Dear Editor,

we appreciate the comments by W. Bleuten, E. Hobbie and four anonymous reviewers for providing useful and constructive comments that have helped us to improve the manuscript. Following their suggestions, we have revised the manuscript carefully. Below you can find our detailed responses (bold) to the comments. The pages and lines mentioned in our responses refer to the pages and lines in the revised manuscript.

Best Regards

Jan Paul Krüger (on behalf of all authors)

Short comment by E. Hobbie

This is an interesting approach and a good use of ash content. The Suess effect will probably contribute some to low d13C values in the uppermost peat layers, since the d13C of atmospheric CO2 has dropped by 1.7 per mil since 1850 (most rapidly since 1950).

Reply: Thank you! That is true, the Suess effect could have contributed to the low δ^{13}C values in the uppermost layer of the near-natural site. But the further increase of δ^{13}C (more than 5 per mil) with depth shows the aerobic decomposition of the peat at this site. We will include a short discussion of this aspect in the revised manuscript.

Anonymous Referee #1

The topic of the manuscript is relevant for Biogeosciences. The paper present important additions to our knowledge on the peatland biogeochemistry. The language of the manuscript is very good except one misprint in the abstract (see below). However, I recommend some revisions before final consideration of this paper for publication.

General comments:

1. The plots for natural peatlands are somewhat inconsistent between Figs. 1 and 2. In the former Figure, δ^{13}C does not depend on depth. The relevant arguments are provided in Sect. 1. However, in Fig. 2, all three NW ('near–natural') plots show significant dependence of

$\delta^{13}C$ on depth. The difference of $\delta^{13}C$ in these plots between the near-surface layer and the depth of ≈ 1 m (the deepest data presented in the paper) for the NW plots is even larger than the corresponding differences for the GE and GI sites. I guess, that this inconsistency should be addressed before considering the paper for publication in Biogeosciences.

Reply: The figure 1 is the theoretical concept for natural and degraded peatland based on literature research. In figure 2 the results of the $\delta^{13}C$ measurements of the three investigated sites are presented. The results show, that the $\delta^{13}C$ depth profiles of the NW site are different to the expected depth profile of natural peatlands in the theoretical concept (Fig. 1). This indicates a degradation of the NW site. The differences of $\delta^{13}C$ values between the near-surface layer and the deepest investigated layer are higher for the NW profiles compared to the grassland sites, which is mainly due to the lower $\delta^{13}C$ values in the first 6 cm at the NW site compared to the grassland sites. The lower $\delta^{13}C$ values of the NW site are probably due the Suess effect (please see reply to short comment by E. Hobbie) due to the fact that these ecosystem has bound more C into the soil than the grassland sites.

2. An additional inconsistency is found between Figs. 1 and 3 is due to $\delta^{15}N$ for managed sites (GI and GE). In the conceptual Fig. 1 $\delta^{15}N$ changes from negative values in the near–surface peat layer to the positive values at greater depths. However, the respective plots in Fig. 3 show an opposite dependence on depth. Again, this matter should be resolved before publication.

Reply: As described in the reply to the first general comment the figure 1 is a theoretical consideration for the expected depth profiles of natural and degraded peatlands and the figure 3 presents the results of our measurements at the three different sites.

Specific and technical comments:

1. p. 16826, line 15: please remove comma after 'near–natural site';

2. Table 2: I would suggest to remove the superscript 'n.s.' and type the numbers with $p < 0.05$ (and with smaller p) in boldface; 3. I would suggest to break all Figures in parts (a, b, c, etc.). It would simplify reference to these parts in the body of the text.

Reply: We will change the specific and technical comments in the revised manuscript.

Reviewer 3

The manuscript is actually an extended case study of the previous one (Alewell et al. 2011 Biogeosciences. 8:1769.). However, the authors in this study appear to over-interpret the results. The author indeed can carefully read the previous paper and discuss the results in a more balanced manner.

Reply: We think there is a misunderstanding here. Our manuscript deals with biogeochemical indicators of peatland degradation along a land use gradient in temperate bogs. Temperate bogs and subarctic palsa peatlands are completely different ecosystems. Also we use a large number of indicators to detect human-induced changes in the peat profile. The current study is therefore not an extension of Alewell et al. (2011) but an application of the Alewell et al. approach to a complete new situation in a different ecosystem context.

(1) The title. The title is relatively vague. The authors claim that 'Biogeochemical indicators of peatland degradation – a case study of a temperate bog in Northern Germany'. One could not understand what are biogeochemical indicators and how precisely these indicators could represent environmental disturbances. The new title is apparently needed in a straightforward manner.

Reply: Our title already gives precise information about the set-up. The specific indicators are described in the abstract. Stable isotopes, C and N concentrations as well as ash content are well known biogeochemical soil parameters which have the potential to indicate disturbance of ecosystems and their biogeochemical cycles.

(2) The conclusion. The authors conclude that 'All investigated biogeochemical parameters together indicate degradation of peat due to conversion to grassland, (ii) historical drainage as well as recent development and land use intensification. These statements are pretty vague and could be imagined without experimentation.

Reply: Our aim was to test if these parameters, particularly stable isotopes of carbon and nitrogen, are suitable indicators for peatland degradation and hence human disturbance. We selected a peatland with known land-use history and clear differences between the study sites to investigate the soil parameters and to test our hypotheses.

With this newly gained knowledge about the indicators these methods can be applied to other peatlands where only little information on previous or ongoing disturbance is available.

(3) Peatland degradation as the theme is not appropriate. It appears there is no solid evidence in support peat degradation in this study. As the authors mentioned, aerobic and/or decomposition can occur in peatland, leading to degradation. However, the indicators, rather than solid evidence of peatland degradation were investigated. It remains uncertain whether these indicators could accurately reflect what is going on in peatland. In addition, it was said that the highest carbon loss was observed in the intensively managed grassland (GI). However, only the carbon in soils was concerned. It seems that a large amount of aboveground biomass will be removed by grazing. What will happen if this was taken into account?

Reply: We disagree with reviewer 3: Peatland degradation is the focus of our study. We could show (significant) differences of the biogeochemical indicators between the two managed (degraded) sites on the one hand and the near-natural site on the other. The managed sites are degraded due to drainage and land use activities. We calculated C loss using the combined method (described in Leifeld et al. 2014) which is a time-integrative profile approach that integrates soil parameters (bulk density, ash content and C concentration) to calculate carbon loss since the onset of drainage. These calculations clearly show that the profiles lost substantial amounts of carbon since onset of drainage, i.e., these soils are degraded. Our aim was to estimate the total C loss of the soil to the atmosphere, whether it comes from peat oxidation or indirectly via harvesting of the aboveground biomass. For this type of calculation, harvest does not need to be included in the equations of the combined method. We agree that the observed carbon losses may have been caused by both, oxidation and smaller plant-derived residue inputs, but this does not change the total carbon budget of the soil. The cuts and manuring for the years 2007/08 and 2008/09 are presented in table 3 in Beetz et al. (2013).

(4) The authors seem to draw no solid conclusion for the usefulness of isotope techniques as indictors of peatland degradation. One point that is interesting I guess is the slope of 13C with depth. This slope appears to be a better predictor, and the authors can relate it to previous

studies (Alewell et al., 2011). In fact, the current manuscript needs to be presented in a manner similar to previous study by Alewell et al. 2011.

Reply: We could show that even the near-natural site is influenced by the surrounding drainage activity which is displayed in the $\delta^{13}C$ profiles as well as in the C loss calculation by the combined method. Hence, also bogs considered as near-natural or even natural could potentially be impaired by anthropogenic activities, at least in the past. Furthermore, the $\delta^{15}N$ profiles show significant differences between the three investigated sites with both, increasing peat decomposition and fertilizer application systematically changing the $\delta^{15}N$ signature of the soil. With this we concluded the usefulness of stable isotopes in bulk samples to detect peatland degradation. We again emphasize that slopes of $\delta^{13}C$ vs. depth are included in our analysis. We put our results, at several places, into context with those of Alewell et al. (2011) but, at the same time, stress that we are dealing with a very different type of ecosystem in the present manuscript.

Anonymous Referee #5

This is a concise and clearly presented paper that draws upon a number of biogeochemical indicators to consider peat degradation at three sites of contrasting management history, in northern Germany. The research is generally described well, and although the results are presented in a descriptive manner, they illustrate the potential to use this approach more widely when assessing peatland degradation. However, it would have been useful if the authors had reflected more on this latter point in the paper (specifically the wider significance of this research). While I feel that the paper is very close to publishable quality already, I suggest that the authors consider the following suggestions to improve the manuscript further: Throughout the manuscript the authors refer to increases (or decreases) in isotopic composition. I would prefer to see isotopic compositions described as enriched (or depleted).

Reply: Thank you. We will alter the conclusion and reflect more on the potential to use the approaches. The increase (and decrease) of isotope values refers to the depth profiles and the change of $\delta^{13}C$ or $\delta^{15}N$ with depth. So what is really meant is a "increase in

enrichment" or a "decrease in enrichment". We will be clearer on this point and will either state the development of enrichment or trend of depth profile.

Site Description: In the light of subsequent comments on the importance of drainage, it would be helpful to see a fuller description of the 'intensive drainage' that occurred (page 16830; line 10);

Reply: We will go back to the literature and present a more detailed description of the drainage that occurred at the Ahlen-Falkenberger peatland.

A location figure would be helpful – to identify the (9) points where samples were located – and the relative size and distribution of the three categories of peatland (wetland; extensively managed grassland; intensively managed grassland);

Reply: Sampling points are the same locations where other investigations were done which are described in Beetz et al. (2013) and Frank et al. (2014). We will add a figure with the study site to the supplementary material (Fig. S1).

Soil sampling and analysis: Why were samples only collected to 50cm depth; and how close were the replicate samples collected at each plot?

