

We thank the reviewers for spending their time and stated constructive comments. All reviewer comments are addressed and requested changes are implemented in manuscript.

Please find attached the full response of reviewer #2 and #3.

Please note the reviewer comments are marked in black and the author comments marked in green.

Interactive comment on “Dynamic C and N stocks– key factors controlling the C gas exchange of maize in a heterogenous peatland” by M. Pohl et al.

Anonymous Referee #2

Received and published: 13 January 2015

This manuscript reports on a study of soil C and N stocks and C gas exchange in a disturbed peat and landscape. Three soils, representing a gradient in soil C stocks and GWL level were investigated. By recognising the heterogeneity of such landscape, and attempting to capture it in GHG exchange studies this project makes a very useful contribution to the scientific literature. Also, the concept of dynamic soil C and N stocks is interesting and warrants discussion in the literature.

Overall I am in agreement with the manuscript in its current form but feel that the following suggestions would improve it.

Comments of #2

1. Comment: Title: While it may have been a peatland can it still be called that? There is a mosaic of soils but can an arenosol be considered peat?
 - Of course, an Arenosol is not a peaty soil. The term “peatland” is used in a broader sense to characterize the landscape. It is (still) largely dominated by organic soils, but reveals smaller patches of sandy soils.
2. Comment: L28 How can this be considered a gradient of pedogenesis? Are these soils not the result of drainage and disturbance? Indeed more detail is need on this regarding the study sites. Can the authors provide information on the disturbance history?
 - The reviewer is right. The sentence is rephrased in **lines 26-27** (page 16136, lines 13-15): “..., where we selected three soil types representing the full gradient in GWL and SOC stocks (0-1m) of the landscape: ...”.
 - As the reviewer suggested we also added a short paragraph summarizing the land use history (point 2.1, page 16140, line 7, now lines 125-141; marked-up manuscript **lines 139-154**).

3. Comment: L167 More detail is needed. Was the model run separately for each soil type and if so how were the differences in soil properties overcome?

- The models were calculated separately for each soil type. We therefore described in this paragraph (page 16141, lines 9-14; marked-up manuscript **lines 181-184**) that site-specific half-hourly temperature data was derived from correlations between the respective half-hourly climate station temperature records and site-specific, manually measured, discontinuous temperature data. Differences in temperatures models between soil types are likely related to differences in soil properties.

4. Comment: L255 More detail is needed on why NEE was transformed in this way.

- In order to allow for application of the log link function for GLM analysis, data must consist of positive values only. As CH₄ and NEE fluxes can be both positive and negative, data was transformed to all-positive values by adding the minimum value to all values (as stated on page 16145, lines 13 and 15), which is a common procedure prior to the application of logarithmic functions in statistical analysis. We changed the beginning of sentence from: “Accordingly, ...” to “Analogously, ...” (page 16145, line 15; now line 270, marked-up manuscript **line 283**).

5. Comment: Given the importance of soil C dynamics I wonder why the authors did not measure heterotrophic respiration? This could reveal more about the influence of GWL and soil C on soil respiration.

- The main reason for not presenting data on heterotrophic respiration is the fact that the function of the plant-soil system as a source or sink C gases is simultaneously determined by soil- and microbe-induced fluxes to the atmosphere and the plant-mediated C gas fluxes into the plant-soil system. In other words: correct statements can only be made if all relevant C gas fluxes are measured – as realized in our methodological approach. Measurements of heterotrophic respiration (i.e. system respiration without plant respiration) are thus insufficient to address the study objectives.

We revised the relevant sentences in the introduction to emphasize this (page 16138, lines 1-10, now lines 64-75; marked-up manuscript **lines 67-78**):

“In light of the extreme complexity of site conditions, it seems quite unlikely that the common focus on interactions between C stocks and particularly relevant control parameters like groundwater and temperature (Adkinson et al. 2011, Berglund et al. 2010, Kluge et al. 2008, Jungkunst and Fiedler 2007, Daulat et al. 1998) will result in

reliable and generalizable conclusions about the C gas fluxes of degraded fens; mainly because this approach fails to account for the plant-induced C gas input counteracting the C gas emissions determined by soil characteristics and microorganisms.

Therefore, new insights are much more likely to be derived from system-oriented studies analysing all interrelated C gas fluxes,”

As well on page 16139, lines 19-24 (now lines 108-111; marked-up manuscript **lines 120-123**):

“The present study tests the above-mentioned assumption by means of multi-year manual chambers measurements, subsequent modeling and complex statistical analysis of all relevant C gas fluxes, i.e. the net CO₂ exchange resulting from gross primary production (plant photosynthesis) and ecosystem respiration (sum of plant and soil respiration) and the CH₄ exchange, of maize cultivated on different groundwater-dependent soil types representing a steep SOC gradient.”

Further details can be found in our reply to comment 1 of Reviewer #3.

Anonymous Referee #3

Received and published: 20 February 2015

General comments (#3)

The manuscript describes the results of a multiyear field study dealing with the carbon gas exchange of maize in a heterogeneous peat land. The results from this study will contribute to a better understanding of the environmental controls of the carbon exchange above cultivated peat lands and improve the upscaling from such sites. I recommend publishing of the manuscript after minor revisions.

1. Comment: The concept of dynamic C and N stocks is presented in the abstract as a hypothesis. I would suggest to present the validity of this concept as a major result of the study. One of the surprising results of this study is that the AR soil having the lowest SOC turned out to be a source for CO₂ to the atmosphere, while the two other soils comprise a sink. To me the potential reasons for this finding do not become clear from the discussion. On page **16150 line 24** the authors state that the soils contain a large stock of decomposable carbon. How was the decomposable fraction of organic carbon in the soils estimated? Given that the GWL has a pronounced effect on the carbon turnover, is it possible that the groundwater itself interacts with the respiratory CO₂ or acts as a source for CO₂?

- Unfortunately, we cannot implement the first recommendation, as it was a main objectives of our study to show that new insights can only be achieved if one follows a system-oriented conventional approach from the start, rather than formulating them afterwards based on the study results. Basically, we want to convey the message that changes in a system's source or sink function for C gases can only be interpreted and predicted if all relevant C gas fluxes and their regulating factors in the plant-soil system are considered simultaneously. To stress this, we revised the introduction as follows:
 - Please refer to the reply to comment 5 of reviewer#2 (page 16138, lines 1-10; marked-up manuscript **lines 67-78**)
 - Page 16139, lines 11-18 (marked-up manuscript **lines 107-117**): "Despite the system orientated approach mentioned above, it can therefore be assumed that the amounts of soil C and N located above the temporally variable GWL – hereafter referred to as dynamic C and N stocks – are of essential relevance to plant- and microbially mediated C gas fluxes on drained peatland soils. Moreover, investigations into the effects of dynamic C and N stocks may yield new insights into the mechanisms controlling the C dynamics at these sites. This would be a significant advancement with respect to a comprehensive and generalizable

understanding of the CO₂ and CH₄ source and sink capacity of drained arable fen peatlands.

- The explanations above similarly apply to the comments and questions regarding the large stocks of mineralizable C (page 16150 line 24). Unfortunately, the respective paragraph was not precise enough in its wording. First, the amount of mineralizable C was not determined in this study – this was only an assumption. Second, we didn't make it clear enough that the results can only be correctly interpreted on the base of a simultaneous analysis of all relevant C gas fluxes and their impact factors. The respective section was rephrased to (now lines 402-407; marked-up manuscript **lines 415-423**): "Surprisingly, the C-rich drained organic soils showed a strong net CO₂ uptake (Table 2), while the C-poor Arenosol was a small net CO₂ source. This observation cannot be entirely explained by the interaction between GWL and the potentially mineralizable soil C stocks. Hence, an integrated consideration of all relevant C gas fluxes and their regulation within the plant-soil system is required, which is discussed in detail below."
2. Comment: For a reader not familiar with the statistics used here it is difficult to follow the outcome of the statistical analysis. To my perception the manuscript would benefit from a more broad description of the statistical method. Moreover phrases such "xy% of the variability can be explained by ..." would be helpful.
- The Generalized linear model (GLM) analyses were performed to determine the relative importance of several environmental controls and their interactions on the cumulated annual CH₄, R_{eco}, GPP, and NEE balances. GLM analysis is not aimed at variance partitioning, but at identifying the main significant influential factors, which we subsequently used in multiple nonlinear regression analysis to derive functional relationships with concrete distribution of variability on the individual factors.
3. Comment: In figure 3 the NEE are extrapolated to SOC_{dyn} levels of 0 kg C yr⁻¹ for groundwater levels ranging from -1.6 to -0.2 m y⁻¹. This suggests somehow that soils containing no SOC would act as a source for CO₂ what is rather implausible. I suggest to limit the regression model to the data field covered by the measurements and to stress out the limits of the regression model in the manuscript.
- The authors are very thankful for this advice. In order to show the range of values more clearly, **Figure 3** was modified to include an illustration of the interpolation and extrapolation range. In the figure caption we added: "... over twelve GWL classes per site (for model statistics see Table 4). Displayed grid represents the derived model surface with i) estimated model area covered by direct measurements (solid black) and ii) non-

empirically approved model area computed by extrapolation (grey). Modelled NEE is separated according to positive (solid lines) and negative (dashed lines) values.”

- As well we specify the sentence on page 16154 in line 13 (marked-up manuscript **line 513**): “ ... and plausible for the range of measured GWL and soil C stocks, ...”
- see also below, comment page 16149 line 28 (marked-up manuscript **line 392**)

Specific comments (#3)

Page 16136 I. 8.: I wonder how the dynamic carbon and nitrogen stocks control methane emissions as methanogenesis is expected to take place under suboxic conditions and thus below the GWL. Do the authors think that the methane flux is mainly controlled by methanotrophy above the GWL? This should be specified.

- Thank you for pointing out this inconsistency. Indeed, the influence of C and N stocks located above the groundwater level on CH₄ fluxes is not identical to their impact on CO₂ fluxes, as CH₄ fluxes originate from soil zones under suboxic conditions, i.e below the GWL. However, due to the dependency on the GWL, CH₄ fluxes are very likely also – albeit inversely – related to dynamic C and N stocks. We clarified this in the manuscript (now lines 22-23; marked-up manuscript **line 23**) by rephrasing as follow “... play a key role in the regulation of plant- and microbially mediated CO₂ fluxes of these soils and, inversely, for CH₄.”

Page 16139. L.13: Please remove “also”.

- Implemented at marked-up manuscript **line 112**.

P. 16143 I. 18ff.: I wonder whether changing moisture inside the chambers is an issue for the flux measurements . Can the authors comment on this?

- In advance, we tested the influence of humidity on gas fluxes. Given the used chamber type, however, the influence of changing humidity levels is negligible due to a high chamber volume, with associated flux errors of < 1%. Therefore, when choosing measurement instruments, we decided to use CO₂ sensors without humidity quantification.

Page 16144, I 16. Some information on the uncertainty is given in the Supplemental material. However it would be fair to provide an estimate of the uncertainty in the manuscript.

- Uncertainty estimates are already presented at several locations throughout the manuscript. First, the uncertainty of annual CO₂ and CH₄ fluxes are provided in Table 2 as the model error ($\pm 95\%$ confidence interval), and are also pointed out in the text (page

16147, line 28 and page 16148, lines 7-8; marked-up manuscript **lines 341 and 347-348**). Second, the confidence intervals for daily CO₂ fluxes are also shown in Figure 2. And finally, the uncertainty of daily CH₄ fluxes is included in the supplement figure S3.

- For additional indications please refer to reply of comment below (page 16147, line 13; marked-up manuscript **lines 321-327**)

p. 16145 line 3. Is this the total number of datasets or the number of datasets per sampling site?

- We specified the sentence in line 259 "... resulting in a total of 111 datasets (37 per site) for..."

Page 16147, l. 1ff: The authors state that exceptional high methane emissions occurred during periods of flooding or high GWL. To my perception flooding or high GWL are linked to strong precipitation and thus to climate variability. In contradiction to this the authors state on **page 16148, l. 23** that climate played a minor role in determining annual methane fluxes could the authors clarify this?

- The Authors specified the sentence on page 16148, line 23 (now lines 350-351; marked-up manuscript **lines 363-364**): "... annual CH₄-C emissions via the effect of precipitation on GWL,"

Page 16147, l. 13: How large was the uncertainty. See also previous comment.

