reported here, 6500 kg DW ha^{-1}, was not the highest yield reported for mineral soil sites in Finland. The RCG yield for mineral soils in Finland has ranged from 6400 to 7700 kg DW ha^{-1} (Pahkala and Pihala, 2000). However, we expect that the above- and belowground biomass of the crop at our mineral soil site will further increase with the crop age. RCG on mineral soil site had higher water use efficiency (12 g CO_2 per kg H_2O) when compared with published WUEs for RCG ~~reference~~comparison site (9.1 g CO_2 per kg H_2O) or for grasslands (3.4 g CO_2 per kg H_2O) and crops (3.2 g CO_2 per kg H_2O) (Law et al., 2002; Shurpali et al., 2013). These results indicate that the RCG crop cultivated ~~on a~~ at this mineral soil site is more efficient, in sequestering atmospheric CO_2 per unit amount of H_2O lost as ET and thus more effective in utilizing the available resources.

As NEE is the balance between the two major opposing fluxes of GPP and TER, it is important to evaluate these processes separately. Average annual GPP (-1300 g C m^{-2}) at the mineral soil site was in the range of what has been reported earlier for RCG cultivation on the comparison ~~reference~~ site (-590 g C m^{-2}, Shurpali et al., 2009) and in organic agricultural field Denmark (-1800 g C m^{-2}, Kandel et al., 2013a). Annual GPP of the present study is higher than what has been published earlier for switchgrass, hybrid poplar and Scots pine forests (Kolari et al., 2009; Skinner and Adler, 2010; Ge et al., 2011; Jassal et al., 2013). Annual GPP for switchgrass cultivation was -930 g C m^{-2} in USA (Skinner and Adler, 2010), -540 g C m^{-2} for hybrid poplar stand in Canada (Jassal et al., 2013), -1100 g C m^{-2} for Scots pine stand in southern Finland (Kolari et al., 2009) and -830 g C m^{-2} for Scots pine stand in eastern Finland (Ge et al., 2011). During the summer months, GPP at our study site was limited primarily by light levels. Especially early in the summer (June–July), plants were developing rigorously. The inherent ability of the crop to sequester maximum atmospheric CO_2 in this phase was seen in the high GP_{max} values (Table 1). Higher photosynthesis activity at the present study on the mineral soil than at the ~~reference~~ comparison site can be explained by the higher plant productivity. Soil moisture conditions and nutrient status of the site were ~~optimal~~ conductive for an optimal crop growth. Additionally, it is vital to realise that the crop water losses from the RCG crop at this site were higher than the water input to the ecosystem through precipitation events during summer periods. The CO_2 uptake rates, however, do not seem to be affected by climatic stress at the mineral soil site as the crop had the mechanism to cope with the stress by drawing the available soil moisture through capillary forces from deeper layers of the soil. This explains why the crop was limited primarily by light levels and other environmental variables had minimal role in regulating the RCG photosynthetic rates at this site.

On an annual basis, the average TER (+1000 g C m^{-2}) for our study was within the range of what has been reported earlier for RCG cultivations at ~~reference~~ comparison site (+480 g C m^{-2}, Shurpali et al., 2009), in cut-away peatland Estonia (+600 g C m^{-2}, two year study, Mander et al., 2012) and in organic agricultural field Denmark (+1900 g C m^{-2}, Kandel et al., 2013a). When compared to annual TER values for switchgrass, hybrid poplar and Scots pine forest (Skinner and Adler, 2010; Jassal et al., 2013; Kolari et al., 2009), the annual TER of the present study is higher. Average annual TER for switchgrass cultivation was +780 g C m^{-2} in USA (Skinner and Adler, 2010), +580 g C m^{-2} for hybrid poplar stand in Canada (Jassal et al., 2013) and +790 g C m^{-2} for 40 year old Scots pine stand in southern Finland (Kolari et al., 2009). Difference in the annual respiration rates between our mineral soil site and the ~~reference~~ comparison site can be explained with differences in the biomass as higher biomass increases also autotrophic and heterotrophic respiration. TER was mainly controlled by soil temperature during the summer months at this site with plant biomass, LAI and GPP also explaining a part of the variation in TER rates. The lack of GA correlation in 2010 could be attributed to the unharvested biomass from the 2009 season. The biomass left at the site may have affected the soil respiration rates in 2010. The base respiration (R_{10}) rate (1.75 and 1.66 µmol m^{-2} s^{-1} in 2010 and 2011, respectively) and Q_{10} (2.17 and 2.35 in 2010 and 2011, respectively) values were estimated in this study with a nonlinear regression of observed TER on soil temperature (Fig. 6). Both R_{10} and Q_{10} in the present study are in the range of what has been reported by other authors. Earlier papers have reported R_{10} values for the ~~reference~~ comparison site ranging from 0.24 to 1.39 µmol m^{-2} s^{-1} (Shurpali et al., 2009) and for grassland in Canada ranging from 0.2 to 3.6 µmol m^{-2} s^{-1} (Flanagan and Johnson, 2005). For Q_{10}, the earlier reported values range from 2.0 to 5.4 for the reference site (Shurpali et al., 2009) and from 1.2 to 2.7 grassland in Canada (Flanagan and Johnson, 2005). The R_{10} was higher and Q_{10} was lower for RCG on mineral soil, an opposite trend has been reported for the RCG ~~reference~~ comparison site (Shurpali et al., 2009). The soil temperatures did not explain the differences between the present study and the comparison site as the soil temperatures were similar in the topsoil during May-September in the sites (Shurpali et al., 2013). Higher base respiration rate observed in this study is reflectiv~~es~~e of the active cycling of soil C in this ecosystem.