Reply: Samples were collected down to approximately 100 cm depth (Page 6; line 10). All three replicates were sampled within about 5m radius close to the investigations plot of Beetz et al. (2013) and Frank et al. (2014).

What depths were selected for radiocarbon dating ? (page 16832; line 4)

For each site, three depths were selected for radiocarbon dating and samples at these depths were investigated for each individual core. Samples for radiocarbon analyses were selected after evaluation of ash content and stable isotope depth profiles and were taken where a clear change in depth pattern was indicated (Page 6; line 31).

Minor points: Abstract: line 21: 'in retrograde' – should this be 'retrospectively'? Page 16829: line 12: 'a posterior' – rephrase. Page 16839: line 24: remove 'been'.

Reply: done

Anonymous Referee #6

General Comments

In this paper, Kruger et al report the results of a study investigating the depth profile of various biogeochemical markers in peatlands. These markers are examined for their suitability in determining both qualitatively and quantitatively the level of peatland degradation. This paper is clearly appropriate for Biogeoscience, providing a useful assessment of the varying degrees to which stable isotopes, bulk density, C/N ratios, radiocarbon age, and ash content can be used to assess peatland health in the past and present. I believe the paper is suitable for publication, provided the authors address the issues brought up in the review process.

The authors may wish to consider rearranging the Results and Discussion section so that section 3.7 (radiocarbon age) appears before the other sections. This would allow them to make explicit linkages between peat age and the other biogeochemical markers. For example, in section 3.5, there is a inference of drainage activities owing to the enhanced ash content in the NW site between 10 and 60 cm. If the radiocarbon ages were presented earlier, this presumed drainage period could be linked to an actual date, and discussed in the context of the historical record.

Reply: The section 3.7 (radiocarbon age) will be presented earlier in the Results and Discussion part. We will discuss the enhanced ash content in the NW site between 10 and 60 cm in the context of the radiocarbon ages.

In some places, the units were a little different than elsewhere in the literature. For example, p2L24 (and others) use t C ha− 1 a− 1 . Consider using kg or Mg, and yr instead of a. This may be a convention for Biogeoscience, though.

Reply: We will change the units into kg C m^{-2} yr^{-1}.

When the authors reference GHG emissions, it is a little unclear whether this refers to just CO 2 emissions from the soil or to a fuller assemblage of GHGs including methane, N 2 O, etc. For example, on P5 it discusses " Current GHG flux measurements", but then presents the actual fluxes in terms of NEP, which implies CO 2 fluxes only. Be clear about the types of emissions you are describing; if it’s CO 2 flux measurements, say that so readers don’t assume methane/N 2 O were also being measured.

Reply: Fluxes will be presented in a clear defined way.

It might be helpful to have a concluding sentence in the abstract guiding readers as to which biogeochemical makers, based on this study, seem most useful for determining peatland degradation. Based on your results, it seems like ash content, in combination with radiocarbon age, presents a much clearer picture than either of the stable isotope profiles (especially nitrogen.)

Reply: An additional sentence with the most useful biogeochemical indicator(s) of peatland degradation will be added to the abstract.

In several places (P8L20, P10L12, P12L29) there is reference to the " upper centimeter" of the soil. Does that actually refer to the soil sample from 0-1 cm, or is it meant to convey soils in the upper horizon? Whichever it is, it needs to be made more explicit; i.e., " In the top 1 cm of the soil" or " From 0-10 cm). The paper could benefit from a close editing for English usage; there were some issues of clarity throughout the paper. I have noted some of them in the " Specific Comments" section.

Reply: In the whole manuscript depths will be presented in a clear manner. We will change “upper centimeter” in the whole manuscript to precise depths.

Specific Comments

P1L16 " lose carbon to the"

Reply: changed

P1L25 based on your results, the enhanced δ15 N is due to both decomposition and fertilizer application (in the GI case); the fertilizer application should be mentioned here as well.

Reply: we will add the fertilizer application in this sentence.

P1L27 . . . "This indicates that not only the managed. . . " It is a little unclear which marker is being described here. It could be read as just the ash marker (from previous sentence), or the whole panel of biogeochemical makers. If you are meaning to refer to the ash content only, saying " These ash profiles, not only in the managed grasslands but in the natural wetlands, indicate that all the sites were influenced by anthropogenic activities either currently in the past, most likely through drainage."

Reply: changed

P2L3-5 " . . . we calculated carbon loss from these sites in retrograde" reads a little awkwardly. Perhaps you could explicitly state the time frame for which you calculated C loss.

Reply: we calculated the total C loss form these soils since the peatland was influenced by anthropogenic activities. The calculated C loss by the combined method presents the total C loss since the peatland was affected by drainage.

P2L21 " GHGs from organic soils comprise 5.1% of Germany’s national total emissions"

Reply: changed

P2L23-28 Keep units consistent! Either use C or CO 2 to trace emissions so readers don’t have to scale on the fly.

Reply: We would like to do so, but the CO_2 emissions are presented as CO_{2eq} which includes the N_2O emissions from these sites and are only presented in this way in the literature.

P3L3 " almost constant with depth"

Reply: changed

P3L7 " show a slight decrease in δ13 C with depth"

Reply: changed

P3L21 I don’t understand the " (wet) oxic soils" formulation. Is it different if the oxic soils are dry? Is this an important distinction to be made?

Reply: no, sorry to be unclear, we will delete (wet).

P3L29-30 Rather than " wider" C/N ratios, use " larger". Substitute " smaller" for " narrower". I think this is a more common way to express these ratios; check for other occurrences later in the text.

Reply: we will change in the whole text wider into larger and narrower into smaller. Please see also our reply to reviewer W. Bleuten.

P4L3 " aa" can be deleted

Reply: changed

P4L14 " weather"whether

Reply: changed

P4L28 remove comma: " The study area is located in Lower Saxony"

Reply: changed

P4L29 remove quotes around peatland name

Reply: changed

P5L7 " when conservation area" " when a conservation area"

Reply: changed

P5L13-25 Here you present a bunch of information on your 3 sites. It would be good if you could keep the sites in the same order throughout. Here you present GE before GI when talking about cut/fertilizer schedule, GI before GE when talking about drainage, and GI, GE, then NW when talking about carbon balances. It will be easier for readers to keep track of the differences between the sites if they are presented the same way each time.

Reply: We will keep the sites in the same order and revise the site description chapter.

P5L23-25 Either give the actual NEP values for all 3 or for none; here you give the exact values for GI but no numbers for GE or NWP.

Reply: We will add the information to the manuscript

P4L23 " The Net ecosystem" " The net ecosystem"

Reply: changed

P9L6-7 A more in depth explanation of how the different slopes point to different peat loss rates might be helpful. I understand how the overall pattern of δ13 C indicates relative levels of degradation, but it’s harder to link the slopes to peat loss.

Reply: We will add a more detailed explanation to this part of our manuscript.

P9L7 " Below this point" - clarify. Below which depth?

Reply: changed in the revised version.

P9L14 " decrease in the upper" " decrease with depth in the upper"

Reply: changed

P9L20 delete " rather"

Reply: changed

P10L14 " Organic fertilizer may be" " Organic fertilizer may also be"

Reply: changed

P10L23 " C/N ratios are narrow" " C/N ratios are smaller"

Reply: changed

P10L26 you could add that these typical values indicate lower levels of microbial activity.

Reply: added

P10L30 " as well as the C/N ratio" " as well as decreasing the C/N ratio"

Reply: changed

P11L28 Include all sites in the first sentence: Carbon losses as induced by drainage are highest at GI and lowest at NW, as estimated by the combined bulk density and ash content method."

Reply: changed

P11L30 " higher current GHG emissions" " higher measured GHG emissions". Also, make sure that GHG emissions is correct; do you really mean CO 2 emissions?

Reply: changed

P12L7 " nowadays a C sink" " nowadays is a C sink"

Reply: changed

P12L22 check GHG vs CO 2 flux

Reply: the net ecosystem carbon balance of the NW site shows that this site is a C sink during the investigated years (Beetz et al. 2013).

Table 2: Is the δ15 N vs δ13 C column really necessary?

Reply: no, we will delete this column from Table 1 in the revised manuscript.

W. Bleuten (Referee)

General comments

The article present an interesting attempt to define decomposition of peat in three different land unit types by radio isotopes of N and C and classical methods (ash content, C/N, Bulk Density, 14C). The results of the different methods have been compared and combined in order to find clues for determination of peat decomposition rates related to land use. The “semi-natural” type (NW), according to the vegetation composition obviously has been degraded. The question rise if the top ”soil” of this NW type can be compared to the grassland types, which both are drained heavily. There is no information about the application level of manure, fertilizer and or lime, nothing mentioned about cattle grazing (and dropping) yes or no. Liming, if occurred, will strongly influence the Carbon and ash content of the top layers and therefore effect the conclusions from the analyses. The location of the cores and the surrounding drainage system development over time could be found in Leifeld et al. (BGD-11-12341-2014 Supplement: Fig S1). It should have been much better if this Figure was included in this paper (I could not find/open any supplement of the article).

Reply: We used stable isotope ratios of carbon and nitrogen as well as ash content, C/N ratio, bulk density and 14-C to indicate peatland degradation. We give an overview of the application of fertilizer and mowing (Page 5; line 21). For detailed description see Beetz et al. (2013) and Frank et al. (2014). Our sites were neither limed nor grazed. We will add a sentence to this aspect to the study site description (Page 5; line 24). The study sites from Leifeld et al. (BGD-11-12341-2014) are not the same as studied here. Study sites from Leifeld et al. (2014) are situated in Paulinenaue, Brandenburg, Germany whereas our study sites are placed near Cuxhaven, Lower Saxony, Germany. We will add a figure with the study sites in the revised manuscript (see Fig. S1). There is a supplement to this article available online at the Biogeosciences homepage (http://www.biogeosciences-discuss.net/11/16825/2014/bgd-11-16825-2014-supplement.pdf).