- We included the uncertainty from line 313 to 314 (marked-up manuscript **line 326**): "... higher uncertainty (± 3.7 g CH₄-C m⁻² y⁻¹ in 2007/08 vs. ± 0.5 and ± 0.2 g CH₄-C m⁻² y⁻¹ in 2008/09 and 2009/10; Table 2)."
- And also from line 309 to 311 (marked-up manuscript **lines 321-324**): "...to 28 ± 4 g CH₄-C m⁻² y⁻¹, and ... the following years (0.3 ± 0.5 and ± 0.2 g CH₄-C m⁻² y⁻¹) and ... for AR and GL ($< 1.2 \pm 0.6$ g CH₄-C m⁻² y⁻¹; Table 2)."

Page 16148 line 2ff: For a reader not familiar with the statistics used here the meaning of significant or "highly significant" as frequently used in chapter 3.3 is not apparent.

- In order to improve the consistency of wording with respect to the significance of statistical analysis, now the significant levels are defined in line 342 "... significant (p -value ≤ 0.05)...", line 343 "... highly significant (p -value ≤ 0.001)..." and line 369 "... no significant (p -value ≥ 0.05)..." (marked-up manuscript **lines 355, 356 and 382**)
- Also, p -values are implemented as a footnote in Table 4

Page 16149 line 28: I may be wrong but the statement NEE being always positive for $\text{SOC}_{\text{dyn}} < 4.3 \text{ kg}$ refers to the regression model. In a more generalized sense it implies that carbon free soils could act as a source for CO_2 . IS this statement substantiated by flux measurements carried out under these conditions?

- Sentence changed in line 379 (marked-up manuscript **line 392**) to “However, the shown relations cannot be assumed as valid outside the measured ranges of SOC_{dyn} and GWL .”

Page 16154 line 5: Please replace und by and.

- Implemented at marked-up manuscript **line 502**.

Figures

Figure 1: This figure needs some rework. It is difficult to differentiate the different sites from the color-coding. Further I can only find data for two soils in the two lower panel of figure 1. Please remove the a in the brackets at the end of the figure caption.

- We revised the **Figure 1**, the different sites are now clearly separable due to different line types and we removed the “a” in the brackets and in the figure.

Figure 3: Please check the legends of figure 3. Why is SOC given in Kg C yr^{-1} and why is the groundwater level given in m yr^{-1} ?

- We modified the legends of **Figure 3** to “Mean annual SOC_{dyn} [kg C m^{-2}]” and “Mean annual groundwater level [m]”.

Supplement

Fig. 2 Please provide a description of legends in the figure caption. What is RWI and what is the time scale?

- The authors modified the axis label and completed the legend description of **Figure S2**: “... half-hour NEE data from 07/07/2008 to 31/07/2008. The upper graph displays modelled NEE time series and corresponding smoothing spline (solid red line). The lower graph shows the continuous wavelet transform and cone of influence (hatched area) within the respective time frequency domain. The wavelet power spectrum is thereby defined as the squared absolute-value of the wavelet coefficients (correlation between wavelet and data array).”

Extra changes for revised manuscript:

- We specified the sentence on page 16136 in lines 3-4: „To date, the significance of such sites as sources or sinks for greenhouse gases like CO₂ and CH₄ is still unclear,…”
- Changed the correspondence of co- author M. Hoffmann (only [2])
- Changed “accepted” to “2015” in line 202, 211, 217, 223, 224 and 229
- Changed in line 624 from “Michel Bechthold” to “M. Bechtold”

Dynamic C and N stocks – key factors controlling the C gas exchange of maize in a heterogenous peatland

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Abstract

Drainage and cultivation of fen peatlands creates complex small-scale mosaics of soils with extremely variable soil organic carbon (SOC) stocks and groundwater-level (GWL). To date, the significance of such sites as sources or sinks for greenhouse gases like CO₂ and CH₄ is still unclear ~~To date, it remains unclear if such sites are sources or sinks for greenhouse gases like CO₂ and CH₄,~~ especially if used for cropland. As individual control factors like GWL fail to account for this complexity, holistic approaches combining gas fluxes with the underlying processes are required to understand the carbon (C) gas exchange of drained fens. It can be assumed that the stocks of SOC and N located above the variable GWL – defined as *dynamic C* and N stocks – play a key role in the regulation of plant- and microbially mediated CO₂ fluxes of these soils and, inversely, for CH₄-C gas fluxes of these soils. To test this assumption, the present study analysed the C gas exchange (gross primary production – GPP, ecosystem respiration – R_{eeco}, net ecosystem exchange – NEE, CH₄) of maize using manual chambers for four years. The study sites were located near Paulinenaue, Germany, where we selected three soil types representing the full gradient in GWL and SOC stocks (0-1m) of the landscape. ~~Here we selected~~

29 ~~three soils, which represent the full gradient in pedogenesis, GWL and SOC stocks (0–1 m) of the~~
30 ~~fen peatland:~~ a) Haplic Arenosol (AR; 8 kg C m⁻²); b) Mollic Gleysol (GL; 38 kg C m⁻²); and c)
31 Hemic Histosol (HS; 87 kg C m⁻²). Daily GWL data was used to calculate dynamic SOC
32 (SOC_{dyn}) and N (N_{dyn}) stocks.

33 Average annual NEE differed considerably among sites, ranging from 47±30 g C m⁻² a⁻¹ at AR to
34 -305±123 g C m⁻² a⁻¹ at GL and -127±212 g C m⁻² a⁻¹ at HS. While static SOC and N stocks
35 showed no significant effect on C fluxes, SOC_{dyn} and N_{dyn} and their interaction with GWL
36 strongly influenced the C gas exchange, particularly NEE and the GPP : R_{eco} ratio. Moreover,
37 based on nonlinear regression analysis, 86% of NEE variability was explained by GWL and
38 SOC_{dyn}. The observed high relevance of dynamic SOC and N stocks in the aerobic zone for plant
39 and soil gas exchange likely originates from the effects of GWL-dependent N availability on C
40 formation and transformation processes in the plant-soil system, which promote CO₂ input via
41 GPP more than CO₂ emission via R_{eco}.

42 The process-oriented approach of dynamic C and N stocks is a promising, potentially
43 generalizable method for system-oriented investigations of the C gas exchange of groundwater-
44 influenced soils and could be expanded to other nutrients and soil characteristics. However, in
45 order to assess the climate impact of arable sites on drained peatlands, it is always necessary to
46 consider the entire range of groundwater-influenced mineral and organic soils and their
47 respective areal extent within the soil landscape.

48 **1 Introduction**

49 Peatlands are one of the most important ecosystems for the terrestrial carbon (C) and nitrogen (N)
50 cycle, storing up to 500 Mg C ha⁻¹ and – particularly in nutrient-rich fens – 120 Mg N ha⁻¹ (Yu et
51 al. 2011, MacDonald et al. 2006, Kunze 1993). Throughout the world, the drainage and
52 subsequent agricultural cultivation of peatlands has increased soil organic carbon (SOC)
53 mineralisation rates and the associated CO₂ emissions (Couwenberg et al. 2010, Kasimir-
54 Klemedtsson et al. 1997, Nykänen et al. 1995), resulting in the creation of small-scale mosaics of
55 soil types with extremely variable SOC stocks, especially in the case of fens. The respective soil
56 types range from deep peat soils to humus-rich sandy soils, which are not classified as peat soils
57 due to an SOC content of <12% (IUSS Working Group WRB 2007). These individual soil types
58 are typically found at similar relative elevations within an increasingly undulating landscape and

59 the ground water level (GWL) is often subject to considerable short-term fluctuations. As a result
60 of the tight coupling between soil types and elevation, mean GWL may differ considerably
61 between individual soil types (Aich et al. 2013, Heller and Zeitz 2012, Dawson et al. 2010, Teh et
62 al. 2011, Dexler et al. 2009, Müller et al. 2007, Schindler et al. 2003). These sites are typically
63 used as grassland or cropland (Joosten and Clark 2002, Byrne et al. 2004).

64 The relevance of these soil type mosaics originating from drained fen peatlands as a source or
65 sink for greenhouse gases like CO₂ and CH₄, especially if used for cropland, still cannot be
66 exactly determined. In particular, knowledge about the influence of variable soil C stocks on the
67 C gas exchange is still limited. In light of the extreme complexity of site conditions, it seems
68 unlikely that the common focus on interactions between C stocks and particularly relevant control
69 parameters like groundwater diversity of site conditions, it is quite unlikely that the common
70 search for particularly relevant control parameters, e.g. groundwater and temperature (Adkinson
71 et al. 2011, Berglund et al. 2010, Kluge et al. 2008, Jungkunst and Fiedler 2007, Daulat et al.
72 1998), will result in reliable and generalizable conclusions about the C gas fluxes of degraded
73 fens; mainly because this approach fails to account for the plant-induced C gas input
74 counteracting the C gas emissions determined by soil characteristics and microorganisms.

75 Therefore, new insights are much more likely to be derived from system-oriented studies
76 analysing all interrelated C gas fluxes. Profound insights are much more likely to be derived from
77 system-oriented studies analysing all interrelated C gas fluxes induced by microorganisms and
78 plants, e.g. CH₄ exchange, CO₂ uptake during photosynthesis and CO₂ emission via respiration,
79 together with the underlying processes and control mechanisms (Chapin III et al. 2009, Schmidt
80 et al. 2011). Indeed, there are numerous indications suggesting that this approach may also be
81 promising for the C gas exchange of drained fen sites.

82 Short- and long-term fluctuations of the GWL and its interactions with soil and plants very likely
83 also play a key role in the C cycle of other groundwater-influenced soil types, similar to true peat
84 soils (Couwenberg et al. 2011, Berglund and Berglund 2011, Flanagan et al. 2002, Augustin et al.
85 1998, Martikainen et al. 1995, Nykänen et al. 1995). For peat soils, many studies documented the
86 impact of GWL on the interactions between soil C dynamics and gaseous C emissions in the form
87 of CH₄ and CO₂, the latter originating from autotrophic root respiration and heterotrophic
88 microbial respiration. Ultimately, these GWL effects are a result of the ratio between SOC stocks

89 located in the aerobic, i.e. above-GWL, and the anaerobic, i.e. below-GWL, zone (Laine et al.
90 1996). However, very few (Leiber-Sauheitl et al. 2014, Jans et al. 2010, Jungkunst et al. 2008,
91 Jungkunst and Fiedler 2007) studies have investigated Gleysols and groundwater-influenced
92 sandy soils, which make up a significant portion of fen landscapes. It also remains unclear if the
93 impact of GWL on the gas exchange is modified by the highly variable density typical of SOC-
94 rich soil horizons of drained peatlands.

95 Knowledge gaps also limit the quantification of direct GWL effects on plant-mediated CO₂
96 uptake via photosynthesis. Site-adapted plants growing on undisturbed peat soils and perennial
97 grasses cultivated on groundwater-influenced soils can tolerate changing GWL without
98 considerable deterioration of photosynthetic performance (Farnsworth and Meyerson 2003,
99 Crawford and Braendle 1996). In contrast, GWL fluctuations likely have a particularly strong
100 impact on annual crops cultivated on drained peatlands, as most crops typically react to
101 waterlogging, i.e. anoxic soil conditions as a result of high GWL, with reduced photosynthesis,
102 plant respiration and growth (Zaidi et al. 2003, Asharf 1999, Singh 1984, Wenkert et al. 1981).
103 Other studies indicate that crops cultivated on groundwater-influenced soils feature better growth
104 when GWL are low (Glaz et al. 2008), but it is unclear if this is a direct result of improved
105 aeration or an indirect effect of increased soil volume, allowing for better root development and
106 thus increased nutrient uptake (Glaz et al. 2008, Livesley et al. 1999).