The comparative analysis of the CO_2 exchange from mineral and drained organic soil suggests that from a CO_2 exchange perspective, the RCG cultivation on mineral soils is more environmentally friendly. ~~In this paper we showed that the RCG was environmentally friendly from the CO_2 balance point of view when cultivated on a mineral soil. When compared to the earlier findings on the same crop on organic soil site, t~~The capacity of the ~~crop~~ RCG to withdraw atmospheric CO_2 was even stronger on the mineral soil site than that on the organic soil site. For a complete ~~full~~ estimation of the climatic impacts of RCG on mineral soil site, other greenhouse gas (N_2O and CH_4) emissions during the crop production phase have to be included in addition to all energy inputs and outputs associated with the crop management. Only then a complete life cycle assessment can be done needed to understand the sustainability of a bioenergy system. Such comparative analyses involving studies on different soil types are important in evaluating national bioenergy policies.

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Table 1. Monthly fit results of a rectangular hyperbolic model together with average climatic conditions. The fit results between gross primary production (GPP, µmol m^{-2} s^{-1}) binned with photosynthetically active radiation (PAR, µmol m^{-2} s^{-1}, bins from 0 to 1800 µmol m^{-2} s^{-1} with an interval of 10 µmol m^{-2} s^{-1}) from mid-May to September in 2010 and 2011. A rectangular hyperbolic model of the form GPP = $(GP_{max} \cdot PAR \cdot \alpha / (GP_{max} + PAR \cdot \alpha)$, where GP_{max} (±SE, µmol m^{-2} s^{-1}) is the theoretical maximum rate of photosynthesis at infinite PAR and α (±SE) is the apparent quantum yield, i.e., the initial slope of the light response curve, was used. Adjusted R^2 of regression and number of PAR bins (n) are shown. Also monthly average (±SD) of air temperature (T, °C), volumetric water content (VWC, m^3 m^{-3}) at 2.5 cm depth and vapour pressure deficit (VPD, kPa) are shown together with number of rain event days (when precipitation > 0.2 mm) in month, precipitation sum (prec., mm mo^{-1}) and monthly averaged green area (GA, m^2 m^{-2}) and leaf area (LAI, m^2 m^{-2}) indices.

Month	GPmax	α	R2	n	T	VWC	VPD	Prec.		GA	LAI
	(µmol m^{-2} s^{-1})				(°C)	(m3 m^{-3})	(kPa)	events	sum		
2010											
May	-21.5 ± 1.7	-0.057 ± 0.009	0.52	133	14.3 ± 5.3	0.26 ± 0.05	0.65 ± 0.6	7	23	8.7	1.8
Jun	-44.5 ± 1.7	-0.047 ± 0.002	0.93	158	13.0 ± 4.6	0.26 ± 0.05	0.54 ± 0.4	9	72	19.0	4.3
Jul	-40.1 ± 1.1	-0.053 ± 0.002	0.95	163	21.0 ± 4.7	0.14 ± 0.03	0.85 ± 0. 7	7	34	17.2	4.0
Aug	-25.2 ± 0.7	-0.057 ± 0.003	0.91	148	15.8 ± 6.2	0.14 ± 0.05	0.53 ± 0.5	14	42	14.0	3.9
Sep	-18.1 ± 2.2	-0.040 ± 0.007	0.93	19	9.8 ± 3.9	0.21 ± 0.04	0.14 ± 0.2	16	53	14.1	4.0
2011											
May	-21.2 ± 1.0	-0.056 ± 0.005	0.76	134	11.2 ± 4.0	0.30 ± 0.03	0.45 ± 0.4	11	38	5.7	1.8
Jun	-45.8 ± 1.4	-0.060 ± 0.002	0.94	163	16.1 ± 4.9	0.21 ± 0.05	0.73 ± 0.6	11	41	16.2	4.6
Jul	-40.4 ± 1.5	-0.050 ± 0.002	0.92	154	19.1 ± 4.4	0.20 ± 0.06	0.65 ± 0.5	11	91	15.5	5.3
Aug	-29.9 ± 1.0	-0.069 ± 0.004	0.90	141	15.0 ± 3.5	0.25 ± 0.05	0.38 ± 0.4	10	80	12.5	3.7
Sep	-24.2 ± 0.7	-0.074 ± 0.004	0.94	103	11.1 ± 3.3	0.31 ± 0.04	0.20 ± 0.2	13	70	8.0	4.3