Specific comments Definition of catotelm as used in this paper is missing. What is the top of the soil: top moss heads, top of acrotelm? That is important for interpretation of decomposition: in acrotelm always rather high.

Reply: We will delete the term catotelm in the revised manuscript, because it is only usable in pristine peatlands. For C loss calculations by the combined method we used the data from depth below the lowest water table throughout the year (Frank et al., 2014) in the profiles as reference layer for the C loss calculation. This was done in a

similar way in the paper by Leifeld et al. (2014). The top of the soil is the vegetation of the site.

No C-concentration data are presented, only ash content

Reply: C concentrations for each sample are presented in the supplementary table (http://www.biogeosciences-discuss.net/11/16825/2014/bgd-11-16825-2014-supplement.pdf).

Depth in Table 1 is missing: regressions refer to different depths?

Reply: We will add the depths to which the regression analyses were done to table 1.

It is not clear which peat layer(s) of the NW cores are used as reference peat

Reply: We used the samples from the lowest 30 cm of our profiles (i.e. 70-100 cm depth) of the NW cores as references. These samples show no enrichment of ash content. We will add a sentence in the revised manuscript.

Technical corrections

P3: 6-7 Alternatively, under anaerobic conditions with anaerobic decomposition the depth profile may show a slight decrease with depth because of an relative enrichment of 13C depleted lignin Not clear what is meant here. Maybe better use instead of “alternatively”: “However,” And what is “13C depleted lignin” ?

Reply: We will use however instead of alternatively. It should be … because of a relative enrichment of ^{13}C depleted substances like lignin.

12-13 Together, peatland drainage induces a change from a uniform δ13C depth profile to increasing δ13C values with depth. That is valid for catotelm layers, not for acrotelm.

Reply: This is the description of our theoretical concept about the effect of drainage on δ^{13}C depth profile. We used the depth patterns of δ^{13}C profiles from the literature and from our own investigations for our theoretical concepts. A water saturated peat soil has a uniform depth profile of δ^{13}C values (Clymo and Bryant, 2008; Alewell et al., 2011; Krüger et al., 2014) throughout the whole profile and in oxic soils the δ^{13}C values increase with depth (Nadelhoffer and Fry, 1988). Please see additionally our response to reviewer 1.

25-27 In intensively managed ecosystems, the application of mineral and/or organic fertilizer, with their different isotopic signals, could additionally alter the stable nitrogen isotope signature in soil Also by droppings from cattle and by atmospheric deposition N balance will be influenced, the latter not only in intensively used peatland.

Reply: Our sites were not grazed (we will add this information in the revised manuscript). Yes, not only the intensively used grassland site is influenced by atmospheric N deposition. We discussed the influence of atmospheric N deposition (Page 10; line 23) on the δ^{15}N values in the soil as well as peat vegetation (Page 10; line 14) in chapter 3.2 in our manuscript.

29-31 Little decomposed peat has wider C/N ratios, reflecting the former plant material, whereas the ratio becomes narrower in strongly decomposed peat owing to a preferential loss of C over N during microbial decomposition. “wider” and “narrower”: low and high? Expected is depletion of N by microbial decomposition and therefore increase of C/N ratio.

Reply: changed to: Little decomposed peat has larger C/N ratios, reflecting the former plant material, whereas the ratio becomes lower in strongly decomposed peat owing to a preferential loss of C over N during microbial decomposition. Please see also our reply to reviewer 6.

P 5 11-12 .. vegetation is dominated by cross-leaved heath (Erica tetralix L.), flat-topped bog moss 11 (Sphagnum fallax Klinggr.), and common cotton grass (Eriophorum angustifolium Honck.). On p10:1 Calluna vulgaris is mentioned to be one of the dominant species. Typically, the presence of heather points at some drainage.

Reply: The vegetation of the near-natural site indicates a mild degradation of this peatland (please see page 13; line 25).

Where were the cores taken? 16 (GI type)

Reply: Cores were taken close to the former study sites (see study site location in Beetz et al. 2013 and Frank et al. 2014).

..fertilized with mineral fertilizer and manure. What about cattles droppings, liming?

Reply: Liming and cattle grazing was not performed on these sites. We will add a sentence to this aspect in the revised manuscript (Page 5; line 24).

16-17 GI is drained with pipes as well as drainage ditches whereas GE is only drained by ditches Depth of drainage?, depths of ditches? Distances of drains and ditches to the core sites?

Reply: A detailed description of drainage ditch depth and drainage pipes can be found in Frank et al. (2014).

18 At the NW site, the water table was around the soil surface What is meant with "around"? Needs specification.

Reply: The water table was close to the soil surface with a variation of -10 cm to 5 cm during the sampling period by Frank et al. (2014). We will change this in the revised manuscript (Page 5; line 26).

28-29 . . .three peat cores per site were collected in the Ahlen-Falkenberger peatland at NW, GE and GI (n=3). No details of the core sites location properties. Is it expected that the 3 land unit types are homogenous spatially?

Reply: We took three cores per site. The cores of each site show a similar stratigraphy, consequently we expect some spatially homogeneity between the three land unit types. The management of the grassland sites has not changed for more than 20 years (Frank et al. 2014).

P6 13-14 The material remaining after heating is defined as the ash content of the sample. The presence of lime (naturally and or applied for agriculture) is included in Carbon content? Results of Organic Matter or Carbon content and of Bulk Density are not presented in this article which is an omission.

Reply: The sites were never limed. Results of all biogeochemical parameters for every single soil sample are presented in a table in the supplementary material of the manuscript. The results represent the organic carbon content of the peat samples. Additionally, the results of bulk density as well as C/N ratio are presented in figures in the supplementary material (http://www.biogeosciences-discuss.net/11/16825/2014/bgd-11-16825-2014-supplement.pdf).

P7 5-7 we assume that the ash content in the catotelm is not affected by drainage and ash from the oxidized peat remains at the site and accumulates in the upper layer. The ash content of the catotelm of each individual core is taken as a reference value Not clear what is meant here with "catotelm". Usually it is dedicated to the permanently saturated peatlayers of pristine bogs. In the bogs described here the lower water table is -40 to -80 cm below the “soil”surface, which means that at least part of the original catotelm fall dry as a result of artificial drainage. What is meant with the “upper layer”? Is that catotelm? Or top of catotelm? It is advisable to avoid the usage of the term catotelm for this study.

Reply: We used the deepest samples of our cores as references. All samples we used as reference are deeper than 80 cm below the soil surface. That’s right the term catotelm in case of degraded peatlands is not usable. We will revise the ash content part and replace the word catotelm. The term “upper layer” will be defined in more detail.

P8: 20-25, p9: 4-5 The interesting differences in d13C increase with depth between the grasslands and the NW type is related to drainage even in the NW site. However, in the (limited) description of the site the water level is said to be “near the surface”. The top layers of the NW site differ substantially to the grassland sites, but this cannot be verified as the article does not give details of the core. Most probably, the top layers of the NW site consists of fresh organic material (acrotelm thickness can be up to 40 cm). In contrary, the top layers of the grasslands consists of already partly decomposed peat (see 14C ages in Fig 2).

Reply: Today the water table at NW is high, but could have been lower in the past due to a stronger influence of drainage activities of the surrounding area. Since the 1990s the NW site is a nature reserve (page 5; line 14) and may thus be more protected against drainage influence. Yes, the top layers of the NW site differ to the top layers of the grassland sites. The NW site consist of fresh organic material and the grassland site are already more stronger decomposed due to aerobic decomposition. Furthermore, the grassland sites have lost peat deposits from almost 1000 years, which is indicated by the radiocarbon ages at the grassland sites.

In Table 1 the regressions coefficients and slopes between the core sites are compared but for the NW site to a depth of ca. -0.5 m and for the GE and GI sites ca. -0.3 m (depth of -25 0/oo, deducted from fig 1).

Reply: We will add the depth used for regression analyses to every single core in table 1. As we described in section 2.5 (page 9; line 2) the regression analyses were done until the δ^{13}C value of -25.0 ‰ was reached.

P9: 20 – p10:20 (3.2 Stable nitrogen isotopes) Here, also the differences between NM and grassland sites are described solely from the analyses. The peat material, in particular of the upper layers are different between NW and grassland sites, which influence the value of the conclusions.

Reply: The results of the stable nitrogen isotope values are presented and discussed in the chapter 3.2 for each land use type. In this part we discuss the influence of the present vegetation types on the stable nitrogen isotope signal (Page 10; line 14). The material in the upper layers is certainly different between the near-natural and both grassland sites. We found stronger decomposed peat material in the upper layers at the grassland sites (indicated by low C/N ratios (Fig. S2), higher bulk densities (Fig. S3), high ash content (Fig. 4)) compared to the near-natural site. Furthermore, we could show with the radiocarbon ages that the grassland sites have lost a substantial amount of peat and that the near-natural site has organic matter fixed during the second half of the last century.

P11 (3.5 Ash content and bulk density) 15-16 (Fig. 4). Bulk density increases at this depth and is higher compared to deeper parts of the profiles and 18-19 We interpret this accumulation as being the result of drainage activities in the vicinity of NW during formation of these peat layers There is no information about the presence of charcoal within the peat as indicators of fires at or near the core sites. Fires may explain the peaks in ash content about ca 1880 and ca 1780 (estimated from Fig 4). Also by deposition of mineral soil material spread from arable land by wind may explain the peaks. The conclusion that any increase in ash content result from drainage can be doubtful. 20-21 At both grassland sites, ash content (Fig. 4) and bulk density (Fig. S1) increase strongly in the upper centimeters Could not find Fig S1

Reply: We found no charcoal layer in the peat profiles. The history of the peatland is well documented and there is no mention of fires. While it is true that we have no proof that there were no fires, we are quite confident that we would know if there had been fires. It is, however possible that ash particles from other burning peatlands in the vicinity may have been deposited. In the late 19th century, peat burning was quite common. If mineral soil material would have been deposited on top of the organic soils, we would expect a stronger ash signal also for the natural site, which we didn't find. Hence, it is reasonable to assume that the ash accumulation stems primarily from a preferential loss of organic matter via oxidation although atmospheric deposition cannot be fully excluded as a contributing process. At both grassland sites, ash content (Fig. 4) and bulk density (Fig. S3) are very high in the upper centimetres compared to the lower parts of the profiles. Figure S3 is in the supplementary material of the manuscript

(http://www.biogeosciences-discuss.net/11/16825/2014/bgd-11-16825-2014-supplement.pdf).