107 Despite the system-orientated approach mentioned above, it can therefore be assumed that the
108 amounts of soil C and N located above the temporally variable GWL – hereafter referred to as
109 dynamic C and N stocks – are of essential relevance to plant- and microbially mediated C gas
110 fluxes on drained peatland soils.~~It can therefore be assumed that – in addition to the GWL itself~~
111 ~~– the amounts of soil C and N located above the temporally variable GWL, i.e. hereafter referred~~
112 ~~to as dynamic C and N stocks, are also of essential relevance to plant- and microbially mediated~~
113 ~~C gas fluxes on drained peatland soils.~~ Moreover, investigations into the effects of dynamic C
114 and N stocks may yield new insights into the mechanisms controlling the C dynamics at these
115 sites. in the plant-soil system. This would be a significant advancement with respect to a
116 comprehensive and generalizable understanding of the CO₂ and CH₄ source and sink capacity of
117 drained arable fen peatlands. This would be a significant advancement with respect to a

118 ~~comprehensive and generalizable understanding of the CO₂ and CH₄ exchange of drained arable~~
119 ~~fen peatlands.~~

120 The present study tests the above-mentioned assumption by means of multi-year manual
121 chambers measurements, subsequent modeling and complex statistical analysis of all relevant C
122 gas fluxes of the C gas exchange, i.e. the net CO₂ exchange resulting from gross primary
123 production (plant photosynthesis) and ecosystem respiration (sum of plant and soil respiration)
124 and the CH₄ exchange, of maize cultivated on different groundwater-dependent soil types
125 representing a steep SOC gradient. In particular, the study focuses on answering the following
126 research questions:

- 127 1. Are there differences among soil types regarding the dynamics and the intensity of the C
128 (CO₂ and CH₄) gas exchange of drained arable peatland soils?
- 129 2. a) Which factors and factor interactions influence the C gas exchange of drained arable
130 peatland soils?
131 b) In particular, what is the influence of the amount and the dynamics of soil C and N
132 stocks located in the aerobic zone above the GWL on the C gas exchange of drained
133 arable peatland soils?

134

135 **2 Materials and methods**

136 **2.1 Site description and land use history**

137 The study sites are located near the village of Paulinenaue, in the shallow and drained peatland
138 complex ‘Havelländisches Luch~~Rhin-Havelluch~~’ of NE Germany (51 km W of Berlin; 52°41`N,
139 12°43`E). This peatland was first drained at the beginning of the 14th century (Behrendt, 1988).
140 A systematic amelioration for the entire “Luch” took place from 1718 until 1724 and included
141 The construction of ditches and dams to drain the formerly swampy terrain and to provide access
142 to the land. Grasslands with hay production dominated the “Luch” at that time. In order to
143 prevent repeated flooding and to increase grassland productivity, a second amelioration with
144 deeper drainage ditches was implemented between 1907 and 1925. A substantial increase in total
145 ditch length occurred between 1958 and 1961, when approx. 1000 km of new ditches were

146 established in the area (Behrendt, 1988). The next huge effort to increase productivity started in
147 the early 1970ies by the so-called “Komplexmelioration”, which lasted until the late 1980ies. The
148 basic idea was to establish a system of pumping stations and related ditches in order to increase
149 and lower the ground water table dynamically throughout the vegetation period depending on the
150 actual plant water demand. In addition, fertilizer application rates, including organic manure,
151 increased and the acreage of arable land doubled at the expense of grassland. After the re-
152 unification of Germany in 1989, a substantial de-intensification took place, resulting in the re-
153 conversion of arable land to grassland, reduction of fertilizer input, and abandonment of
154 hydraulic technical devices for economic reasons.

155 The region is characterized by a continental climate with a mean annual air temperature of 9.2°C
156 and a mean annual precipitation of 530 mm (1982–2012).

157 The study sites are located along a representative and steep landscape gradient in terms of soil
158 organic carbon stocks ($\text{SOC}_{\text{stocks}}$; 0–1 m), which is related to topographic position (Table 1): AR
159 – a Haplic Arenosol developed from aeolian sands with low $\text{SOC}_{\text{stocks}}$ ($8 \text{ kg C m}^{-2} \text{ m}^{-1}$) at a
160 microhigh (29.6 m a.s.l.); GL – a Mollic Gleysol developed from peat overlying fluvial sands
161 with medium $\text{SOC}_{\text{stocks}}$ ($38 \text{ kg C m}^{-2} \text{ m}^{-1}$) at 29.0 m a.s.l.; and HS – a Hemic Histosol developed
162 from peat featuring high $\text{SOC}_{\text{stocks}}$ ($87 \text{ kg C m}^{-2} \text{ m}^{-1}$) at the edge of a local depression
163 (28.8 m a.s.l.). Moreover, the vertical distribution of C and N differ between sites: at AS almost
164 all SOC and N is concentrated in the plough layer (Ap horizon), whereas GL and HS show larger
165 portions of SOC and N in subsoil horizons (Fig. S1 in supplement).

166 All sites were identically managed during the study period (Table S1 in supplement), i.e.
167 cultivated with a monoculture of grain maize with annually changing varieties. The AR and HS
168 sites are located 150 m apart within the same managed field, while GL is located 1.5 km from
169 AR/HS. However, field operations such as tillage, sowing, fertilisation and harvest were
170 conducted almost concurrently at all sites. Maize was fertilised with diammonium phosphate
171 (DAP) containing 22 kg N ha^{-1} and 24 kg P ha^{-1} in the course of sowing, followed approx. 2
172 weeks later by fertilisation with calcium ammonium nitrate (CAN) containing 100 kg N ha^{-1} .
173 During harvest, total plant biomass within the measurement plots was collected, chipped, dried at
174 60°C to constant weight and weighed. Grain yield was not recorded due to technical

175 complications. Total plant biomass subsamples were analysed for C content at the ZALF Central
176 Laboratory. After harvesting, all sites were mulched and ploughed.

177 **2.2 Environmental controls**

178 Half-hourly values of air temperature (20 cm height), soil temperatures (2, 5 and 10 cm depth),
179 PAR, and precipitation were continuously recorded by a climate station installed within 1 km of
180 the sites. Site-specific air and soil temperatures were manually measured simultaneously with
181 CO₂ and CH₄ flux measurements. Site-specific half-hourly air and soil temperature models were
182 derived from correlations between the respective climate station temperature records and site-
183 specific manual temperature data. Sunshine hours and long-term climate data originate from the
184 'Potsdam' station of the German Weather Service (DWD).

185 GWL at GL and HS was measured manually every two weeks using short 1.5 m dip wells. The
186 measured piezometric heads are considered representative of the phreatic water levels in the peat
187 layer because the organic soil layer directly overlies a sand aquifer without any major low-
188 conductance soil horizons in between. At HS, GWL was additionally recorded every 15 min by a
189 data logger (Mini-diver, Schlumberger). Time series modeling was used to fill several small data
190 gaps and to obtain continuous daily GWL data for the entire study period. The applied PIRFICT
191 approach (von Asmuth et al. 2008) implemented in the *Menyanthes* software (von Asmuth et al.
192 2012a) is a physically-based statistical time series model specifically developed to model
193 hydrologic time series, including shallow GWL fluctuations. As input, the model requires
194 continuous precipitation (DWD station 'Kleßen') and evapotranspiration data (FAO56 Penman-
195 Monteith; DWD station 'Kyritz') and optional control parameters, e.g., in our case, deep GWL
196 data recorded from a local dip well (LUGV Brandenburg). The calibrated model explained 80–
197 87% of the data variance; a good result for this data and model type (von Asmuth et al. 2012b).
198 Confidence intervals of GWL time series predictions were obtained by means of stochastic
199 simulation (see von Asmuth et al. 2012a). Due to the short distance between AR and HS and the
200 highly significant correlation of GWL at these sites ($R^2 = 0.836$), daily GWL values for AR were
201 calculated by shifting the modeled time series of HS with a constant offset of 0.9 m.

202 **2.3 Concept and calculation of dynamic C and N stocks**

203 The concept of ‘dynamic’ groundwater-dependent C and N stocks was developed to account for
204 the interaction of the most important drivers of the C gas fluxes of peatlands, namely GWL and
205 soil C and N stocks. The underlying idea is to derive a quantitative, dynamic proxy for the
206 aerated, unsaturated zone which determines the actual nutrient and O₂ availability and is therefore
207 highly relevant for root and shoot growth, microbial activity, and, consequently, all C gas fluxes.
208 Using daily GWL data, it was determined for each 1-cm soil layer up to a depth of 1 m if the
209 respective layer was saturated with groundwater or not. In daily time steps, SOC and N stocks
210 were then calculated for all non-saturated 1-cm layers and cumulated over the entire non-
211 saturated soil profile, i.e. above the GWL, to generate daily dynamic SOC (SOC_{dyn}) and N (N_{dyn})
212 stocks. For further analysis, daily SOC_{dyn} and N_{dyn} values were averaged monthly and annually.

213 **2.4 Gas flux measurements**

214 Periodic trace gas measurements were carried out at three permanently installed soil collars
215 (0.75 x 0.75 m) at each site. In summer 2007, due to flooding, soil collars at the HS site had to be
216 relocated within a radius of 10 m to i) technically allow for gas flux measurements; and ii) ensure
217 that all soil collars contained flood-affected but viable plants in order to maintain comparability
218 with the GL and AR sites, where maize mortality was not increased by flooding.

219 Throughout the entire study period, CH₄ measurements were conducted 1–2 times per month
220 using static *non-flow-through non-steady-state* opaque chambers (vol. 0.296 m³; Livingston and
221 Hutchinson 1995, Drösler 2005), for a total of 51–60 campaigns per site. At HS, CH₄
222 measurements were terminated already in October 2010 due to management constraints.
223 Exchange of CH₄ was measured by taking four consecutive 100-ml gas samples from the
224 chamber headspace in 20-min intervals (closure time 60 min), subsequently analyzed using a gas
225 chromatograph (Shimadzu GC 14B, Lofffield, Göttingen, Germany) equipped with a flame
226 ionization detector.

227 CO₂ exchange was measured using dynamic *flow-through non-steady-state* transparent (net
228 ecosystem exchange – NEE); light transmission of 86%) and opaque (ecosystem respiration –
229 R_{eco}) chambers (Livingston and Hutchinson 1995, Drösler 2005) attached to an infrared gas
230 analyzer (Li-820, Lincoln, NE, USA). Full-day CO₂ measurement campaigns with repeated (30–

231 50) individual chamber measurements (closure time 3–5 min) were conducted regularly every 4–
232 6 weeks from 05/2007–04/2011, for a total of 29–37 full campaigns per site. Further details on
233 CO₂ measurement methodology are given in Hoffmann et al. ([accepted2015](#)).

234 **2.5 Flux calculation and gap filling**

235 Flux calculation for CO₂ and CH₄ was based on the ideal gas equation accounting for chamber
236 volume and area, air pressure, and average air temperature during the measurement. CH₄ fluxes
237 were calculated with the R package ‘flux 0.2-2’ (Jurasinski et al. 2012), using linear regression
238 analysis with stepwise backward elimination of outliers based on the normalized root mean
239 square error (NRMSE \geq 0.2) up to a minimum of three data points. Fluxes with NRMSE $>$ 0.4
240 were rejected. The calculated flux rates were then averaged for the respective measurement day
241 and linearly interpolated to determine annual CH₄ exchange.

242 For CO₂, the R script of Hoffmann et al. ([accepted2015](#)) was used for flux calculation as well as
243 the subsequent separation into and modeling of R_{eco}, gross primary production (GPP), and NEE.
244 Measurements $<$ 30 s were rejected and measurements $>$ 1 min were shortened by a death band of
245 10% at the beginning and end, respectively (Kutzbach et al. 2007). For each measurement, the
246 final flux rate was selected from all potential flux rates generated by a moving window approach
247 using a stepwise algorithm, numerous quality criteria and the Akaike information criterion (AIC;
248 for details see Hoffmann et al., [accepted2015](#)). For R_{eco}, gap filling between measurement
249 campaigns was performed using campaign-specific temperature-dependent Arrhenius-type
250 models by Lloyd and Taylor (1994). GPP fluxes were calculated by subtracting modeled R_{eco}
251 fluxes from measured NEE fluxes, and then modeled using campaign-specific hyperbolic PAR-
252 dependent models (Wang et al. 2013, Elsgaard et al. 2012, Michaelis-Menten 1913). Average
253 measured flux rates were used if no significant fit was achieved for campaign-specific R_{eco} or
254 GPP models (Hoffmann et al., [accepted2015](#)). Half-hourly NEE values were calculated from
255 modeled R_{eco} and GPP fluxes (Hoffmann et al. [2015](#), ~~accepted~~, Drösler 2005), and cumulated
256 from May 1st to April 30th of the following year (Table S1 in supplement), resulting in four
257 consecutive annual CO₂ balances. Negative values represent a C gas flux from the atmosphere to
258 the ecosystem; positive values a flux from the ecosystem to the atmosphere. The uncertainty of
259 the annual CH₄ and CO₂ exchange was quantified using a comprehensive error prediction
260 algorithm described in detail by Hoffmann et al. ([accepted2015](#)).