Table 2. The estimated annual CO_2 balances of the reed canary grass cultivation. Annual values of net ecosystem CO_2 exchange (NEE), total ecosystem respiration (TER) and gross primary production (GPP) are shown in ~~two units:~~ g C m^{-2} ~~and g CO_2 m^{-2}~~. Negative values stand for uptake and positive for emission to the atmosphere. Note that 2009 is not a full year (23 July - 31 December).

	2009	2010	2011
NEE	56.8	-262	-256
TER	434	969	1043
GPP	491	-1231	-1299

	~~2009~~	~~2010~~	~~2011~~
~~NEE (g m^{-2})~~			
~~C~~	~~-56.8~~	~~-262~~	~~-256~~
~~CO_2~~	~~-208~~	~~-959~~	~~-940~~
~~TER (g m^{-2})~~			
~~C~~	~~434~~	~~969~~	~~1043~~
~~CO_2~~	~~1592~~	~~3550~~	~~3821~~
~~GPP (g m^{-2})~~			
~~C~~	~~-491~~	~~-1231~~	~~-1299~~
~~CO_2~~	~~-1800~~	~~-4509~~	~~-4760~~

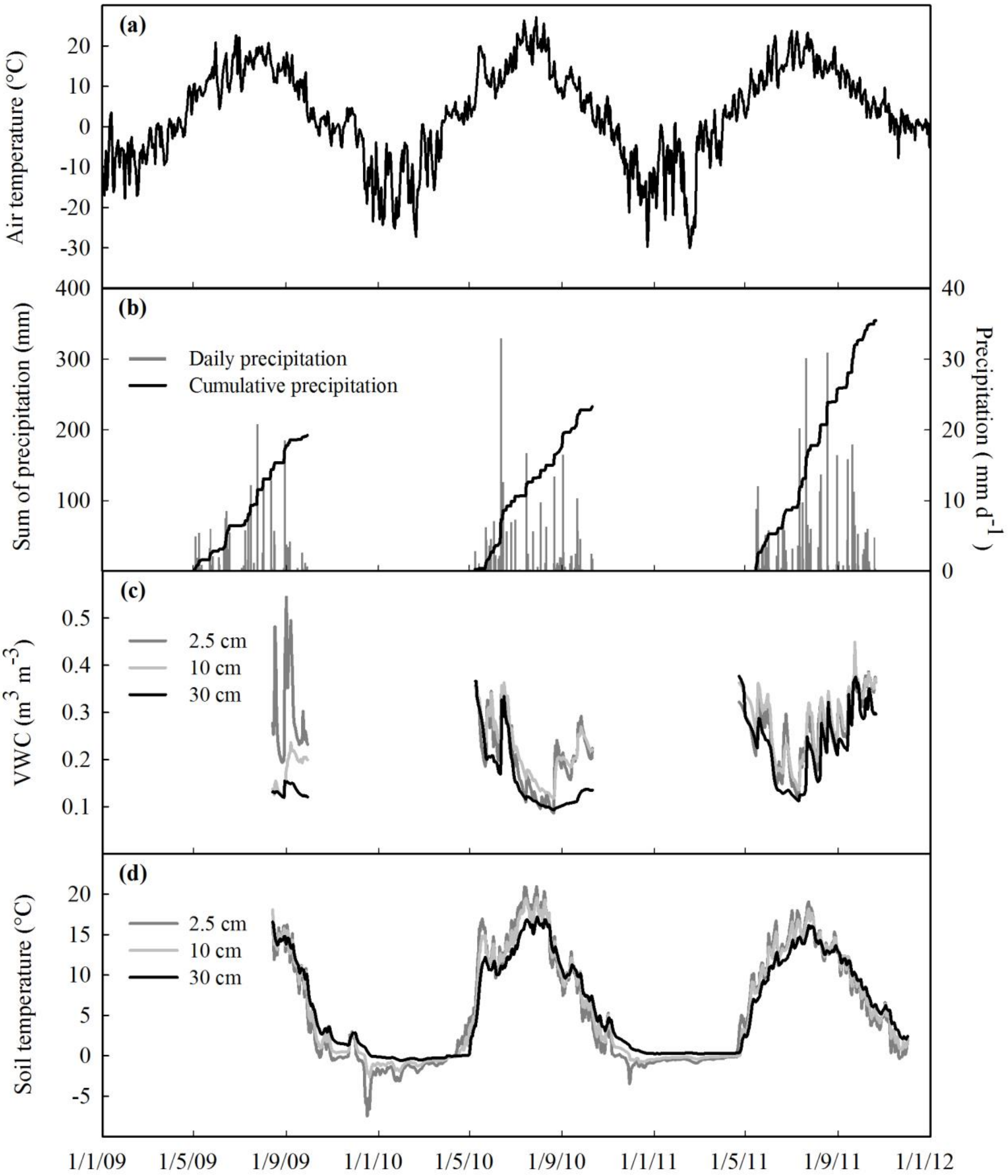