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Biogeochemical indicators of peatland degradation – a case study of a temperate bog in Northern Germany

J. P. Krüger[1], J. Leifeld[2], S. Glatzel[3], S. Szidat[4] and C. Alewell[1]

[1](Environmental Geosciences, University of Basel, Bernoullistrasse 30, 4056 Basel, Switzerland)

[2](Air Pollution/Climate Group, Agroscope Reckenholz-Tänikon ART, Reckenholzstrasse 191, 8046 Zürich, Switzerland)

[3](Department of Geography and Regional Research - Geoecology, University of Vienna, Althanstrasse 14, 1090 Vienna, Austria)

[4](Department of Chemistry and Biochemistry & Oeschger Centre for Climate Change Research, University of Bern, Freiestrasse 3, 3012 Bern, Switzerland)

Correspondence to: J. P. Krüger (janpaul.krueger@unibas.ch)

Abstract

Organic soils in ~~P~~peatlands store a great proportion of the global soil carbon pool and can l~~o~~ose carbon via the atmosphere due to degradation. In Germany, most of the greenhouse gas (GHG) emissions from organic soils are attributed to sites managed as grassland. Here we investigated a land~~-~~ use gradient from near-natural wetland (NW) to an extensively managed (GE) to an intensively managed grassland site (GI), all formed in the same bog complex in northern Germany. Vertical depth profiles of δ^{13}C, δ^{15}N, ash content, C/N ratio, bulk density, as well as radiocarbon ages were studied to identify peat degradation and to calculate carbon loss. At all sites, including the near-natural site, δ^{13}C depth profiles indicate aerobic decomposition in the upper horizons. In the topsoil, δ^{15}N increased in the order NW<GE<GI owing to differences in peat decomposition and fertilizer application. Depth profiles of δ^{15}N differed significantly between sites with increasing δ^{15}N values in the top soil layers ~~with~~ parallel to an ~~increasing~~ increase in land use intensity~~ of use.~~, ~~, indicating that the peat is more decomposed.~~ At both grassland sites, the ash content peaked within the first centimeters. In the near-natural site, ash contents were highest in 10-60 cm depth. The ash profiles,~~is~~

~~indicates that~~ not only at the managed grassland sites, but also at the near-natural site indicate that all sites were influenced by anthropogenic activities either currently or in the past, most likely due to drainage.~~,~~ ~~is influenced by anthropogenic activities, most likely due to the drainage of the surrounding area.~~ Based on the enrichment of ash content and changes in bulk density, we calculated total carbon loss from the sites since the peatland was influenced by anthropogenic activities. Carbon loss increased in the order NW<GE<GI. Radiocarbon ages of peat in the topsoil of GE and GI were hundreds of years, indicating loss of younger peat material. In contrast, peat in the first centimeters of the NW was only a few decades old, indicating recent peat growth. It is likely that the NW site accumulates carbon today but was perturbed by anthropogenic activities in the past. Together, all biogeochemical parameters indicate degradation of peat due to (i) conversion to grassland with historical drainage and (ii) land use intensification. ~~However, we found very young peat material in the first centimeter of the NW, indicating recent peat growth. The NW site accumulates carbon today even though it is and probably was influenced by anthropogenic activities in the past indicated by $\delta^{13}C$ and ash content depth profiles. Based on the enrichment of ash content and changes in bulk density, we calculated carbon loss from these sites in retrograde. As expected land use intensification leads to a higher carbon loss which is supported by the higher peat ages at the intensive managed grassland site. All investigated biogeochemical parameters together indicate degradation of peat due to (i) conversion to grassland, (ii) historical drainage as well as recent development and (iii) land use intensification.~~

1 Introduction

Peatlands ~~are~~ comprise the most important soil organic carbon (C) pool, ~~and~~ storinge more than 600 Pg ~~carbon~~ C (Yu et al., 2011; Jungkunst et al., 2012). In these water saturated soils, anoxic conditions hinder organic matter decomposition and favour peat accumulation (Clymo, 1984). Drainage of peatlands induces oxic conditions and causes increasing carbon dioxide emissions (Maljanen et al., 2001) ~~and~~ resulting in a net loss of carbon to the atmosphere. Over the last century, more than 50 % of the peatland area in Europe has been converted mainly to agriculture or forestry (Byrne et al., 2004). In Germany, 75 % of the greenhouse gas (GHG) emissions from organic soils are attributed to agricultural use (Höper, 2007) and more than half of the GHG emissions from managed peatlands originate from grassland sites ~~managed~~

~~as grasslands~~ (Drösler et al., 2008). Together, GHG's from organic soils ~~contribute~~ comprise 5.1 % ~~to~~ of Germanys' national total emissions (Drösler et al., 2013).

In the temperate zone GHG emissions from peatlands under grassland use ~~for the temperate zone~~ average 0.6~~.1 t~~ kg C m^{-2} yr^{-1} ~~C ha^{-1} a^{-1}~~ for deeply drained and 0.4 ~~3.6~~ kg C m^{-2} yr^{-1} ~~t C ha^{-1} a^{-1}~~ for shallowly drained peatlands (IPCC, 2013). Ranked by land ~~-~~use intensity, intensively managed grasslands emit 2.8~~.3~~ kg CO_{2eq} m^{-2} yr^{-1} ~~t CO_{2eq} ha^{-1} a^{-1};~~ and extensively managed grasslands between 0.2~~.2~~ and 2.0~~.1~~ kg CO_{2eq} m^{-2} yr^{-1} ~~t CO_{2eq} ha^{-1} a^{-1}~~ (depending on the water table) (Drösler et al., 2013)~~),~~. ~~near~~Near-natural bogs are almost climate-neutral, but dry bogs emit up to 1.0~~9.6~~ kg CO_{2eq} m^{-2} yr^{-1} ~~t CO_{2eq} ha^{-1} a^{-1}~~ (Drösler et al., 2013).

To study soil degradation in different environments, stable carbon and nitrogen isotopes are a useful tool (Schaub and Alewell, 2009; Alewell et al., 2011; Conen et al., 2013; Meusburger et al., 2013; Krüger et al., 2014). In two recent studies in the subarctic region, stable carbon isotope depth profiles were shown to be a meaningful indicator of peatland degradation as well as of the uplifting by permafrost (Alewell et al., 2011; Krüger et al., 2014).

In a natural peatland with low decomposition rates, the δ^{13}C signature is almost constant with depth, because in water saturated soils the oxygen availability is low, decomposition of organic material is ~~limited~~reduced, and therefore ~~the~~ isotopic fractionation is small (Clymo and Bryant, 2008; Skrzypek et al., 2008; Alewell et al., 2011). ~~Alternatively~~However, under ~~anaerobic~~ conditions ~~with~~ of anaerobic decomposition, ~~the depth profile may show a slight decrease~~ δ^{13}C may slightly decrease with depth because substances like lignin, which require aerobic conditions for their decomposition, are relatively enriched in ^{13}C~~of an relative enrichment of ^{13}C depleted lignin~~ (Benner et al., 1987; Alewell et al., 2011). Under aerobic conditions, decomposers preferentially use the lighter ^{12}C for respiration. Hence the heavier ^{13}C accumulates in the remaining organic matter and the δ^{13}C value increases with depth (Nadelhoffer and Fry, 1988; Ågren et al., 1996). Increasing δ^{13}C values with depth are typical for well drained or mineral soils (Nadelhoffer and Fry, 1988; Alewell et al., 2011). With a switch from anaerobic to aerobic conditions, peatland drainage is suggested to~~Together, peatland drainage~~ induce~~s~~ a change from a uniform δ^{13}C depth profile to increasing δ^{13}C values with depth (Fig. 1).

Because atmospheric N is the primary source of N in ~~the~~natural terrestrial ecosystem, δ^{15}N values in ~~natural~~ bogs are assumed to scatter around 0 ‰ (Fig. 1) (Jones et al., 2010; Broder et al., 2012). However, plant species in intact peatlands vary substantially ~~show a high~~

~~variability of~~ in their δ^{15}N signature~~s~~ from -11.3 ‰ to +2.7 ‰ (Asada et al., 2005b), which could influence the δ^{15}N signature of the remaining peat material. A second source of variability comes from nitrogen~~Nitrogen~~ isotope fractionation during decomposition, ~~processes~~ leadings to an enrichment of ^{15}N in the remaining material and an increase of soil ^{15}N with depth and age (Nadelhoffer and Fry, 1988; Nadelhoffer et al., 1996). Therefore, δ^{15}N values in ~~(wet)~~ oxic soils increase with depth (Fig. 1) ~~with lower δ^{15}N values in the upper horizon and higher δ^{15}N values in deeper horizons~~ (Nadelhoffer et al., 1996; Kohzu et al., 2003). ~~Consequently, we~~ We ~~assume~~ hypothesize that also in drained and/or degraded peatlands, owing the above mentioned processes, δ^{15}N values ~~are increasing~~ increase with depth~~, owing to the above mentioned process~~ (Fig. 1). In intensively managed ecosystems, the application of mineral and/or organic fertilizer, with their different isotopic signals (Bateman and Kelly, 2007), ~~could~~ additionally alters the stable nitrogen isotope signature in soil.