261 2.6 Data analysis

262 Daily values for CH₄ efflux, GPP, R_{eco}, NEE were cumulated monthly for a total of 48 monthly
263 datasets per site to reduce the effects of temporal autocorrelation. The respective environmental
264 controls were cumulated (sunshine hours, precipitation and linear modelled biomass) or averaged
265 (for GWL, SOC_{dyn}, N_{dyn}, air and soil temperature) for each month. Gas flux balances for longer
266 time periods may vary considerably depending on the duration of the respective cumulation
267 period. As the wavelet analysis of daily NEE data for inherent signals revealed strong annual
268 dynamics (Stoy et al. 2013; Fig. S2 in supplement), a 365-day cumulation period was used to
269 calculate gas flux balances. Additional variability in annual balances can result from arbitrarily
270 chosen starting dates of the cumulation period. To account for this uncertainty in the calculation
271 of annual balances, a 365-day moving window was shifted in monthly time steps through the
272 | entire study period, resulting in a total of 111 datasets (37 per site) for annual NEE, GPP, R_{eco}
273 and CH₄ efflux and the respective environmental control parameters.

274 Subsequently, generalized linear model (GLM) analyses (SPSS GENLIN procedure) were
275 performed to determine the influence of environmental controls and their interactions on the
276 cumulated annual CH₄, R_{eco}, GPP, and NEE balances as well as the GPP : R_{eco} ratio. Models were
277 defined using a gamma probability distribution and a log link function and calculated in a
278 stepwise backward elimination procedure, dropping non-significant variables until no further
279 improvement of the AIC was achieved (correction for finite sample sizes: AIC_c). Parameter and
280 interaction effects were evaluated based on the Wald χ^2 statistic, appropriate for non-normally
281 distributed continuous variables. Prior to analysis, CH₄ data were log-transformed after adding
282 the minimum CH₄ value to each data value, in order to allow for application of the GLM log link
283 | function. Analogously Accordingly, absolute values of GPP were used for the analysis and NEE
284 data were transformed to positive values by adding the minimum NEE value to each data value.

285 Multiple nonlinear regression analyses were performed to derive a model for NEE based on
286 GWL and SOC_{dyn}, N_{dyn}, SOC_{dyn} : N_{dyn} ratio and biomass, representing the main GLM parameter
287 groups. For model calculation, data was averaged for twelve site-specific GWL classes to account
288 for uncertainty from GWL model data. Class number was determined using Sturges' rule,
289 appropriate for n < 200 (Scott 2009). All data analyses were performed using the R (R 3.0.3) and
290 SPSS (SPSS 19.0.1, SPSS Inc.) software.

291

292 **3 Results**

293 **3.1 Environmental controls**

294 During the study period (05/2007–04/2011), weather conditions were somewhat cooler (8.7°C)
295 and wetter (634 mm) compared to the long-term average (1982–2012; 9.2°C; 530 mm).
296 Particularly the 2010/11 measurement year considerably deviated from the long-term temperature
297 average, with an annual air temperature that was 1.5°C below the long-term average -1 SD (*data*
298 *not shown*). While PAR and air temperature showed high daily and seasonal dynamics (Fig. 2a),
299 no pronounced seasonal patterns were observed for precipitation (Fig. 1). Instead, precipitation
300 featured an extremely high interannual variability with particularly heavy rainfalls during the
301 summer months of 2007 (May–July; Fig. 1). The precipitation sum during this period (507 mm)
302 exceeded the long-term average (179 mm) by $>180\%$ (*data not shown*). Reflecting the
303 precipitation dynamics, the GWL showed similar temporal dynamics of the three sites, but at
304 different levels. In summer, GWL remained generally low, with the exception of July–August
305 2007. The HS site, which consistently featured the highest average GWL (-0.5 m; Fig. 1,
306 Table S2 in supplement), was flooded during this period (GWL $+0.2$ m; *data not shown*).

307 The SOC_{dyn} and N_{dyn} stocks calculated based on the modeled GWL showed the highest
308 fluctuations at the HS site (Fig. 1). During times of high GWL, such as in summer 2007, the HS
309 and GL site featured drastically lowered SOC_{dyn} and N_{dyn} values, amounting to only 6.2 kg C m^{-2}
310 and 0.5 kg N m^{-2} , respectively, with SOC_{dyn} and N_{dyn} reduced to zero during flooded periods. In
311 contrast, pronounced peak values at HS were calculated for the low-GWL summer months during
312 the rest of the study period, with monthly averages of $21\text{--}86 \text{ kg C m}^{-2}$ and of $2\text{--}5 \text{ kg N m}^{-2}$. The
313 HS site always featured the highest annual SOC_{dyn} (52 kg C m^{-2}) and N_{dyn} (4 kg N m^{-2}) stocks,
314 except for 2007/08 (Fig. 1; Table S2 in supplement).

315 **3.2 Daily and annual carbon gas exchange**

316 All sites generally featured very low daily CH_4 fluxes (-0.01 to $0.01 \text{ g CH}_4\text{-C m}^{-2} \text{ d}^{-1}$) throughout
317 the study period (Fig. S3 in supplement). However, considerable CH_4 emission peaks were
318 observed at the HS and GL sites during times of flooding or high GWL, e.g. during summer 2007
319 and spring 2008. At HS, this resulted in a maximum CH_4 flux of $1.2 \text{ g CH}_4\text{-C m}^{-2} \text{ d}^{-1}$ on

320 August 1st, 2007, which is approx. 60 times higher than the median flux ($0.02 \text{ g CH}_4\text{-C m}^{-2} \text{ d}^{-1}$) at
321 this site. As a result of the flooding, annual CH_4 emissions in 2007/08 at HS amounted to $28 \pm$
322 $428 \text{ g CH}_4\text{-C m}^{-2} \text{ y}^{-1}$, and were thus nearly 100 times higher than observed for HS in the
323 following years (0.3 ± 0.5 and $\pm 0.2 \text{ g CH}_4\text{-C m}^{-2} \text{ y}^{-1}$) and at least 25 times higher than observed
324 for AR and GL ($< 1.2 \pm 0.6 \text{ g CH}_4\text{-C m}^{-2} \text{ y}^{-1}$; Table 2). However, as the high annual CH_4 emissions
325 2007/08 at HS result from a peak described by three measurement campaigns during the flooded
326 period (Fig. S3 in supplement), they are also associated with a higher uncertainty ($\pm 3.7 \text{ g CH}_4\text{-}$
327 $\text{C m}^{-2} \text{ y}^{-1}$ in 2007/08 vs. ± 0.5 and $\pm 0.2 \text{ g CH}_4\text{-C m}^{-2} \text{ y}^{-1}$ in 2008/09 and 2009/10; Table 2).

328 The modeled CO_2 exchange rates (for model evaluation statistics see Table S3 in supplement)
329 reflected the daily and seasonal dynamics of air temperature and PAR, with generally higher
330 fluxes in the growing season compared to fall and winter (Fig 2a, b). In summer, peak GPP fluxes
331 considerably exceeded the amplitude of R_{eco} fluxes. At all sites, the CO_2 exchange was also
332 influenced by management events, with particularly pronounced peaks of R_{eco} following tillage.
333 In addition, GPP was immediately reduced to zero after maize harvest due to the removal of the
334 photosynthetically active aboveground plant biomass. In general, the organic GL and HS sites
335 showed the highest CO_2 exchange intensity, with maximum R_{eco} and GPP fluxes of $23 \text{ g CO}_2\text{-}$
336 $\text{C m}^{-2} \text{ d}^{-1}$ and $-46 \text{ g CO}_2\text{-C m}^{-2} \text{ d}^{-1}$, respectively, observed at the HS site (Fig 2a, b). However,
337 during the wet summer of 2007, the mineral AR site featured the highest intensity of CO_2
338 exchange, resulting in cumulated annual R_{eco} and GPP fluxes that were 25–44% and 52–61%
339 higher, respectively, than in the following years (2008–2011, Table 2). In contrast, at HS, the
340 2007 flooding resulted in strongly reduced CO_2 flux intensities and large net annual $\text{CO}_2\text{-C}$ losses
341 (NEE of $493 \pm 83 \text{ g CO}_2\text{-C m}^{-2}$) compared to the following years. Although the CO_2 fluxes
342 measured during the flooded period are associated with higher error values compared to periods
343 without flooding (Table 2), the modelled results are plausible, clearly reflecting the negative
344 effects of flooding on plant growth and thus plant C exchange. Hence, in 2007/08, cumulated
345 annual R_{eco} and GPP fluxes at AR were 76% and 49% higher than at the HS site (Table 2).

346 Excluding 2007/08, the average NEE during the study period at the mineral AR site was close to
347 zero with $50 \pm 32 \text{ g CO}_2\text{-C m}^{-2} \text{ y}^{-1}$ (Table 2), whereas the organic sites were net $\text{CO}_2\text{-C}$ sinks with
348 $-385 \pm 133 \text{ g CO}_2\text{-C m}^{-2} \text{ y}^{-1}$ (GL) and $-334 \pm 61 \text{ g CO}_2\text{-C m}^{-2} \text{ y}^{-1}$ (HS). Including the flood-
349 dominated year of 2007/08 resulted in a 62% and 21% reduction of the overall NEE at the HS

350 and GL sites, respectively. In contrast, when 2007/08 is included in the overall 2007–2011
351 average for the AR site, cumulated R_{eco} and GPP increase by 63% and 67%, respectively, while
352 NEE remains unaffected.

353 **3.3 Impact of environmental controls on carbon gas exchange**

354 Despite the wide range of control parameters included in the complex analysis, site (i.e. soil) had
355 a significant (p -value ≤ 0.05) effect on all gas fluxes (Table 3). The generally highly significant
356 (p -value ≤ 0.001) interactions between site and controls like biomass, GWL and soil parameters
357 show that the selected study sites represented a wide range of the respective control parameters.
358 Especially annual $\text{CH}_4\text{-C}$ emissions were dominated by site, suggesting the presence of additional
359 important control factors not considered in this analysis. However, little residual variability
360 indicates that most of the variability in annual R_{eco} and GPP was explained by the factors
361 included in the GLM analyses, with more residual variability remaining for NEE and the
362 $\text{GPP} : R_{\text{eco}}$ ratio.

363 While climate played a minor role in determining annual $\text{CH}_4\text{-C}$ emissions via the effect of
364 precipitation on GWL, climate controls were more relevant for CO_2 exchange (Table 3). There,
365 the importance of climate was higher for cumulated GPP and R_{eco} than for NEE and the
366 $\text{GPP} : R_{\text{eco}}$ ratio. The impact of climate variability on CO_2 exchange was even more pronounced at
367 the monthly scale, as indicated by highly significant interactions between climate controls and
368 month of year (*data not shown*). Biomass was equally important as climate in determining annual
369 GPP, whereas for R_{eco} biomass and its interactions were less relevant than climate (Table 3). In
370 contrast, the derived variables NEE and $\text{GPP} : R_{\text{eco}}$ were less influenced by biomass than the
371 individual fluxes R_{eco} and GPP.

372 Direct groundwater influence was particularly pronounced for R_{eco} , GWL by far being the most
373 important GLM parameter (Table 3). Groundwater influence on $\text{CH}_4\text{-C}$ emissions and the
374 $\text{GPP} : R_{\text{eco}}$ ratio was expressed mainly through the interaction between GWL and site.

375 Groundwater-dependent soil parameters and their interactions with site and GWL dominated
376 annual $\text{CH}_4\text{-C}$ emissions (Table 3). Soil parameters were also the main controls on NEE,
377 particularly the $\text{SOC}_{\text{dyn}} : \text{N}_{\text{dyn}}$ ratio and its interactions with site. Dynamic soil parameters and
378 their associated interactions thus were of higher relevance for the derived variables NEE and

379 GPP : R_{eco} than for the NEE flux components R_{eco} and GPP. This indicates differences between
380 R_{eco} , and GPP with respect to their reaction to changing GWL and soil parameters, i.e. a shift in
381 the ratio between R_{eco} , and GPP throughout the range of GWL, SOC_{dyn} and N_{dyn} stocks. In
382 contrast, static $\text{SOC}_{\text{stocks}}$ and N_{stocks} showed no significant ($p\text{-value} \geq 0.05$) effect on cumulated
383 annual or monthly fluxes of either R_{eco} , GPP, or NEE (*data not shown*).