Figure 1. Climatic conditions at the study site during the measurement years. (a) Daily averaged air temperature (°C) during 2009-2011, (b) Daily precipitation (mm d^{-1}, grey line) and its cumulative sum (mm, black line) during the growing seasons. (c) Daily averaged volumetric water content (VWC, m^3 m^{-3}) at 2.5cm (dark grey line), 10 cm (light grey line) and 30 cm (black line) during the growing seasons, from August 14, 2009 onwards. (d) Soil temperatures (°C) at the 2.5cm (dark grey line), 10 cm (light grey line) and 30 cm (black line) depths as daily means from August 14, 2009 until December 2, 2011.

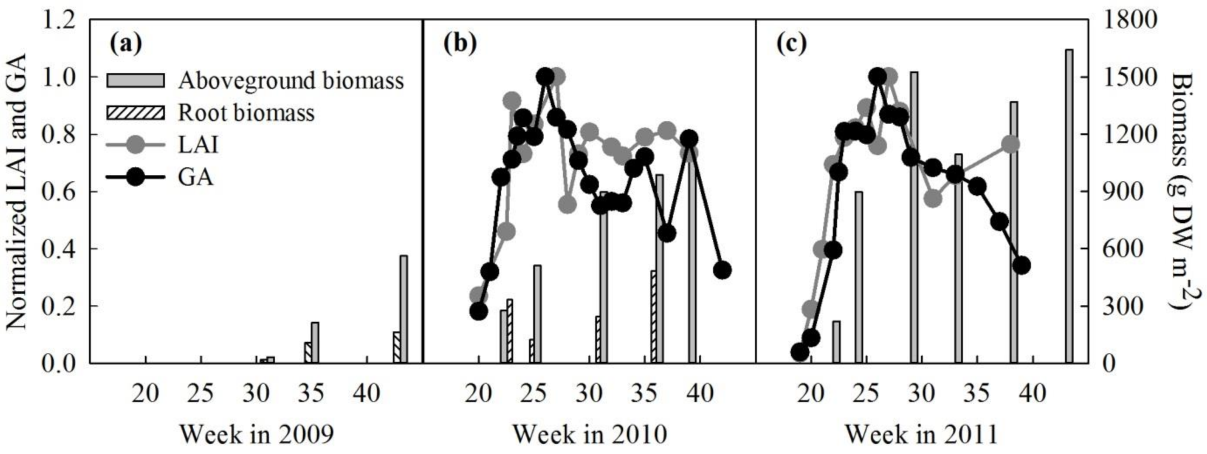

Figure 2. Vegetation parameters determined on the reed canary grass (RCG) cultivation. Approximately monthly determined above-ground (grey bars) and root biomass (hatched bars) in g dry weight (DW) m^{-2} between week 15 and 45 in (a) 2009, (b) 2010 and (c) 2011. Also approximately weekly determined normalized green area index (GA, black dots) and leaf area index (LAI, grey dots) for (b) 2010 and (c) 2011 is shown.