In natural peat profiles the radiocarbon signature shows an increasing age with depth (Shotyk et al., 1998) due to peat accumulation in the course of time. Owing to the loss of peat which has been accumulated in the last several hundreds or thousands of years a degrading peatland, with a loss of the younger, more recently accumulated C of the upper layers to the atmosphere, changes the ^{14}C depth profile towards higher ages near the peat surface.

~~Another indicator of organic matter decomposition is t~~The C/N ratio indicates the degree of decomposition of the peat material ~~of the peat~~ (Malmer and Holm, 1984; Kuhry and Vitt, 1996). Little decomposed peat has ~~wider~~ larger C/N ratios, reflecting the former plant material, whereas the ratio becomes ~~narrower~~ smaller in strongly decomposed peat owing to a preferential loss of C over N during microbial decomposition.

A simple but reliable estimate of C loss from cultivated peatlands can be obtained based on differences in ash content throughout the peat profile (Grønlund et al., 2008; Rogiers et al., 2008; Leifeld et al., 2011a).~~,~~ These methods base~~d~~ on the premise of ~~aa~~ accumulation of mineral matter (or ‘ash’) with peat oxidation, i.e. preferential loss of organic vs. mineral matter. In a pristine state of a bog, where ~~the~~ mineral input solely derives from the atmosphere, we assume a relative homogeneous ash depth profile. Drainage induces peat oxidation and net CO_2 emission, leading to peat subsidence and a relative enrichment of ash content in the upper layers, where decomposition is strongest. A so-called combined method (Leifeld et al., 2014) makes use of differences in bulk density and ash content in the profile, in order to estimate not only C-loss~~ estimates~~, but also volumetric changes of the peat. It distinguishes between primary (settling) and secondary (oxidation) subsidence of the peat after drainage (Ewing and Vepraskas, 2006).

The main goal of our study was to test, ~~how~~ whether stable isotopes of carbon and nitrogen can be used as indicators of peatland degradation along a gradient of land use and drainage intensity and whe~~a~~ther we could estimate carbon loss a posterior. We apply the above concepts to a typical and well-studied peatland complex, the Ahlen-Falkenberger peatland, in northern Germany. Our hypotheses are:

(I) The δ^{13}C depth profile changes from a constant signal under near-natural conditions to increasing δ^{13}C values with depth in degrading peatlands.

(II) Higher decomposition of the peat in the degraded sites leads to an ~~increase~~ enrichment of ~~δ~~^{15}N values in the upper layers.

(III) C losses are higher in the intensively managed compared to the extensively managed grassland.

Analysis of other indicators, such as radiocarbon age, ash content and C/N ratio, will be used for validation of the interpretation of the stable isotope depth profiles.

2 Material and Methods

2.1 Site description

The study area is located in~~,~~ Lower Saxony, north western Germany, close to the North Sea coast. The peat bog complex called ~~“~~Ahlen-Falkenberger peatland~~”~~ (53°41’N, 8°49’E) is one of the largest peat bog complexes in northern Germany. The climate is humid Atlantic with an ~~average~~ mean annual precipitation of 925.7 mm and an ~~average~~ mean annual temperature of 8.5°C (reference period 1961–1990; German Weather Service, 2010). Bog formation ~~started~~ began at about 6000 years BP on a former fen area (Schneekloth, 1970). Since the late 17th century, peat was extracted at the edges of the bog. ~~Intensive d~~Drainage activities started at the beginning of the 20th century~~,~~. ~~and~~ In the middle of the 20th century over 50 homesteads were established in the Ahlen-Falkenberger peatland and land use was intensified ~~in the middle of the 20th century~~ (Ahrendt, 2012). Industrial peat extraction at the Ahlen-Falkenberger peatland began in 1957 (Schneekloth, 1981) and was terminated in the 1990s, when a conservation area was established (Beckmann and Krahn, 1991; Beller et al., 1994).

About 60 % of the remaining former bog ~~area~~ is currently used as grassland, and only a small area in the centre of the peat bog complex (approx. 5 %) was never drained or cultivated and remains as a natural peat bog today (Höper, 2007). In this area, vegetation is dominated by cross-leaved heath (*Erica tetralix* L.), flat-topped bog moss (*Sphagnum fallax* Klinggr.), and common cotton grass (*Eriophorum angustifolium* Honck.). We consider this near-natural wetland (NW) as unmanaged. Further, we studied two ~~former~~ areas of the former bog which are drained and nowadays managed as grassland: The extensive grassland (GE) is neither fertilized nor manured and only cut once per year~~.~~, ~~The~~ the intensive grassland (GI) is cut 4-5 times per year and fertilized with mineral fertilizer and manure (see details for the years 2008/2009 in Beetz et al. 2013). Liming and cattle grazing was never performed on these sites. GI is drained ~~with~~ by pipes as well as drainage ditches whereas GE is only drained by ditches which were closed in 2003/2004. At the NW site, the water table was around the soil surface with a variation of -10 cm to 5 cm -in 2012 and fluctuated between the surface and ~~80~~ 40 cm depth (~~GI~~GE) and between surface and ~~40~~ 80 cm depth (~~GE~~GI) (Frank et al., 2014). Across the former bog complex, peat thicknesses ~~of peat~~ range from 330 cm in cultivated to 515 cm in uncultivated, near-natural areas (Beetz et al., 2013). ~~Current~~ Recent GHG flux measurements at the Ahlen-Falkenberger peatland (2007-2009) indicate site NW was C neutral in one year (-0.002 kg C m^{-2} yr^{-1}) and accumulated C in the other year (-0.124 kg C m^{-2} yr^{-1}) (Beetz et al., 2013). ~~a carbon source at GI of about 5-8 t C ha^{-1} yr^{-1}.~~ The ~~Net~~ net ecosystem carbon balance at site GE was positive in one (0.088 kg C m^{-2} yr^{-1}) and negative in the following year (-0.147 kg C m^{-2} yr^{-1}) ~~at GE~~ (Beetz et al., 2013). GI was a carbon source for both years with C loss of about 0.548 to 0.817 kg C m^{-2} yr^{-1} (Beetz et al., 2013). ~~Site NW was C neutral in one year and accumulated C in the other year (Beetz et al., 2013).~~

2.2 Soil sampling and analyses

In November 2012, three peat cores per site were collected in the Ahlen-Falkenberger peatland at NW, GE and GI (n=3) (Fig. S1). We took our cores close to the same locations from earlier studies by Beetz et al. (2013) and Frank et al. (2014). Peat samples were taken in the first 50 cm with a soil corer (Giddings Machine Company, US) and in deeper parts with a Russian peat corer (Eijkelkamp, Netherlands) down to approximately one meter. Cores were embedded in plastic shells, wrapped with plastic foil and transported directly to the lab. Cores were cut into 2 cm sections and oven-dried at 40-50°C for 72 h. All samples were ground and homogenised in a vibrating ball mill (MM 400, Retsch, Germany). Stable carbon and stable nitrogen isotopes as well as C and N content were measured by combined mass spectrometry coupled to a SL elemental analyser (Integra2, Sercon, UK). The C/N ratio represents the mass relationship between carbon and nitrogen content of the bulk peat material. Stable carbon isotope ratios are reported as $\delta^{13}C$ in [‰] relative to the V-PDB standard. Stable nitrogen isotope ratios are reported as $\delta^{15}N$ in [‰] relative to the atmospheric nitrogen standard. The analytical standard deviation is 0.15 % and 0.1 % for $\delta^{15}N$ and $\delta^{13}C$, respectively.

The ash content was determined by thermogravimetry (prepAsh, Precia, Switzerland), using 0.5-1.0 g sample material. A pre-drying at 130°C was used to correct the dry mass and to evaporate the residual moisture. The sample was than heated to 600°C in air until no significant mass change (constant mass) could be measured (see detailed description of the method by Leifeld et al. (2011a)). The material remaining after heating is defined as the ash content of the sample.

2.3 Radiocarbon analyses

Radiocarbon (^{14}C) analysis was performed with accelerator mass spectrometry (AMS) at the Laboratory of for the Analysis of Radiocarbon with AMS (LARA) at the University of Bern (Szidat et al., 2014). ~~For~~ At each site, three depths were selected for radiocarbon dating and the ^{14}C content of samples ~~at~~ from these depths ~~were investigated~~was measured for each individual core. Samples were selected after evaluation of stable isotope and ash content depth profiles. Segments where stable isotope and ash contents clearly changed were selected for radiocarbon analysis. ~~and were taken where a clear change in depth pattern was indicated.~~ The ground and homogenised material was combusted, transformed into solid targets using an automated graphitisation equipment (AGE) (Nemec et al., 2010), and measured with the MIni CArbon DAting System MICADAS (Synal et al., 2007). Sample homogeneity and measurement reproducibility was proven by double analysis of 8 random samples, whereas general accuracy and precision was reported earlier (Szidat et al., 2014). ^{14}C ages were calibrated using the IntCal13 dataset (Reimer et al., 2013). Samples with bomb signature were dated using the Bomb13 NH1 dataset (Hua et al., 2013). ~~Results of the individual measurements are shown in Tab. S1.~~

Radiocarbon ages are presented for each site and selected depth as means (n=3) with 1 SD in cal. years AD or cal. years BC. Results of the individual measurements are shown in Tab. S1.

2.4 Calculation of carbon loss by the ash content and bulk density (combined method)

The integrated calculation of carbon loss of the peatland since the beginning of drainage is based on the simplified assumption of a constant ratio between carbon to ash content during accumulation of peat and that ash content before drainage is the same at all depths. After drainage, peat starts to oxidize and carbon is lost as CO_2 (Rogiers et al., 2008). Additionally, we assume that the ash content in the ~~catotelm~~ deeper parts of the profile is not affected by drainage. ~~and a~~Ash from the oxidized peat remains at the site and accumulates in the upper layer of the profile. Differences in soil properties of bulk density, ash content and organic C content between the topsoil and undisturbed subsoil can be used to infer pre-drainage soil thickness and C stocks. The mean ash content of the deeper parts of the profiles, where samples show no enrichment of ash, in our case below 80 cm depth~~catotelm~~ of each individual core ~~is~~ was taken as a reference value (Leifeld et al., 2011a). The ~~carbon~~ C loss was calculated separately for each core.