384 Nonlinear regression analysis of annual NEE versus GWL and either SOC_{dyn} , N_{dyn} , $\text{SOC}_{\text{dyn}} : \text{N}_{\text{dyn}}$
385 or biomass across all sites resulted in highly significant 2-parameter models (Table 4; Fig. 3).
386 While all models explained $>86\%$ of the overall variability of annual NEE, model fit was best for
387 GWL and SOC_{dyn} , likely because the study sites represent a wide range of SOC_{dyn} . For all sites,
388 the model shows a negative NEE optimum for GWL of 0.8–1.0 m below the soil surface, with
389 NEE increasing at higher or lower GWL (Fig. 3). In contrast, the model reflects a linear effect of
390 SOC_{dyn} on NEE with more negative NEE for higher SOC_{dyn} . Depending on SOC_{dyn} , NEE
391 changes to positive values at GWL above -0.43 m (for $\text{SOC}_{\text{dyn}} = 60 \text{ kg C m}^{-2}$) or -0.61 m
392 ($\text{SOC}_{\text{dyn}} = 30 \text{ kg C m}^{-2}$). However, the shown relations cannot be assumed as valid outside the
393 measured ranges of SOC_{dyn} and GWL. NEE is always positive for $\text{SOC}_{\text{dyn}} < 4.3 \text{ kg C m}^{-2}$.

394

395 4 Discussion

396 4.1 Soil influence on C gas exchange

397 As indicated in the introduction, data about the CO_2 exchange of groundwater-influenced arable
398 soils is generally scarce, particularly for maize, although some data is available for organic soils.
399 Although the maximum CO_2 fluxes observed during a 1-year study of maize cultivated on a
400 Haplic Gleysol in the Netherlands (Jans et al. 2010) are $\sim 25\%$ lower compared to the studied
401 Gleysol (Fig. 2), the flux dynamics and the cumulative net CO_2 exchange of the organic soil
402 types are relatively similar in both studies, with mean annual NEE of $-385 \text{ g CO}_2\text{-C m}^{-2} \text{ y}^{-1}$
403 (Gleysol) and $-334 \text{ g CO}_2\text{-C m}^{-2} \text{ y}^{-1}$ (Histosol) in this study (Table 2) vs. $-332 \text{ g CO}_2\text{-C m}^{-2} \text{ y}^{-1}$
404 (Jans et al. 2010). Moreover, the dynamics and the intensity of the CO_2 exchange observed for
405 the groundwater-influenced soils in this study are in the same order of magnitude as reported for
406 maize cultivated on soils without groundwater influence (Gilmanov et al. 2013, Kalfas et al.
407 2011, Zeri et al. 2011, Ceschia et al. 2010). The observed biomass yield of maize (257–

408 3117 g DM m⁻² y⁻¹) is also in line with previous studies (500–2800 g DM m⁻² y⁻¹; Zeri et al. 2011,
409 Verma et al. 2005). According to Gilmanov et al. (2013) and Ceschia et al. (2010), maize
410 cultivation generally resulted in a net annual CO₂ sink across a wide range of sites in America
411 and Europe, but – like in this study – with considerable variability between sites and years (+89
412 to –573 g CO₂-C m⁻² y⁻¹).

413 The results of this study demonstrate for the first time a considerable influence of groundwater-
414 influence soils on crop CO₂ exchange, particularly on cumulative NEE (Tables 3, 4, Fig. 3), thus
415 clearly affirming the research question (1) regarding the soil effect. Surprisingly, the C-rich
416 drained organic soils showed a strong net CO₂ uptake (Table 2), while the C-poor Arenosol was a
417 small net CO₂ source. This observation cannot be entirely explained by the interaction between
418 GWL and the potentially mineralizable soil C stocks. Hence, an integrated consideration of all
419 relevant C gas fluxes and their regulation within the plant-soil system is required, which is
420 discussed in detail below.~~Although the drained organic soils contain large stocks of~~
421 ~~decomposable C, surprisingly, they generally showed strong net CO₂ uptake (Table 2) while a~~
422 ~~small CO₂ release was observed at the C-poor Arenosol. Potential reasons for these observations~~
423 ~~will be discussed in detail below.~~ We are unaware of any previous study ever reporting such an
424 effect, likely because any systematic effects may only be observed in longer-term studies due to
425 the high interannual variability of C gas fluxes. This strongly supports the high relevance of such
426 investigations for the accurate evaluation of the C dynamics of groundwater-influenced arable
427 soils.

428 **4.2 Relevance of interactions between GWL and maize ecophysiology**

429 Apart from soil type and SOC content, the study sites are mainly differentiated by different
430 average GWL, which our study results show to be a crucial factor determining the high short- and
431 long-term variability of maize C gas exchange across the entire range of groundwater-influenced
432 soils. Previous studies have mainly shown an influence of GWL on CH₄ fluxes from peat soils,
433 mainly reporting an exponential increase of CH₄ fluxes for rising GWL with particularly high
434 CH₄ losses for GWL ≥ –0.2 m (Couwenberg et al. 2011, Jungkunst & Fiedler 2007, Drösler 2005,
435 Fiedler & Sommer 2000). Annual CH₄ emissions (–0.2 to 1.2 g CH₄-C m⁻² y⁻¹) for GWL between
436 –1.6 and –0.6 m and peak fluxes during flooding (≤ 28 g CH₄-C m⁻² y⁻¹; GWL of –0.3 m)
437 observed at the HS site are similar to values of Couwenberg et al. (2011) and Drösler (2005).

438 However, for crops cultivated on groundwater-influenced mineral soils, little data is available on
439 the impact of GWL on CH₄ fluxes (e.g., Pennock et al. 2010).

440 CO₂ exchange has also been intensively studied for organic soils, but mostly for pristine
441 peatlands and grasslands on peat soils (e.g., Leiber-Sauheitl et al. 2014, Berglund and Berglund
442 2011, Couwenberg et al. 2011), while data on maize are lacking. For peatland NEE, one study
443 reports a linear decrease with rising GWL over a range of -0.4 m to -0.1 m, with maximum NEE
444 observed at -0.4 m (Leiber-Sauheitl et al. 2014). Couwenberg et al. (2011) also observed
445 decreasing NEE when GWL rose above -0.5 m, but net CO₂-C uptake was only reported for very
446 high GWL above -0.1 m. In contrast, in this study, maize NEE was largely negative across the
447 entire range of GWL recorded at the studied groundwater-influenced soils (-2.1 m to +0.2 m),
448 changing to positive values when GWL rose above -0.4 m to -0.6 m. Moreover, the GWL-NEE
449 relationship for maize shows a clearly nonlinear relationship to GWL, with a distinct optimum at
450 considerably lower GWL (between -0.8 m and -1.0 m; Fig. 3) than observed for grasslands.
451 Further studies are required to determine if this is a general pattern applicable to other
452 groundwater-influenced soil types and crops.

453 Our study results further indicate that R_{eco} and GPP also feature specific GWL optima (*data not*
454 *shown*). For example, maximum R_{eco} fluxes were observed for GWL of -0.8 m to -1.0 m, similar
455 to data from grassland on four GWL-influenced soil types (Fiedler et al. 1998). Similar to the
456 R_{eco} of maize at the organic HS and GL sites, R_{eco} fluxes of grasslands on organic soils typically
457 decrease with rising GWL (Leiber-Sauheitl et al. 2014, Berglund and Berglund 2011, Laine et al
458 1996, Silvola et al. 1996), particularly if GWL rises above the soil surface (Koebisch et al. 2013).
459 The impact of GWL on GPP was relatively small in this study (Table 3); except for the effect of
460 the 2007 flooding, which resulted in a drastic reduction in GPP (Table 2) as also observed by
461 Koebisch et al. (2013) after rewetting.

462 Most of the study results concerning the individual CO₂ fluxes can be explained by the
463 interactions between GWL and maize plant activity, because the magnitude and the variability of
464 GPP and R_{eco} is most pronounced during the short period from May to September, which
465 corresponds to the growing period of maize (Fig. 2). For example, the drastic reduction of the
466 CO₂ fluxes during the flooding in 2007 at HS and GL (Fig. 1, 2) is very likely caused by the
467 previously mentioned negative effect of anoxic soil conditions on maize metabolism. On the

468 other hand, the lower CO₂ fluxes during the summer of 2009 especially at the AR site probably
469 result from an inhibition of maize gas exchange due to drought stress (Vitale et al. 2008, Jones et
470 al. 1986), i.e. long periods of very low GWL (Fig. 1, 2). Apart from these extreme situations,
471 GWL were mostly at soil depths which were favourable for the metabolism and the productivity
472 of a C4 plant like maize (Tollenaar and Dwyer 1999).

473 For example, maize features considerably higher gas exchange activity under maximum PAR and
474 temperature conditions than all C3 grasses and crops (Zeri et al. 2011, Kutsch et al. 2010). As a
475 consequence, although the main growing period of maize (~2 months) is much shorter than that
476 of most C3 plants (3–4 months), the CO₂ flux intensity of maize throughout this short active
477 period is large enough to result in higher annual cumulative R_{eco} and GPP values compared to C3
478 crops (Beetz et al. 2013, Klumpp et al. 2011, Zeri et al. 2011, Flanagan et al. 2002). It is very
479 likely that the GWL optima of GPP and R_{eco} can be traced back to this fact, e.g., as indicated by
480 the enhanced amplitudes of the GPP as well as the R_{eco} fluxes at the AR site during the wet
481 summer 2007 compared to years with lower GWL (Fig. 2). However, the interactions between
482 GWL and maize growth do not offer explanations for the observed differences in cumulative
483 NEE among sites and the functional relationship between NEE and GWL.

484 **4.3 Relevance of interactions between GWL and dynamic soil C and N stocks**

485 The strong effect of GWL on the C gas exchange is likely also the reason for the lack of any
486 effect of total, i.e. static, soil C and N stocks on daily, monthly or annual C gas exchange. In the
487 few existing studies on this subject, an impact of soil C and N stocks on C gas fluxes was only
488 found for if GWL was either constant (Mundel 1976) or irrelevant for the soil water regime
489 (Lohila et al. 2003). Moreover, in agreement with the results of this study, Leiber-Sauheitl et al.
490 (2014) found no relationships between static soil C and N stocks and the C gas exchange of
491 Gleysols with highly variable GWL during a 1-year study. In contrast, our study revealed a very
492 strong effect of mainly GWL-determined dynamic soil C and N stocks on C gas dynamics
493 (Table 3), thus indicating a higher relevance of SOC and N stocks located in the aerobic zone
494 above the GWL for plant and soil gas exchange than of total soil SOC_{stocks} and N_{stocks} in the soil
495 profile.

496 However, the functional GWL-related mechanisms mentioned in the introduction cannot fully
497 explain the results of this study. Several observations indicate that the influence of the dynamic
498 soil C and N stocks on the C gas exchange extends beyond the mere GWL effect:

499 i) All C gas fluxes are differently and specifically influenced by the dynamic soil C and
500 N stocks (Tables 3, 4).

501 ii) Compared to the GWL, the effects of dynamic soil C and N stocks on NEE are
502 considerably stronger than on the individual R_{eco} ~~and~~ and GPP fluxes, also reflected
503 by the associated shift in the GPP : R_{eco} ratio (Table 3). It must be pointed out that
504 these two parameters differ in their informational value: while NEE is the absolute
505 difference between the opposing CO_2 fluxes R_{eco} and GPP, the GPP : R_{eco} ratio
506 reflects the relative proportion of these fluxes, thus giving indications for the reasons
507 of changing NEE values. Interestingly, the dynamic C : N ratio shows a similarly
508 strong effect on these two parameters. The potential relevance of these observations
509 for explaining the study results is also discussed in section 4.2.

510 iii) The effects of the GWL and the dynamic soil C or N stocks on the cumulative CO_2
511 fluxes clearly differ with respect to their type and direction (Fig. 3, Table 4).

512 Despite a limited number of sites, clustering of sites with respect to GWL range, and a single
513 crop, the results of this study are considered consistent and plausible for the range of measured
514 GWL and soil C stocks, as the results from several very different statistical methods point to the
515 same conclusions. Still, subsequent studies which consider other sites and plants are required to
516 determine if the discussed conclusions regarding the type and intensity of the effect of dynamic
517 soil C and N stocks on cumulative NEE, their differentiated effects on GPP and R_{eco} as well as
518 their interactions with GWL are generally valid. A reassessment of data from previous studies
519 using continuous GWL data (if available) for the calculation of dynamic soil C and N stocks
520 could be helpful to determine if similarly strong effects of dynamic soil C and N stocks on C gas
521 dynamics exist for other sites and plants. System-oriented investigations, which are aiming to
522 understand the underlying processes and mechanisms, might reveal if and how the observed
523 phenomena are related and from which underlying processes they originate.