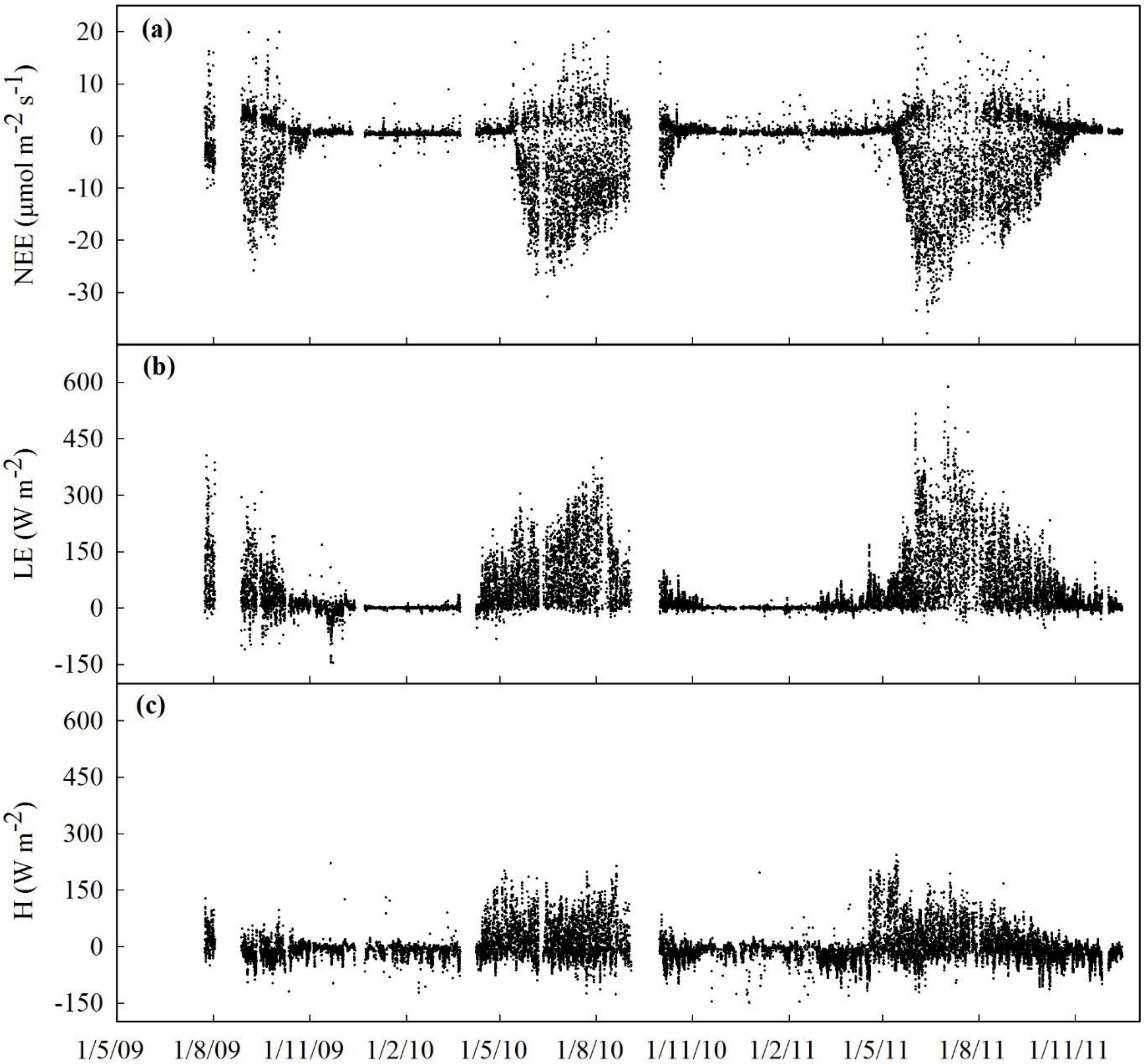

Figure 3. Measured CO_2 and energy fluxes from July 2009 to December 2011. (a) Net ecosystem CO_2 exchange (NEE, μmol m^{-2} s^{-1}). (b) Latent heat flux (LE, W m^{-2}). (c) Sensible heat flux (H, W m^{-2}).