The method of Leifeld et al. (2014) combines two previously published methods which were based on changes in bulk density (Leifeld et al., 2011b) and changes in ash content (Rogiers et al., 2008; Leifeld et al., 2011a) in peat profiles. This so-called combined method (Leifeld et al., 2014) estimates the physical primary subsidence due to the loss of pore water and peat shrinkage, and the chemical secondary subsidence due to the oxidative loss of organic matter.

The primary subsidence S_p [m] is calculated as follows (Leifeld et al., 2014):

$$S_P = PT_{0i} - PT_i \qquad (1)$$

with

$$PT_{0i} = Bd_{OSi} / Bd_{OSr} \times PT_i \qquad (2)$$

Where PT~~V~~$_{0i}$ is the pre-drainage thickness of layer i [m], Bd~~-~~$_{OSi}$ is organic matter density in layer i, Bd~~-~~$_{OSr}$ is organic matter density of the reference layer [t m^{-3}], and PT_i is the thickness of layer i [m] at time of sampling. Bd~~-~~$_{OS}$ is calculated from the soil mass of per unit soil volume minus the ash mass and the ash volume of the same soil volume, assuming a specific density of ash particles of 2.65 t m^{-3} .

The secondary subsidence S_s is calculated from the pre-drainage thickness ST_{0i} [m] attributable to organic matter oxidation (Leifeld et al., 2014):

$$ST_{0i} = ST_i \times F_{ashi} / F_{ashr} \quad (3)$$

with ST_i the thickness of layer i [m], F_{ashi} the ash concentration of layer i, F_{ashr} the ash concentration of the reference layer.

$$S_s = ST_{0i} - ST_i \quad (4)$$

Before drainage, any layer ST_{0i} contained the same amount of carbon per soil volume as the contemporary undisturbed reference layers ST_r in the deeper soil profile. ~~and t~~The amount of soil carbon in any single layer C_{di} [~~t~~kg m^{-2}] lost by oxidation is given as

$$C_{di} = S_s \times C_r / ST_r \quad (5~~4~~)$$

with C_r the soil carbon stock of the reference layer [t m^{-2}], ST_r ~~-~~the thickness of the reference layer [m] and the volumetric loss due to peat oxidation ~~T_d~~ S_s [m] ~~given~~.

~~$T_d = T_{0i} - T_i$ (5)~~

Beside the carbon loss, total peat subsidence [m] can be calculated by the combined method. Carbon losses are displayed as ~~t~~ kg C ~~ha~~m$^{-~~1~~2}$ and loss rates as ~~t~~ kg C ~~ha~~m$^{-~~1~~2}$ ~~a~~yr^{-1} by dividing the carbon loss by the number of years passed since the peatland was drained.

The NW site could not be ~~used~~ taken as a reference for the calculation of C loss for the managed sites because it was also influenced by drainage activities in surrounding areas as, ~~because of the influence of drainage activities of surrounding areas,~~ indicated by higher ash contents at 10-50 cm depth. We instead used the deeper layers (samples below 80 cm depth) of the grassland sites as a reference, similar to the approach taken in previous studies (Rogiers et al., 2008; Leifeld et al., 2011a).

2.5 Statistical analyses

Spearman correlation analyses were used to identify the relationship between $\delta^{13}C$, $\delta^{15}N$ and C/N. Regression analysis of $\delta^{13}C$ and depth was carried out with the software R2.15.1. At each individual core $\delta^{13}C$ values against depth were used from the uppermost sample down until $\delta^{13}C$ reaches a value below -25.0 ‰.

3 Results and Discussion

3.1 Stable carbon isotopes

In both grassland soils, $\delta^{13}C$ values increase from about -30 ‰ in the upper centimeters to about -25 ‰ in deeper layers (Fig. 2b, Fig. 2c). This increase of $\delta^{13}C$ values with depth indicates aerobic conditions in the peat profile, as aerobic ~~decomposition~~ decomposers selectively uses the lighter isotope ^{12}C for respiration ~~and~~ whereas the heavier ^{13}C is enriched in the remaining organic material of the soil (Nadelhoffer and Fry, 1988; Ågren et al., 1996). This $\delta^{13}C$ depth pattern was also found at site NW, indicating also aerobic degradation ~~also at this site~~ (Fig. 2a). In general, natural peatlands are expected to show a uniform $\delta^{13}C$ depth profile (Clymo and Bryant, 2008; Skrzypek et al., 2008) or a trend towards slightly lower values, caused by an enrichment of recalcitrant substances depleted in ^{13}C (Benner et al., 1987; Krull and Retallack, 2000; Alewell et al., 2011). The Suess effect could have contributed to the low $\delta^{13}C$ values in the uppermost layer of the near-natural site, but the further increase of $\delta^{13}C$ with depth is connected to peat material much older than the Suess effect and is very likely owing to aerobic decomposition of the peat. An increase of $\delta^{13}C$ values with depth by about 4.0 to 5.0 ‰ is typical for well drained mineral soils (Becker-Heidmann and Scharpenseel, 1986; Nadelhoffer and Fry, 1988) and are in accordance with oxic grassland soils (Accoe et al., 2003). ~~In northern peatlands, increases of $\delta^{13}C$ with depth were found in dry hummocks in contrast to uniform depth profiles in water saturated hollows (Alewell et al., 2011; Krüger et al., 2014).~~

In the upper layers of both grassland sites ~~D~~depth profiles of $\delta^{13}C$ values are apparently compressed ~~in the upper part of both grasslands~~ compared to ~~site~~ NW (Fig. 2). A linear regression analyses with $\delta^{13}C$ vs. depth reveals~~results in d~~ a tendency towards steepest slopes of $\delta^{13}C$ vs. depth at GI followed by GE and NW ~~at site GI~~ (Tab. 1~~),~~). ~~which might point to a higher peat loss there compared to GE~~ However, we do not regard this pattern as a quantitative indicator. Below the inversion at ~~depth where~~ -25.0 ‰ ~~this point the~~ $\delta^{13}C$ values of all profiles ~~are~~ remain more or less constant throughout the deeper profile, indicating low decomposition with limited fractionation (Clymo and Bryant, 2008).

3.2 Stable nitrogen isotopes

The δ^{15}N signal in peat soils is mainly driven by following processes: vegetation input, decomposition, N deposition and fertilizer application. The δ^{15}N values of a natural bog should be constant at around 0.0 ‰, because atmospheric N is the primary source of N (Jones et al., 2010; Broder et al., 2012).

At NW Tthe δ^{15}N values first increase and then decrease with depth at the NW site (Fig. 3a). The inversion is located at ca. 20-40 cm depth, corresponding to δ^{15}N values of -2.0 to -4.0 ‰. At the grassland sites, stable nitrogen isotopes decrease with depth in the upper partfirst 20 cm of the soil and remain constantwith no further clear trend in the deeper parts of the profile. In the first few centimeters of the GE profileAt GE, δ^{15}N values are slightly positive in the upper few centimetres of the profile and reach values of around -4.0‰ below 20 cm (Fig. 3b). At GI, on the other hand, δ^{15}N values are positive in the upper uppermost centimetres (up to 4.0 ‰) and a decrease to updown to -10.5 ‰ in deeper layers (Fig. 3c). Compared to GE δ^{15}N is The values at GI are more variable at GI and reaches more negative δ^{15}N values in the deeper part of the soil profile as compared to GE.

The δ^{15}N values of a natural peatland should be rather constant at around 0.0 ‰, because atmospheric N is the primary source of N (Jones et al., 2010; Broder et al., 2012). At natural peatlands, like NW, However, peat plant species show a wide range of δ^{15}N values from below -11.0 to above +2.0 ‰ (Asada et al., 2005b), and thiswhich may influence the δ^{15}N values of the remaining peat material in the profile. The δ^{15}N depletion in the upper part of NW profiles may be assignable to the very low δ^{15}N values of the vegetation (Nordbakken et al., 2003; Bragazza et al., 2010). Sphagnum mosses are depleted in ^{15}N compared to the atmospheric nitrogen and have even lower δ^{15}N values in areas affected by agricultural activities (Bragazza et al., 2005). Incubation of peat mosses have shown a ^{15}N enrichment with time resulting inwith an increase of δ^{15}N values with depth in the near surface (Asada et al., 2005a). Below approximately 20 cm, δ^{15}N values are less negative and in the range of nitrogen isotope values typical for mosses (Asada et al., 2005b). Human activities greatly influence δ^{15}N values in mosses beyond triggering decomposition via atmospheric N depositions. The various N sources vary in their isotopic signatureHuman activities have a great influence on δ^{15}N values in mosses by different atmospheric depositions and their N sources and are not simply related to the total N deposition (Bragazza et al., 2005). Low δ^{15}N values were reported in areas with high local ammonia emissions (from livestock during animal husbandry, manure storage and spreading) (Asman et al., 1998) owing to the with very low $\delta^{15}N$ values in wet (NH_4) and dry (NH_3) deposition (Bragazza et al., 2005). ~~Sphagnum mosses are depleted in ^{15}N compared to the atmospheric nitrogen and have lower $\delta^{15}N$ values in areas affected by agricultural activities (Bragazza et al., 2005). The $\delta^{15}N$ depletion in the upper part of NW profiles may be assignable to the very low $\delta^{15}N$ values of e.g. *Calluna vulgaris*, which might have mean $\delta^{15}N$ value as low as -9.0 ‰ (Nordbakken et al., 2003;Bragazza et al., 2010), and is nowadays one of the dominating species at this site. Atmospheric N deposition, as discussed above, may be another reason. Below approximately 20 cm, $\delta^{15}N$ values are less negative and in the range of nitrogen isotope values typical for mosses (Asada et al., 2005b).~~