524 **4.4 The nature and relevance of mechanisms causing the effect of the dynamic**
525 **soil C and N stocks**

526 **4.4.1 Potential mechanisms**

527 A common observation may be used as a starting point for a comprehensive explanation: crop
528 growth on groundwater-influenced soils is mainly influenced by rooting depth, which in turn is
529 mostly influenced by GWL (e.g., for maize: Kondo et al. 2000). In this context, stress due to O₂
530 deprivation only plays a minor role, i.e. via the GWL-defined lower limit of the root-able soil
531 volume (Glaz et al. 2008, Livesley et al. 1999). More importantly, larger root systems enable
532 improved supply of plants with nutrients and water (especially at the AR site), likely resulting in
533 increased photosynthetic capacity and thus higher primary productivity. The link between
534 increasing N content and increased GPP was previously documented in studies by Flanagan et al.
535 (2002) and Ashraf et al. (1999). Interestingly, several long-term field trials with crops grown on
536 mineral soils also show that changing SOC stocks not only depend on crop rotation and organic
537 fertiliser amount, but also on the nutrient supply to the crops *per se*. In these trials, the mere
538 application of mineral fertiliser results in a significant increase of soil organic matter compared to
539 non-fertilised treatments (Jung and Lal 2011, Banger et al. 2010, Thomas et al. 2010, Christopher
540 and Lal 2007, Sainju et al. 2006.). Among other crops, this also applies to maize (Kaur et al.
541 2007).

542 In particular, the N supply plays a key role: up to a threshold, the gradual increase of mineral N
543 fertiliser amount generally results in higher SOC and SON stocks (e.g., for maize: Kaur et al.
544 2007, Blair et al. 2006a, Blair et al. 2006b). Pot experiments with maize indicate that N
545 fertilisation increases the input of newly assimilated C more than CO₂ emissions from root
546 respiration and mineralisation of soil organic matter (Gong et al. 2012, Conde et al. 2005), thus
547 resulting in the accumulation of SOC. Moreover, in field trials, mineral N fertilisation reduced
548 the decomposition rate of maize residues in the soil (Grandy et al. 2013). Therefore – apart from
549 the impact of C export (removal during harvesting) and import (input through organic
550 fertilisation) on the soil C budget – it seems highly likely that the N fertilisation of arable crops
551 contributes to an increase of SOC stocks by promoting C input through gross and net primary
552 productivity more than C loss via ecosystem respiration. Although this has not yet been
553 experimentally confirmed in its entirety, scientific evidence on the individual effects of N

554 fertilisation on the SOC stocks of arable soils without groundwater influence makes this
555 hypothesis plausible.

556 **4.4.2 Indications for similar mechanisms on groundwater-influenced soils**

557 Several results of this study suggest a strong N impulse on C gas fluxes. All sites received a total
558 of 122 kg N ha⁻¹ y⁻¹ throughout the entire study period, providing sufficient N for plant growth.
559 The dynamic soil N stocks and the SOC_{dyn} : N_{dyn} ratio had strong effects on cumulative NEE and
560 the GPP : R_{eco} ratio (Table 3). Formally, this also holds true for the dynamic SOC stocks, but –
561 unlike for N – this effect results from the tight correlation of soil C and N contents rather than
562 from direct effects of organic matter production or decomposition. The large influence of GWL
563 on dynamic soil N stocks, reflected by a strong interaction, indicates that both parameters control
564 N mineralisation. It has been repeatedly observed both for organic and mineral soils that the
565 lowering of the GWL, i.e. an increase of the dynamic N stocks due to improved soil aeration,
566 increases N mineralisation, while a rising GWL, i.e. decreasing dynamic N stocks, results in the
567 opposite (Eickenscheid et al. 2014, McIntyre et al. 2009, Venterink et al. 2002; Hacin et al. 2001,
568 Goettlich 1990, Reddy and Patrick 1975).

569 Increased dynamic soil N stocks are equivalent to an improved N supply to plants and
570 microorganisms, which should be similar in effect to the N fertilisation in the above-mentioned
571 long-term field trials. In this study, the tight correlation between the dynamic soil N stocks and
572 the maize biomass development during the vegetation period ($r^2 = 0.817$; *data not shown*)
573 indicates that most of the N mineralised when GWL were low and root systems deep likely
574 played a significant role in plant N supply and thus plant development – regardless of the
575 fertilisation-induced N impulse and the fact that the monthly biomass values were not measured
576 but calculated using a simple linear approach. Similarly strong biomass and dynamic C and N
577 stocks effects on cumulative NEE (Table 3) further support this line of thought, as an increased
578 biomass production stimulated by higher N availability is always associated with increased CO₂
579 input into the plant-soil system via gross primary production.

580 In other words: the N supply in the plant-soil system and its effects on C formation and
581 transformation processes likely also play a key role in the C gas exchange of groundwater-
582 influenced soils, by promoting CO₂ input via gross primary production more than CO₂ emission
583 via ecosystem respiration. The observed effects of the dynamic soil C and N stocks on

584 cumulative NEE can thus be plausibly explained. However, the relatively low optimum GWL for
585 minimizing NEE (Fig. 3) likely requires additional explanatory mechanisms. For example, an
586 improved plant water and nutrient supply, e.g. with macro-nutrients like P and K, could increase
587 root and shoot growth and thus CO₂ input, as observed for soils without groundwater influence
588 (Ladha et al. 2011, Poirier et al. 2009, Al-Kaisi et al. 2008, Reay et al. 2008, Kaur et al. 2007).

589 **4.4.3 Future improvements of the dynamic stocks concept**

590 Most of the functional mechanisms discussed above are somewhat speculative and require
591 subsequent validation by means of experiments which consider all mentioned processes of the
592 plant-soil system and their respective regulating factors. Special attention should be paid to the
593 determination of the scope of all relevant processes, as several studies state that the input of N
594 and other nutrients does not always have only positive effects on net CO₂ exchange and the C
595 sink function of arable soils (Thangarajan et al. 2013, Hoffmann et al. 2009, Mulvaney et al.
596 2009, Al-Kaisi et al. 2008, Khan et al. 2007).

597 Moreover, the concept of dynamic soil C and N stocks is only an indicator of real dynamic
598 stocks, because in this study dynamic stocks were modeled exclusively based on GWL dynamics.
599 Further developments might include precipitation-related topsoil water dynamics or soil
600 hydraulic properties (e.g., capillary fringes), which might considerably reduce dynamic soil C
601 and N stocks. The concept of dynamic stocks could also be expanded to other plant nutrients like
602 plant-available P or K. However, these suggested refinements require very detailed high-
603 resolution data on soil and plant properties and processes, including their vertical variability in
604 the soil profile, and were thus beyond the scope of this study.

605

606 **5 Conclusions**

607 Results clearly showed that the studied soils differ considerably with respect to the intensity and
608 dynamics of C gas exchange. In order to accurately assess the climate impact of arable sites on
609 drained peatlands, it is therefore necessary to consider the entire range of groundwater-influenced
610 mineral and organic soil types and their respective areal extent within a heterogeneous soil
611 landscape.

612 While climatic controls like PAR, temperature and precipitation mainly have short-term effects
613 on C gas fluxes, the effects of dynamic soil C and N stocks are clearly observable at all temporal
614 scales. It is to be determined by future studies in how far this also applies to i) crops other than
615 maize, ii) other land use forms like grasslands, and iii) other groundwater-influenced sites.
616 Dynamic soil C and N stocks may be major controlling factors of C gas fluxes and the CO₂
617 source or sink function of the entire range of wetlands, potentially of higher and more global
618 relevance than GWL and vegetation, which are the main factors favoured to date (Couwenberg et
619 al. 2011, Byrne et al. 2004). The insight, that the effect of the dynamic soil C and N stocks very
620 likely results from the regulation of C formation and transformation processes by N and –
621 potentially – nutrient and water supply as such, may be of particular importance. This mechanism
622 would be a favourable prerequisite for the development of generalizable process-based models,
623 which would be very useful in providing more precise estimates of the impact of important
624 factors like climate, site conditions and land use on the C gas fluxes of wetlands.

625 Overall, the presented results and subsequent analyses show the enormous potential of combining
626 long-term measurements of C gas fluxes with process-oriented analyses of the functional
627 mechanisms and their regulation within the soil-plant system when aiming for an improved
628 understanding of the biogeochemistry of wetlands.

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630

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645

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953

954 **Tables**

955

Table 1. Characteristics of study sites: soil type, elevation, and 0–1 m stocks of soil organic C and total N.

Site	Soil type [†]	Elevation	SOC _{stocks}	total N _{stocks}
		[m a.s.l.]	[kg SOC m ⁻²] [‡]	[kg N _t m ⁻²] [‡]
AR	Haplic Arenosol	29.6	8.0	0.7
GL	Mollic Gleysol	29.0	37.8	3.1
HS	Hemic Histosol	28.8	86.9	5.4

[†] WRB 2006; [‡] 0–1 m soil depth

956

Table 2. Annual fluxes of CO₂ (R_{eco}, GPP and NEE) and CH₄ by site and year (\pm model error; 95 % confidence interval); and average fluxes (\pm 1 SD) for the entire study period (2007/08-2010/11) and excluding the flooded year 2007/08.

Site	C flux [g C m ⁻² y ⁻¹]	Year				Periodic average	
		2007/08	2008/09	2009/10	2010/11	2007/08- 2010/11	2008/09- 2010/11
AR	CH ₄	0.17 (0.07)	0.15 (0.32)	-0.10 (0.06)	0.00 (0.04)	0.06 (0.06)	0.01 (0.07)
	R _{eco}	2880 (183)	1729 (32)	1267 (21)	1547 (40)	1856 (354)	1514 (134)
	GPP	-2889 (52)	-1670 (34)	-1143 (34)	-1534 (58)	-1810 (377)	-1449 (158)
	NEE	-9 (190)	59 (47)	125 (40)	13 (70)	47 (30)	66 (32)
GL	CH ₄	1.19 (0.61)	-0.10 (0.03)	-0.04 (0.10)	-0.17 (0.08)	0.22 (0.32)	-0.10 (0.04)
	R _{eco}	1733 (191)	2131 (30)	1288 (51)	1409 (36)	1640 (189)	1609 (263)
	GPP	-1799 (43)	-2279 (43)	-1895 (97)	-1809 (40)	-1946 (113)	-1994 (144)
	NEE	-65 (196)	-148 (52)	-607 (110)	-400 (54)	-305 (123)	-385 (133)
HS	CH ₄	27.57 (3.70)	0.26 (0.51)	0.30 (0.20)	n.a. [†]	n.a. [†]	n.a. [†]
	R _{eco}	1479 (55)	1853 (33)	2131 (68)	1995 (52)	1864 (141)	1993 (80)
	GPP	-985 (62)	-2065 (61)	-2535 (53)	-2382 (122)	-1992 (350)	-2327 (139)
	NEE	493 (83)	-212 (70)	-404 (86)	-387 (133)	-127 (212)	-334 (62)

[†] Data not available

Table 3. Summary statistics of generalized linear model (GLM) analysis describing the influence of site and environmental controls (GWL, climate, soil, plants) on cumulative annual CH₄ efflux, R_{eco}, GPP, NEE and the ratio of GPP : R_{eco}.