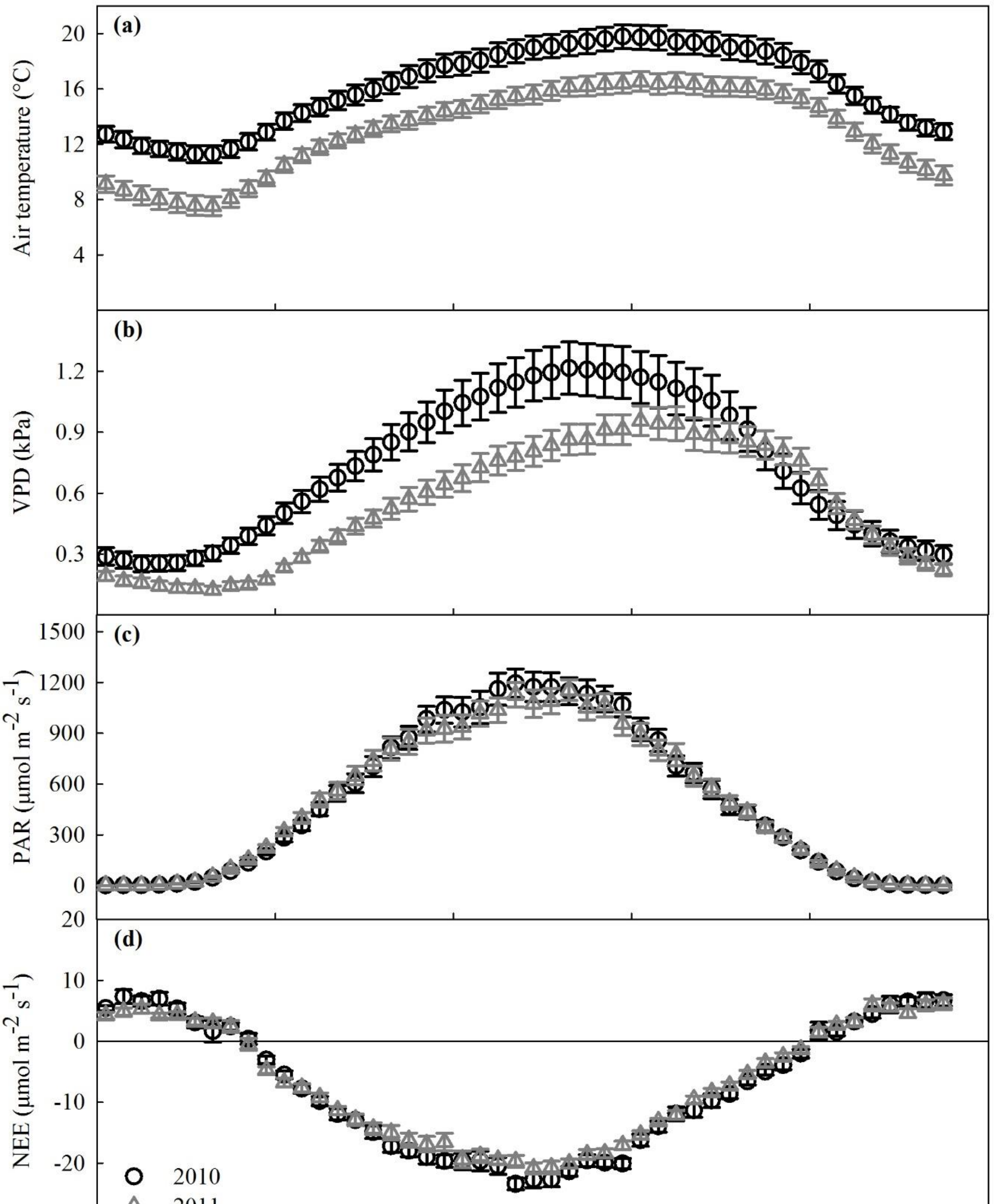

Figure 4. Mean diurnal variations in June 2010 (open grey triangles) and 2011 (open black circles). (a) Air temperature (°C). (b) Vapour pressure deficit (VPD, kPa). (c) Photosynthetically active radiation (PAR, μmol m^{-2} s^{-1}). (d) Net ecosystem CO_2 exchange (NEE, μmol m^{-2} s^{-1}). Data are half-hour means with standard error.