$\delta^{15}N$ depth profiles of our drained sites show a completely different depth pattern as hypothesized in our theoretical concept for drained peatlands (Fig. 1) and ~~with~~ decreas~~ing~~e ~~instead of increasing $\delta^{15}N$ values~~rather than increase with depth (Fig. 3). High $\delta^{15}N$ of the topsoil in our grassland sites (Fig. 3) most likely indicate increased microbial activity, caused by drainage, in conjunction with effects from organic fertilizer application at GI. Decomposition is often linked to an enrichment of ^{15}N, because of preferential use of ^{14}N (Högberg, 1997; Novak et al., 1999; Kalbitz et al., 2000). Increased microbial activity in the ~~upper~~ first centimeters of the drained peatland leads to increased turnover of N which results in an enrichment of ^{15}N (Kalbitz et al., 2000), especially in the first 2-5 centimet~~re~~ers. It can therefore be postulated that decomposition of peat material results in an enrichment of ^{15}N. This is one possible explanation for the higher $\delta^{15}N$ values at GE and GI as compared to NW. Atmospheric N deposition, as discussed above, could additionally influence the $\delta^{15}N$ signal in these profiles, however we do not see any effect at site NW. Organic fertilizer may also be enriched in ^{15}N (Watzka et al., 2006), which may contribute to ~~explain~~ higher $\delta^{15}N$ values in the topsoil of GI. A study of nitrogen isotopes from mineral and organic fertilizer demonstrated that organic fertilizer has a mean $\delta^{15}N$ value of +8.5 ‰ (Bateman and Kelly, 2007). However GE, which does not receive any fertilizer, is also enriched in ^{15}N in the ~~upper part~~first centimeters of the profile. We therefore assign the (smaller) ^{15}N enrichment at GE to ongoing oxidative peat decomposition and the (stronger) ^{15}N enrichment at GI to the combined effect of peat decomposition and organic fertilizer applications.

3.3 Radiocarbon ages

Radiocarbon signatures from the upper peat layers (8-10 cm depth) of site NW indicate the presence of bomb carbon and organic matter fixed during the second half of the last century. This recent C accumulation of almost 1.0 kg C m^{-2} in the last approximately 50 years at NW is in accordance with the current GHG flux measurements (Beetz et al., 2013), showing that the bog has been sequestering carbon during recent years. In deeper parts (65-81 cm depth) of NW, mean peat ages range between 1328 and 1796 cal. years AD. The small differences between the mean radiocarbon ages at 65 cm and 81 cm depth at NW are an indicator for undisturbed peat. They point to an average 16 cm of peat growth in approximately 62 years.

At both grassland sites, calibrated radiocarbon ages in the upper centimeters are much higher than at NW. This finding can be taken as an indicator for peat degradation and carbon loss. Drainage-induced carbon loss starts from the top, selectively removing younger peat and exposing older peat to the surface. We found >500-year-old peat in the upper 14 centimeters at these sites. In 14 to 19 cm depth at GE and 27 to 34 cm depth at GI the peat is almost 1000 and 1300 years old, respectively. Peat in deeper parts of the grassland profiles show calibrated mean ages of 165 to 325 cal. years AD and 313 to 34 cal. years BC at GE and GI, respectively. The higher ages in the upper parts of the profile at GI indicate higher peat and C losses compared to the GE, when similar conditions in the peat profiles before onset of drainage are assumed. In comparison to NW, peat ages in deeper parts of the two grassland sites are up to 1500 years older. The grassland sites have lost almost all peat that has accumulated in the last several centuries.

3.~~3~~ 4 C/N ratio

At both grassland sites, C/N ratios are ~~narrow~~ smaller in the upper layers of the soil profile (Fig. S2), indicating strong microbial transformation of the peat (Malmer and Holm, 1984; Kuhry and Vitt, 1996) and possible influence of fertilization (GI). In most ~~of~~ samples from NW and in deeper layers of GI and GE, C/N ratios are in the range considered as typical for ombrotrophic peatlands (Kuhry and Vitt, 1996) and indicate low microbial activity.

3.~~4~~ 5 Correlations between stable isotopes and soil C/N

Decomposition affects both stable $\delta^{13}C$ and $\delta^{15}N$ by an enrichment of the heavier isotopes in the remaining soil organic matter as well as decreasing ~~the~~ C/N ratio. A linear correlation between these parameters is expected if the material is influenced by strong decomposition during peat formation or post-sedimentation (Wynn, 2007; Engel et al., 2010). However, no correlation between the above mentioned parameters will be found in well-preserved peat (Engel et al., 2010; Jones et al., 2010).

Stable isotopes and C/N ratio correlate weakly positive ~~Correlation analyses of isotopes and C/N ratio show a weak positive~~ (r = 0.40 to 0.60) and weakly negative ~~correlation~~ (r = -0.41 to -0.52) ~~between $\delta^{13}C$ and C/N ratio and $\delta^{15}N$ and C/N ratio, respectively, for the~~at NW for $\delta^{13}C$ and $\delta^{15}N$, respectively (see Tab. 2), indicating that the peat is not strongly decomposed and/or that decomposition did not alter the original isotope signal (Sharma et al., 2005). Zaccone et al. (2011) also found a positive, albeit not significant correlation between $\delta^{13}C$ and C/N in a well-preserved peat bog in the Swiss Jura mountains.

At our grassland sites, $\delta^{13}C$ and C/N ratio correlate positively (r = 0.32 to 0.70) and $\delta^{15}N$ and C/N ratio negatively (r = -0.74 to -0.85), indicating that ~~its~~ the peat is strongly decomposed.

3.~~5~~ 6 Ash content and bulk density

Ash content and bulk density are indicators for peat decomposition (Clymo, 1984). At NW, ash content~~s are~~ is enriched between 10 and 60 cm depth at NW (Fig. 4a). Bulk density increases at this depth and is higher compared to deeper parts of the profiles (Fig. ~~S1~~S3). Higher ash content in these depths compared to the deeper layers suggest an increase of decomposition of the peat (Engel et al., 2010). We interpret this ash accumulation as being the result of drainage activities in the vicinity of NW during formation of these peat layers. The peat layers with the enriched ash content at the NW site are on average between 50 and 500 years old, which corresponded to the beginning of first land use intensification in this peatland. Above and below this depth, the ash content is small, indicating less decomposed ~~ition of the~~ peat. High ash contents (Fig. 4b, Fig. 4c) and bulk densities (Fig. S3) in the first centimeters of the profile at both grassland sites indicate peatland degradation and refer to recent and ongoing peat oxidation. ~~At both grassland sites, ash content (Fig. 4) and bulk density (Fig. S1) increase strongly in the upper centimetres of the profiles, referring to recent and ongoing peat oxidation.~~ In deeper layers of ~~GI~~ GE and ~~GE~~GI, ash contents are constant and very low (Fig. 4) and in the range of natural peatlands (Clymo, 1984) and also in the range of deeper, undisturbed layers at NW. ~~Thus we used these data as reference layers to calculate the amount of carbon lost since onset of peatland drainage.~~

3.~~6~~ 7 Carbon loss ~~and peat subsidence~~

Carbon losses estimated by the combined method ~~as induced by drainage~~ are highest at GI, ~~and~~ intermediate at GE and lowest at NW. The mean (±SD) C losses are 11.5 (±6.3), 18.8 (±2.8) and 42.9 (±10.9) kg C m^{-2} ~~931 (±167) and 555 (±190) t C ha^{-1}~~ for NW, GE and GI, respectively~~ and GE, respectively~~. The C loss at site NW may be attributed to the intensive drainage and peat extraction activities of the surrounding area in the last century, which may also have impaired the hydrology of this remaining bog. However, in recent years/decades, peat at NW is again accumulating C (Beetz et al., 2013) and can therefore nowadays be considered a C sink. This is attributed to the current designation of restoration activities in the frame of a nature conservation area at this site with an accompanying increase of the water table (Beckmann and Krahn, 1991; Beller et al., 1994). The heath vegetation at NW, as it is common for peat bogs in Germany, suggests a mild degradational stage (Ellenberg, 1954) with likely historical anthropogenic influences. The~~se results~~ carbon loss of the grassland sites determined in this study are in accordance with higher ~~current~~ measured GHG emissions ~~in~~ at site GI than ~~in~~ at site GE (Beetz et al., 2013). In general, the net GHG emission from extensively managed grasslands is smaller than from intensively managed grasslands, owing to a combination of smaller C exports and higher water tables (Drösler et al., 2013). The total carbon loss at these sites since the onset of drainage is ~~similar~~ comparable to drained peatlands in Switzerland under extensive management (Leifeld et al., 2011a). ~~Site NW had also lost carbon in the magnitude of 234 (±38) t C ha^{-1}. This C loss may be attributed to the intensive drainage and peat extraction activities of the surrounding area in the last century, which may also have impaired the hydrology of this remaining bog. However, in recent years/decades, peat at NW is again accumulating C (Beetz et al., 2013) and therefore nowadays a C sink. This is attributed to the current designation of a nature conservation area at this site with an accompanying increase of the water table (Beckmann and Krahn, 1991; Beller et al., 1994). The heath vegetation at NW, as it is common for peat bogs in Germany, suggests a mild degradation stage (Ellenberg, 1954) with historical anthropogenic influences.~~

~~3.7 Radiocarbon ages~~

~~Radiocarbon signatures from the upper peat layers (8-10 cm depth) of site NW indicate the presence of bomb carbon and thus accumulation of organic matter fixed during the second~~