	CH ₄ [g CH ₄ -C m ⁻² y ⁻¹]		R _{eco} [g CO ₂ -C m ⁻² y ⁻¹]		GPP [g CO ₂ -C m ⁻² y ⁻¹]		NEE [g CO ₂ -C m ⁻² y ⁻¹]		GPP : R _{eco}		
	Wald χ^2	<i>p</i>	Wald χ^2	<i>p</i>	Wald χ^2	<i>p</i>	Wald χ^2	<i>p</i>	Wald χ^2	<i>p</i>	
Intercept	1.312	0.252	7.626	0.006*	14.311	$\leq 0.001^*$	96.005	$\leq 0.001^*$	29.743	$\leq 0.001^*$	
Site	72.812	$\leq 0.001^*$	25.571	$\leq 0.001^*$	26.040	$\leq 0.001^*$	90.685	$\leq 0.001^*$	65.869	$\leq 0.001^*$	
Climate	Air temperature	11.218	0.001*	33.135	$\leq 0.001^*$	18.706	$\leq 0.001^*$	30.960	$\leq 0.001^*$	17.566	$\leq 0.001^*$
	Soil temperature	1.666	0.197	14.456	$\leq 0.001^*$	5.927	0.015*	36.618	$\leq 0.001^*$	18.096	$\leq 0.001^*$
	Precipitation	19.008	$\leq 0.001^*$	9.093	0.003*	4.827	0.028*	11.562	0.001*	17.588	$\leq 0.001^*$
	Sunshine hours	10.201	0.001*	21.158	$\leq 0.001^*$	9.646	0.002*	†	†	†	
	Year	†		6.004	$\leq 0.001^*$	8.210	0.004*	7.629	0.006*	4.650	0.031*
	Year * Air temp.	†		50.403	$\leq 0.001^*$	37.758	$\leq 0.001^*$	†	†	9.919	0.002*
	Year * Sunshine hours	†		37.816	$\leq 0.001^*$	24.348	$\leq 0.001^*$	†	†	†	
	Soil temp. * Air temp.	12.791	$\leq 0.001^*$	†		†		29.049	$\leq 0.001^*$	12.913	$\leq 0.001^*$
	Soil temp. * Sunshine h.	11.667	0.001*	20.182	$\leq 0.001^*$	11.059	0.001*	29.049	$\leq 0.001^*$	†	
	Plants	Biomass	†		17.810	$\leq 0.001^*$	23.071	$\leq 0.001^*$	49.537	$\leq 0.001^*$	7.361
Biomass * Site		†		72.633	$\leq 0.001^*$	70.273	$\leq 0.001^*$	80.039	$\leq 0.001^*$	33.074	$\leq 0.001^*$
Biomass * Sunshine h.		†		16.733	$\leq 0.001^*$	23.268	$\leq 0.001^*$	†	†	†	
GWL	GWL	3.173	0.075	273.627	$\leq 0.001^*$	13.516	$\leq 0.001^*$	2.667	0.102	38.940	$\leq 0.001^*$
	GWL * Site	27.256	$\leq 0.001^*$	†		17.779	$\leq 0.001^*$	†	†	61.005	$\leq 0.001^*$
	GWL * Precipitation	†		†		†		6.653	0.010*	23.737	$\leq 0.001^*$
Soil	SOC _{dyn}	5.843	0.016*	15.668	$\leq 0.001^*$	8.330	0.004*	32.101	$\leq 0.001^*$	18.340	$\leq 0.001^*$
	N _{dyn}	8.683	0.003*	26.541	$\leq 0.001^*$	8.479	0.004*	23.224	$\leq 0.001^*$	†	
	SOC _{dyn} : N _{dyn}	0.869	0.351	†		13.120	$\leq 0.001^*$	106.424	$\leq 0.001^*$	4.146	0.042*
	SOC _{dyn} * Site	24.005	$\leq 0.001^*$	93.546	$\leq 0.001^*$	25.348	$\leq 0.001^*$	†	†	13.538	0.001*
	N _{dyn} * Site	†		93.868	$\leq 0.001^*$	25.267	$\leq 0.001^*$	8.349	0.004*	†	
	SOC _{dyn} : N _{dyn} * Site	73.365	$\leq 0.001^*$	†		26.078	$\leq 0.001^*$	92.340	$\leq 0.001^*$	66.370	$\leq 0.001^*$
	SOC _{dyn} * GWL	17.551	$\leq 0.001^*$	†		†		†	†	†	
	N _{dyn} * GWL	22.532	$\leq 0.001^*$	†		9.169	0.002*	64.724	$\leq 0.001^*$	†	

* Asterisks denote significant factors ($\alpha = 0.05$).

† Redundant parameter/parameter interaction.

Table 4. Summary statistics of multiple nonlinear regression analysis of the form $NEE = \text{poly}(\text{GWL}) + \text{lin } y^{(1; 2; 3 \text{ or } 4)}$ describing the influence of GWL and one environmental parameter, either 1) SOC_{dyn} , 2) N_{dyn} , 3) $\text{SOC}_{\text{dyn}} : \text{N}_{\text{dyn}}$ or 4) biomass, on cumulative annual NEE: mean absolute error (MAE), RMSE-observations standard deviation ratio (RSR), adjusted coefficient of determination (R^2), modified index of agreement (md), percent BIAS (PBIAS) and Nash-Sutcliffs model efficiency (NSE), Akaike Information Criterion (AIC) and Bayesian information criterion (BIC).

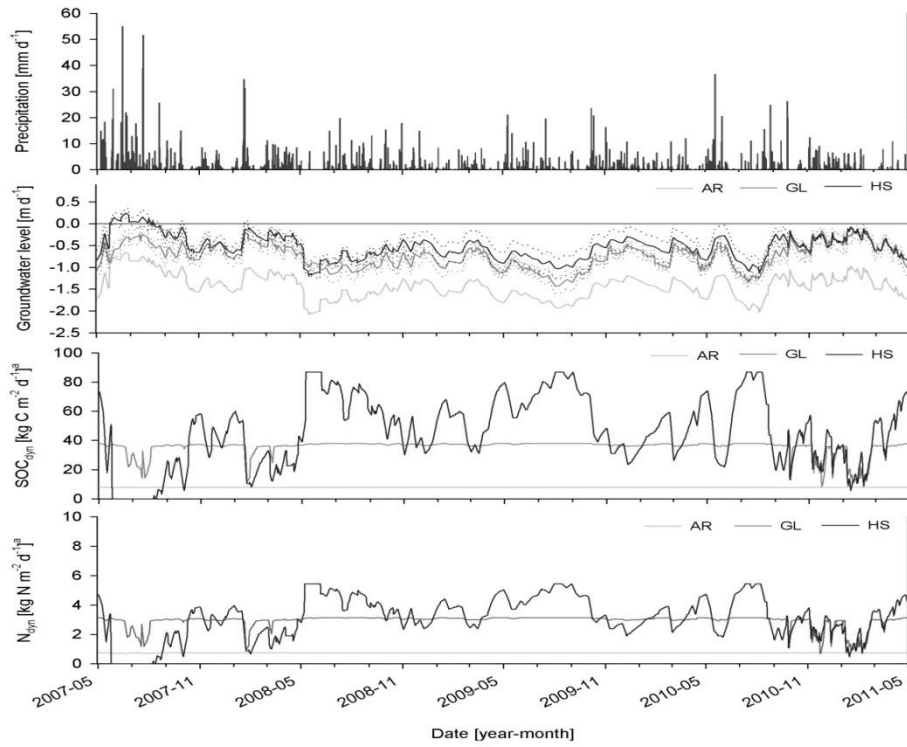
Summary statistic	Environmental parameter			
	¹ SOC_{dyn}	² N_{dyn}	³ $\text{SOC}_{\text{dyn}} : \text{N}_{\text{dyn}}$	⁴ Biomass
MAE [$\text{g m}^{-2} \text{y}^{-1}$]	80.99	83.86	78.99	84.78
RSR	0.353	0.362	0.355	0.354
adj. R^2	0.869	0.862	0.867	0.868
md	0.847	0.842	0.850	0.840
PBIAS [%]	0.000	0.000	0.000	0.000
NSE	0.872	0.866	0.871	0.871
AIC	503.38	505.37	503.88	503.67
BIC	515.20	517.20	515.70	515.49

Note: bold values highlight the best value for each summary statistic across the four models; all models significant at p -value ≤ 0.001

959 **Figures**

960

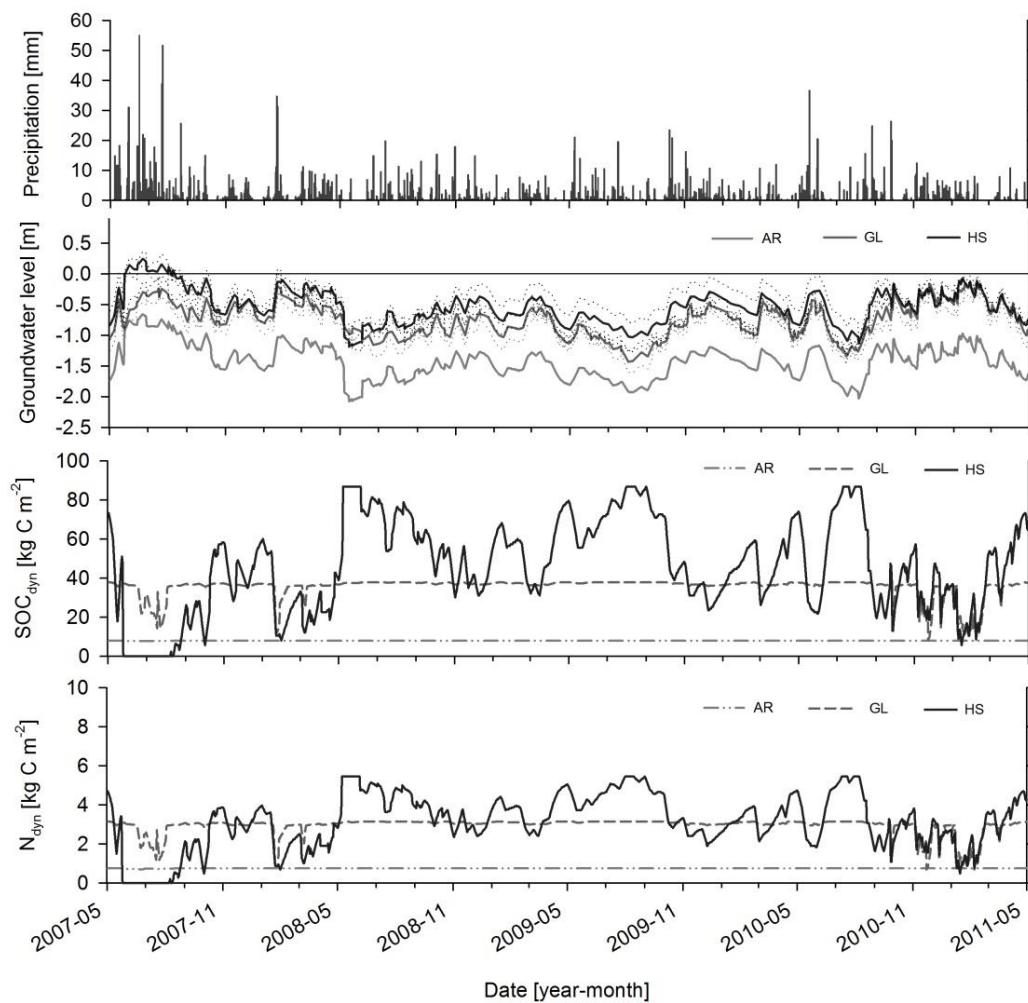
961 **First version of figure 1**



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Figure modified!