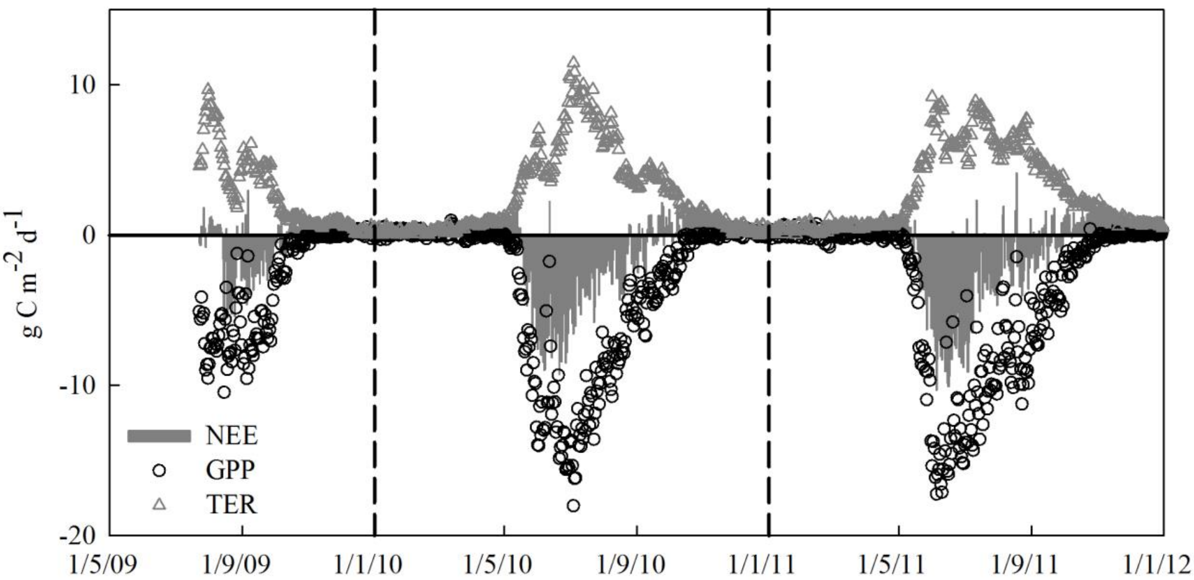

Figure 5. The components of daily CO_2 exchange over the measurement period. Daily sum of net ecosystem CO_2 exchange (NEE, grey bars), gross primary production (GPP, open black circles) and total ecosystem respiration (TER, open grey triangles) as g C m^{-2} d^{-1}. Horizontal solid black lines show the zero level and vertical dashed black lines mark beginning of the year.

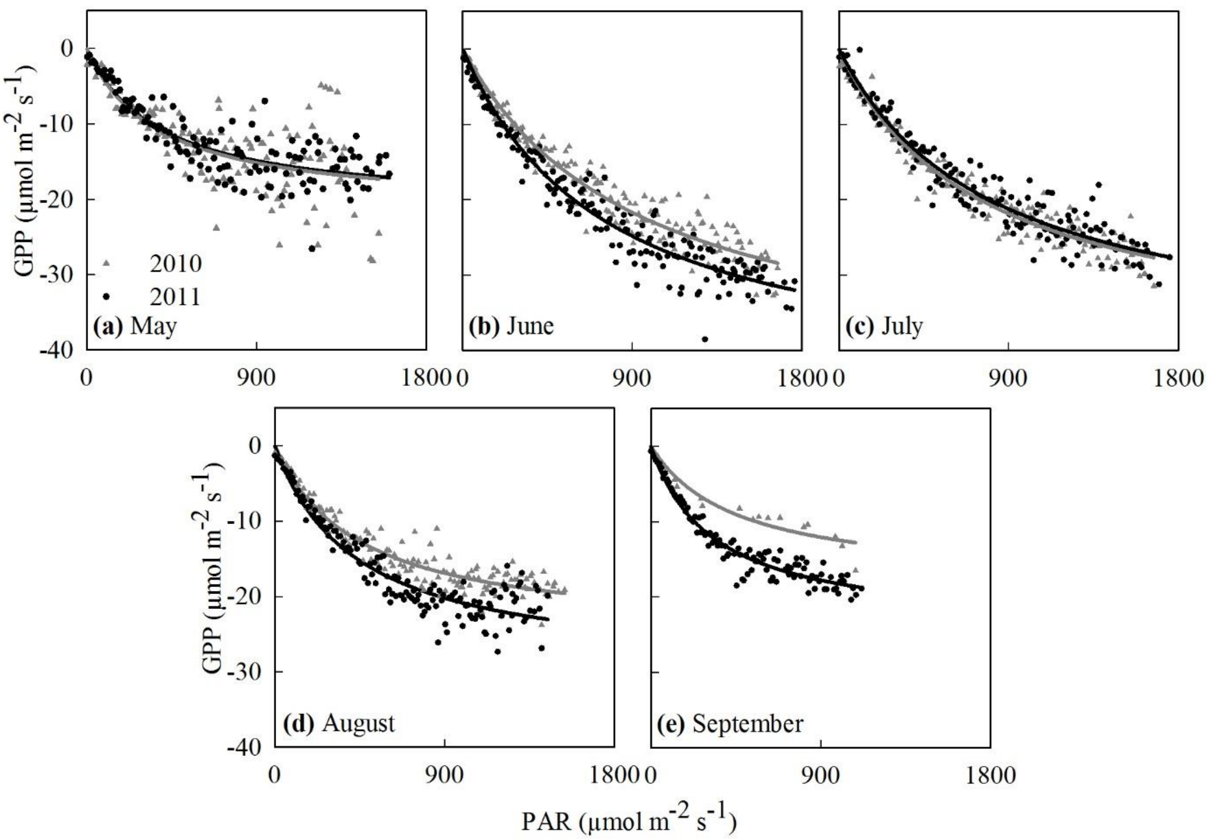

Figure 6. Relationship of gross primary production (GPP) to incident photosynthetically active radiation (PAR). Measured monthly (mid-May-September) GPP (µmol m^{-2} s^{-1}) averaged with binned (steps of 10 µmol m^{-2} s^{-1}) PAR (µmol m^{-2} s^{-1}) for 2010 (closed grey triangles) and 2011 (closed black circles). Data are fitted with nonlinear regression (GPP = ($GP_{max} \cdot PAR \cdot \alpha$ / ($GP_{max} + PAR \cdot \alpha$)) between GPP and PAR (fit results in Table 1). Only measured data were used in the analysis.

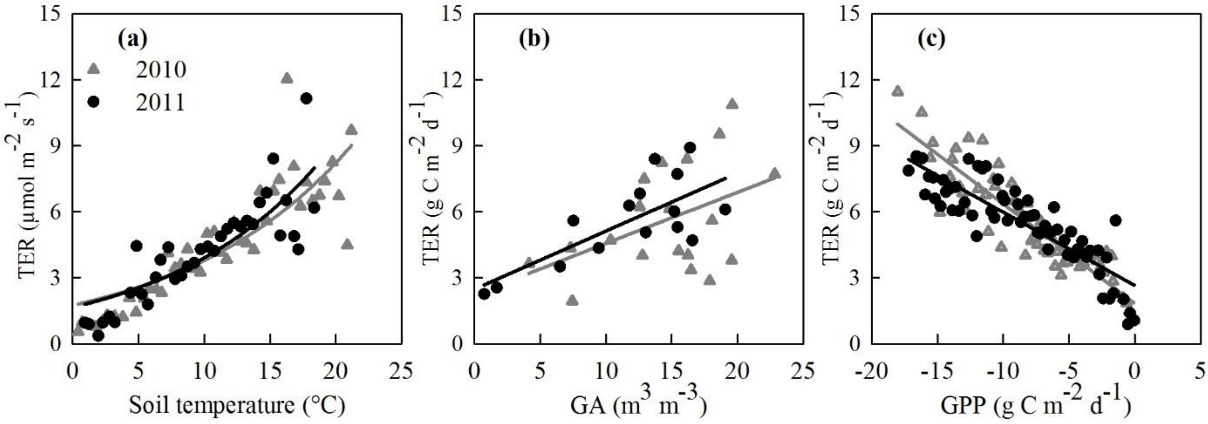

Figure 7. Relationships between total ecosystem respiration (TER) and environmental variables. (a) TER (µmol m^{-2} s^{-1}) and soil temperature (°C) at 2.5 cm depth (binned with steps of 0.5°C) in May-September period fitted with an exponential nonlinear regression (TER = $R_{10} \cdot Q_{10}^{(Ts / T10)}$, where R_{10} and Q_{10} are fitted parameters). (b) Weekly averaged TER (g C m^{-2} d^{-1}) and green area index (GA, m^3 m^{-3}) in May-October period fitted with linear regression. (c) Daily values of TER (g C m^{-2} d^{-1}) and gross primary production (GPP, g C m^{-2} d^{-1}, binned with steps of 0.25 g C m^{-2} d^{-1}) in May-September period fitted with linear regression. Closed grey triangles are data for 2010 and closed black circles for 2011. Fit results are given in the text.

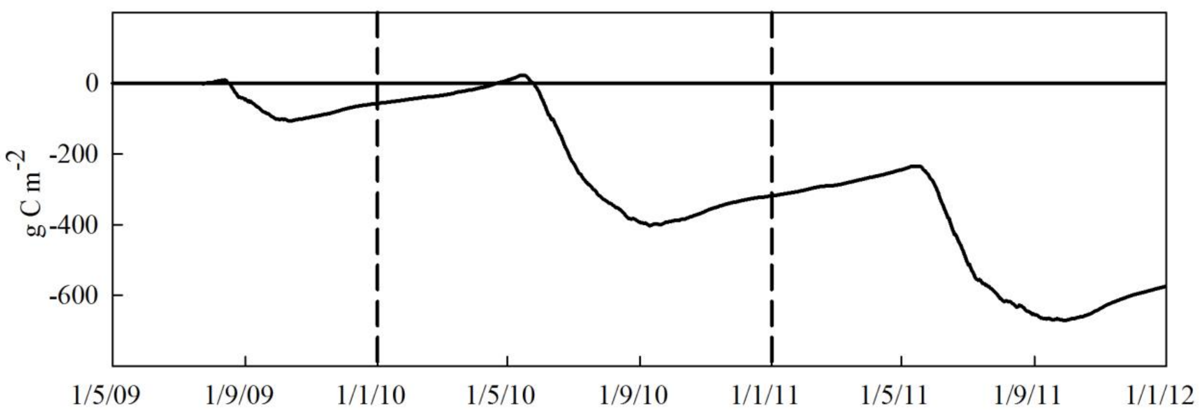

Figure 8. Cumulative NEE over the study period. Negative values indicate uptake of CO_2 and positive values emission to the atmosphere. Horizontal solid black lines show the zero level and vertical dashed black lines mark beginning of the year.