967

Figure 1. Seasonal dynamics of (from top to bottom) daily precipitation, average daily GWL

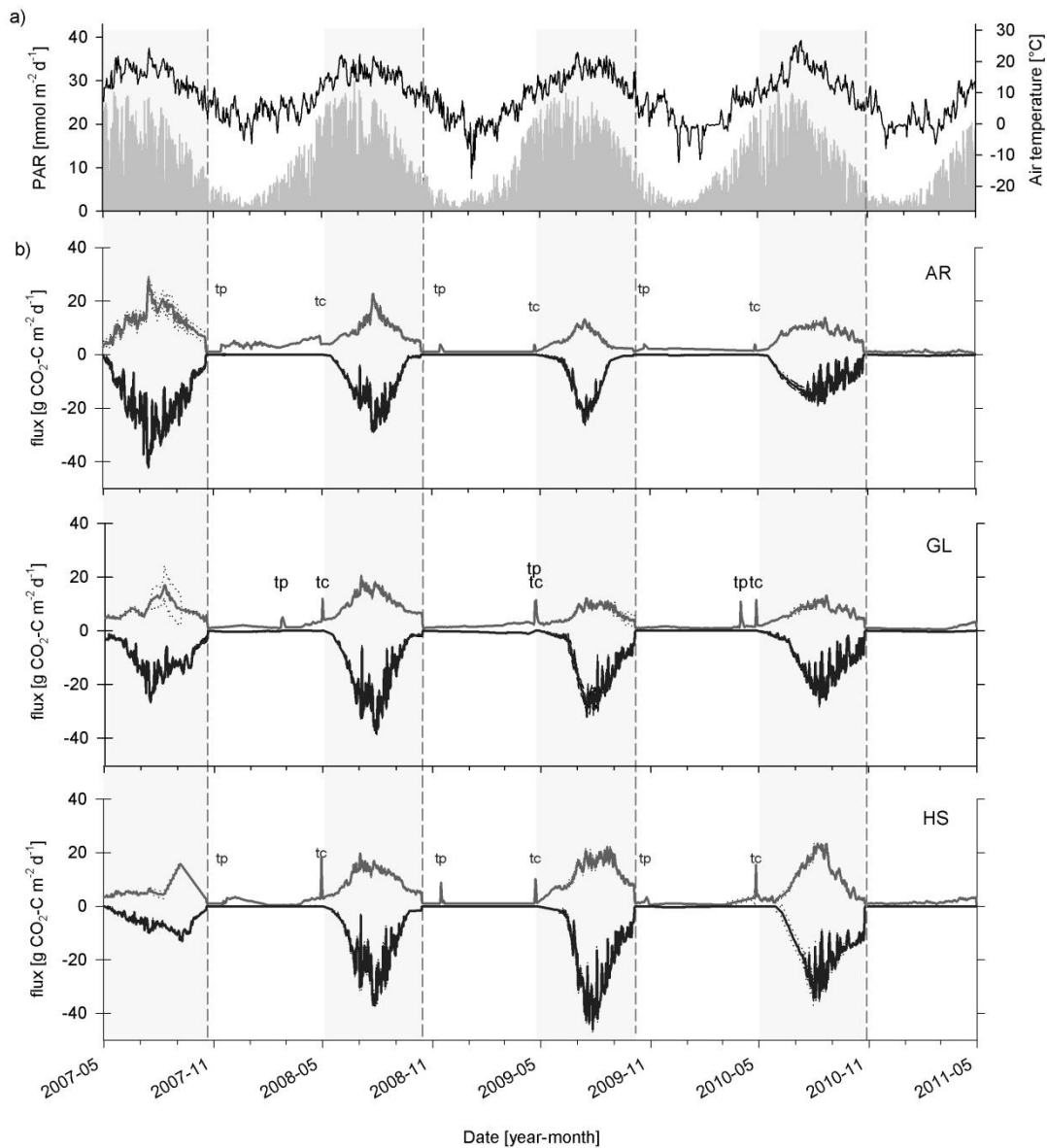
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including 95% confidence intervals (dotted lines), and daily dynamic SOC_{dyn} and N_{dyn} stocks

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by site (AR for 0–1 m depth).

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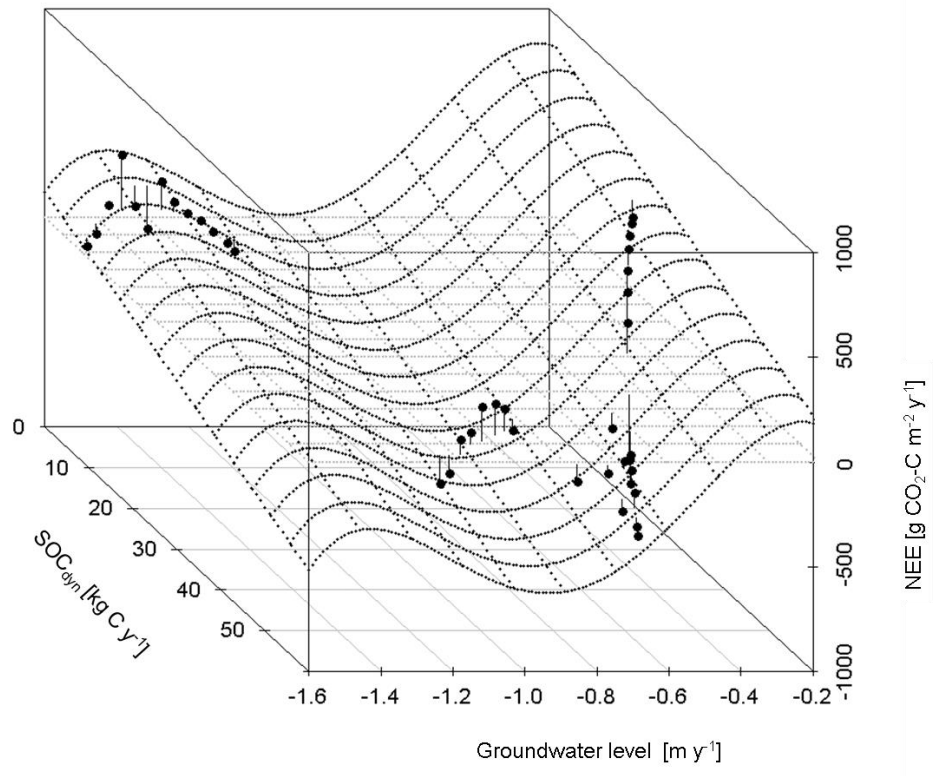


971

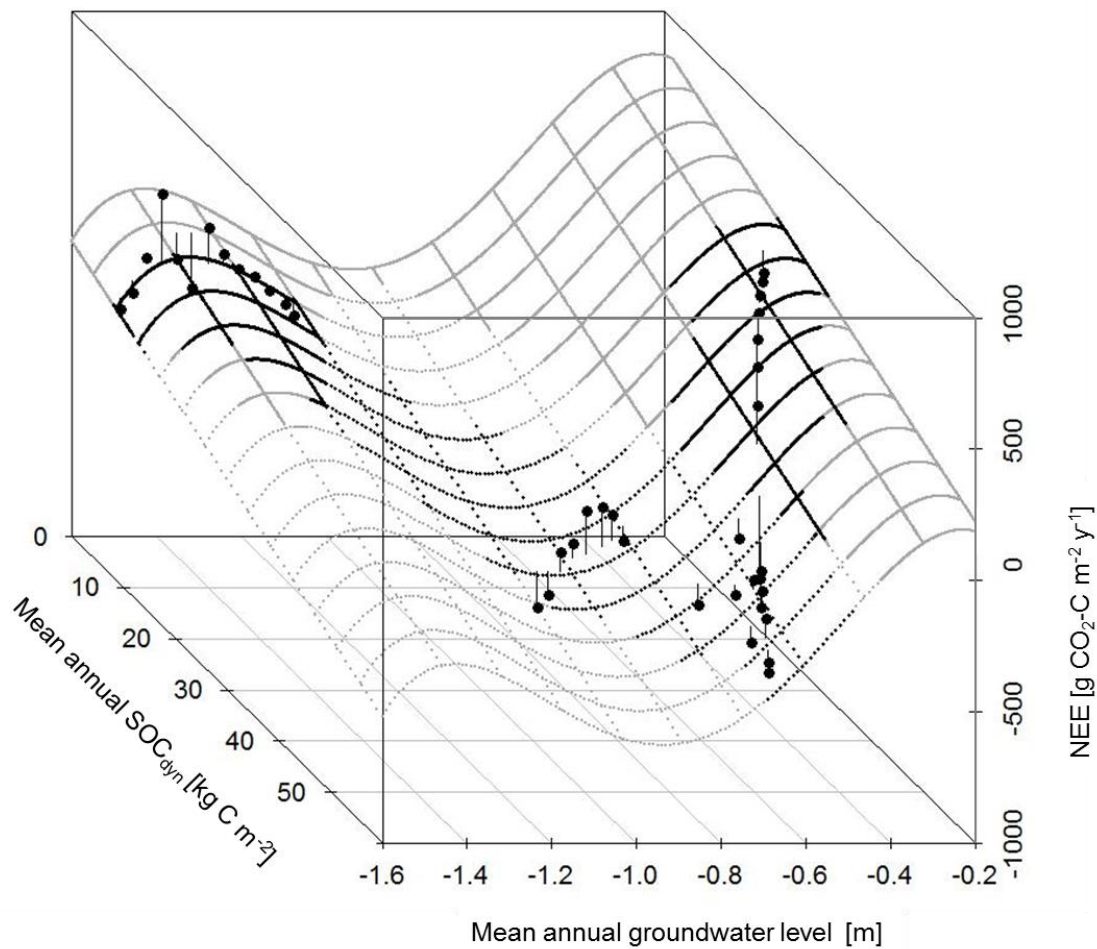
972 **Figure 2.** Dynamics of daily a) cumulated PAR (grey vertical bars) and average air
 973 temperature at 20 cm height (black line); and b) modeled CO₂-C fluxes (grey line: R_{eco}; black
 974 line: GPP) including 95% confidence intervals (dotted lines) by site. Shaded areas indicate the
 975 period between maize sowing and harvest (dashed vertical line); tp – ploughing, tc –
 976 cultivation (sowing, fertilization).

977

978 **First version of figure 3**



979



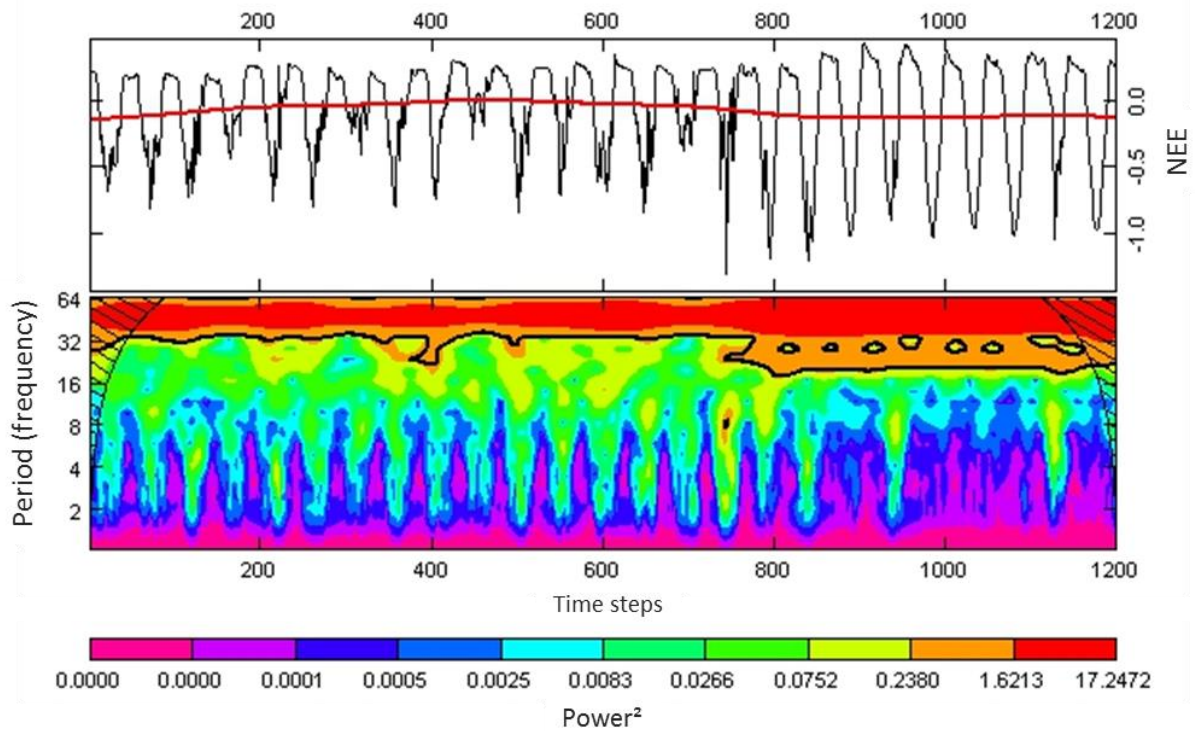
980

981 **Figure 3 modified!**

982 **Figure 3.** Result of nonlinear regression analysis between NEE, GWL and SOC_{dyn} originating
 983 from 365-day moving-window analysis averaged over twelve GWL classes per site (for
 984 model statistics see Table 4). Displayed grid represents the derived model surface with i)
 985 estimated model area covered by direct measurements (solid black) and ii) non-empirically
 986 approved model area computed by extrapolation (grey). Modelled NEE is separated according
 987 to positive (solid lines) and negative (dashed lines) values. twelve site-specific GWL classes
 988 per site (for model statistics see Table 4).

989

990 **Reworking in supplement:**



991

992 **Figure S2.** Diurnal variability as detected by wavelet analysis of modelled half-hour NEE
993 data (range from 07/07/2008 to 31/07/2008). The upper graph displays modelled NEE time
994 series and corresponding smoothing spline (solid red line). The lower graph shows the
995 continuous wavelet transform and cone of influence (hatched area) within the respective time
996 frequency domain. The wavelet power spectrum is thereby defined as the squared absolute-
997 value of the wavelet coefficients (correlation between wavelet and data array).