~~half of the last century. This recent accumulation is in accordance with the current GHG flux measurements (Beetz et al., 2013), which indicate that the bog has been sequestering carbon during the recent years. In deeper parts (65-81 cm depth) of NW, mean peat ages range between 1328 and 1796 cal. years AD. The small differences between the mean radiocarbon ages at 65 cm and 81 cm depth are an indicator for undisturbed peat layers in this depth.~~

~~At both grassland sites, high calibrated radiocarbon ages in the upper centimetres are taken as an indicator for peat degradation and carbon loss. We found >500-year-old peat in the upper centimeter at these sites. In 14 to 19 cm depth at GE and 27 to 34 cm depth at GI the peat is almost 1000 and 1300 years old, respectively. Deeper parts of the grassland profiles show calibrated mean ages of peat material with 165 to 325 cal. years AD and 313 to 34 cal. years BC at GE and GI, respectively. The higher ages at the intensively managed grassland profile indicate higher peat and C losses from this site compared to the extensively managed grassland site, assuming similar conditions in the peat profiles before onset of drainage. In comparison to site NW, peat ages in deeper parts of the grassland sites are up to 1500 years older. The grassland sites have lost almost all peat that has been accumulated in the last several centuries.~~

3.8 Indicators for peatland degradation and quantification of C loss

All parameters ($\delta^{13}C$, $\delta^{15}N$, ash content, C/N ratio, bulk density, and radiocarbon ages) indicate a degradation of the former bog at the Ahlen-Falkenberger peatland when managed as grassland (GE and GI)~~ at the Ahlen-Falkenberger peatland~~. All of these parameters might be useful~~All those data could be used as~~ indicators for peatland degradation, but not all in a quantitative manner (Tab. 3).

Stable carbon isotope depth profiles indicate degradation at all sites at the peatland. At NW in the upper 10 cm and below 65 cm depth as well as in deeper parts of the grassland sites $\delta^{13}C$ is constant with depth indicating a natural peat. Stable nitrogen isotope, ash content, C/N ratio as well as bulk density depth profiles show a higher decomposition of the peat material in the upper part at the grassland sites as well as in 20-60 cm depth at NW. The $\delta^{15}N$ signal in the peat profiles is mainly driven by decomposition (GE and GI) and fertilizer application (GI). Radiocarbon ages, $\delta^{13}C$ as well as ash content in the first centimeter of the NW depth profiles provide evidence for contemporary peat accumulation with young peat material formed in the last decades. Peat from topsoil segments of both grassland sites is much older than peat from deeper segments of the NW site. These data illustrate the consequences of peatland drainage that induces loss of peat material which has been accumulated over the last centuries. The ash content in combination with bulk density and C content (combined method) gives reasonable estimates of C loss since the onset of drainage activities in this peatland.

Soil ash content and radiocarbon signatures have the potential to provide quantitative estimates on peatland carbon loss whereas changes in stable isotope patterns and C/N ratios serve as qualitative indicators and support the understanding of processes and mechanisms involved.

~~Peat loss as well as carbon loss is higher when the grassland is used more intensively as shown by the depth profiles of $\delta^{13}C$ and ash content. These results are in accordance with the higher peat ages of the deeper parts of the intensively compared to the extensively managed grassland.~~

~~At site NW, both depth profiles of stable carbon isotopes and ash content indicate degradation processes by increasing $\delta^{13}C$ signatures with depth and a relative enrichment of ash in 20-60 cm depth, respectively. From about 65 cm depth the $\delta^{13}C$ signatures at NW are almost constant indicating a natural peat which is supported by the small differences in the mean radiocarbon ages of 65 cm and 81 cm depth. Above the uniform depth trend the $\delta^{13}C$ signatures increase indicating a degradation of the peatland since 1534±228 cal. years AD. However, in the upper soil profiles of NW, radiocarbon ages as well as low ash contents in the first centimetres provide evidence for contemporary peat accumulation with young peat material formed in the last decades. Correspondingly, stable carbon isotopes signatures are constant in the first ten centimetres, indicating the development of growing conditions without disturbance.~~

~~Furthermore, the radiocarbon ages indicate that the disturbance at NW shown by $\delta^{13}C$ as well as ash content depth profiles is not displayed in both grassland sites, because this peat material has been lost due to peat oxidation. The peat material in both grassland sites is much older than at the deeper parts of the NW site and shows the consequences of peatland drainage with peat loss which has been accumulated over the last centuries.~~

4 Conclusions

Depth profiles of different biogeochemical parameters together provide a detailed insight into peatland formation and the effects of management on peat degradation. $\delta^{13}C$, $\delta^{15}N$, ash content, C/N ratio, bulk density, as well as radiocarbon ages in peat depth profiles indicate degradation of all peatlands, but to very different degrees. Peat and C loss could be quantified by the combination of ash content and bulk density and is supported by the radiocarbon ages. ~~At the near-natural site (NW), stable carbon isotopes and ash contents indicate degradation due to the drainage of the surrounding area, which affected the NW site in the past. Hence, also bogs considered semi-natural were impaired by anthropogenic activities, at least in the past.~~

(I) Increasing $\delta^{13}C$ values with depth indicate aerobic decomposition of the peat material at all sites. ~~We found no absolute differences in the $\delta^{13}C$ patterns, but could show that the slopes of the $\delta^{13}C$ depth profiles differ significantly, as a result of peat degradation.~~

(II) At the near-natural site (NW), stable carbon isotope and ash content depth profiles as well as radiocarbon dating indicate moderate degradation due to the drainage of the surrounding area in the past. Hence, also bogs considered semi-natural were impaired by anthropogenic activities. Recent organic matter accumulation, as indicated by the ^{14}C values, indicates rehabilitation of the peatland.

(III) With conversion to grassland increasing peat decomposition and fertilizer application systematically alter the $\delta^{15}N$ signature of the soil. ~~With conversion to grassland (extensive (GE) and intensive (GI)), $\delta^{15}N$ depth profiles change significantly compared to a semi-natural situation. Both, increasing peat decomposition and fertilizer application systematically changed the $\delta^{15}N$ signature of the soil. The $\delta^{15}N$ values in the upper soil profiles reflect the decomposition degree of the peat material and show a completely different depth pattern as hypothesized.~~

(IV) Based on ash accumulation calculations the three sites lost carbon in the order NW < GE < GI. Higher losses under intensive management are supported by (i) higher peat ages at this site and (ii) steeper slopes of $\delta^{13}C$ depth profiles.

~~(III) The three sites lost carbon in the order NW < GE < GI. Higher losses under intensive management are supported by higher peat ages at this site as well as the steeper slopes of $\delta^{13}C$ with depth. To quantify the carbon losses from the soil due to the degradation of the peatland,~~

~~the applied combined method gives reasonable C losses since the onset of human intervention.~~

~~Biogeochemical soil parameters of peat profiles are applicable to detect peat degradation and to determine the order of quantitative peat and C loss. Solely one parameter in soil depth profiles is often not enough to detect peat degradation but with the combination of different biogeochemical parameters in a high resolution it is possible to detect the degradation.~~

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Tab. 1: Slope, depth and coefficient of determination of regression analyses between $\delta^{13}C$ and depth until the $\delta^{13}C$ value of -25.0 ‰ was reached in the depth profile. Three profiles of each site, near-natural (NW), extensive managed grassland (GE) and intensive managed grassland (GI) site from the Ahlen-Falkenberger peatland are presented. 'n' refers to number of soil segments per site and replication included in the regression.

Site/core	depth (cm)	slope	R^2	p	n
NW1	25.0	0.26	0.97	0.0004	7
NW2	65.0	0.07	0.92	0.0000	17
NW3	65.0	0.08	0.94	0.0000	17
GE1	23.7	0.13	0.92	0.0023	6
GE2	40.3	0.09	0.74	0.0015	10
GE3	31.7	0.11	0.92	0.0022	6
GI1	28.4	0.21	0.96	0.0008	6
GI2	31.0	0.14	0.89	0.0016	7
GI3	18.7	0.20	0.90	0.0146	5

Tab. 2: Correlation coefficient and p value (p<0.05 in boldface) between δ^{13}C~~, δ^{15}N~~ and C/N ratio as well as between δ^{15}N and C/N ratio for the whole profiles at the near-natural (NW), extensive managed grassland (GE) and intensive managed grassland (GI) site at the Ahlen-Falkenberger peatland.

Site/core	δ^{13}C vs. C/N	δ^{15}N vs. C/N
NW 1	0.40~~n.s.~~(0.051)	-0.41~~n.s.~~(0.051)
NW 2	0.60****(0.002)**	-0.52****(0.010)**
NW 3	0.46***(0.022)**	-0.49***(0.016)**
GE 1	0.49***(0.012)**	-0.81*****(0.000)**
GE 2	0.70*****(0.000)**	-0.85*****(0.000)**
GE 3	0.32~~n.s.~~**(0.000)**	-0.74*****(0.002)**
GI 1	0.61****(0.002)**	-0.78**(0.000)*****
GI 2	0.68**(0.000)*****	-0.75**(0.000)*****
GI 3	0.32~~n.s.~~(0.109)	-0.74**(0.000)*****

~~n.s. = not significant, * p< 0.05, ** p< 0.01, *** p<0.001~~

Tab. 3: Biogeochemical parameters from the Ahlen-Falkenberger peatland profiles as indicators for peatland degradation as well as peat and carbon loss.

Parameters	Reliable indicator for peat degradation?	Quantification of C loss possible?
$\delta^{13}C$	yes	no
$\delta^{15}N$	yes	no
Ash content	yes*	yes
^{14}C age	yes	(yes)
C/N	(yes)	no
Bulk density	(yes)	(yes with ash content)
Correlation between $\delta^{13}C$, $\delta^{15}N$ and C/N	yes	no

* for bogs and assuming homogeneous atmospheric input

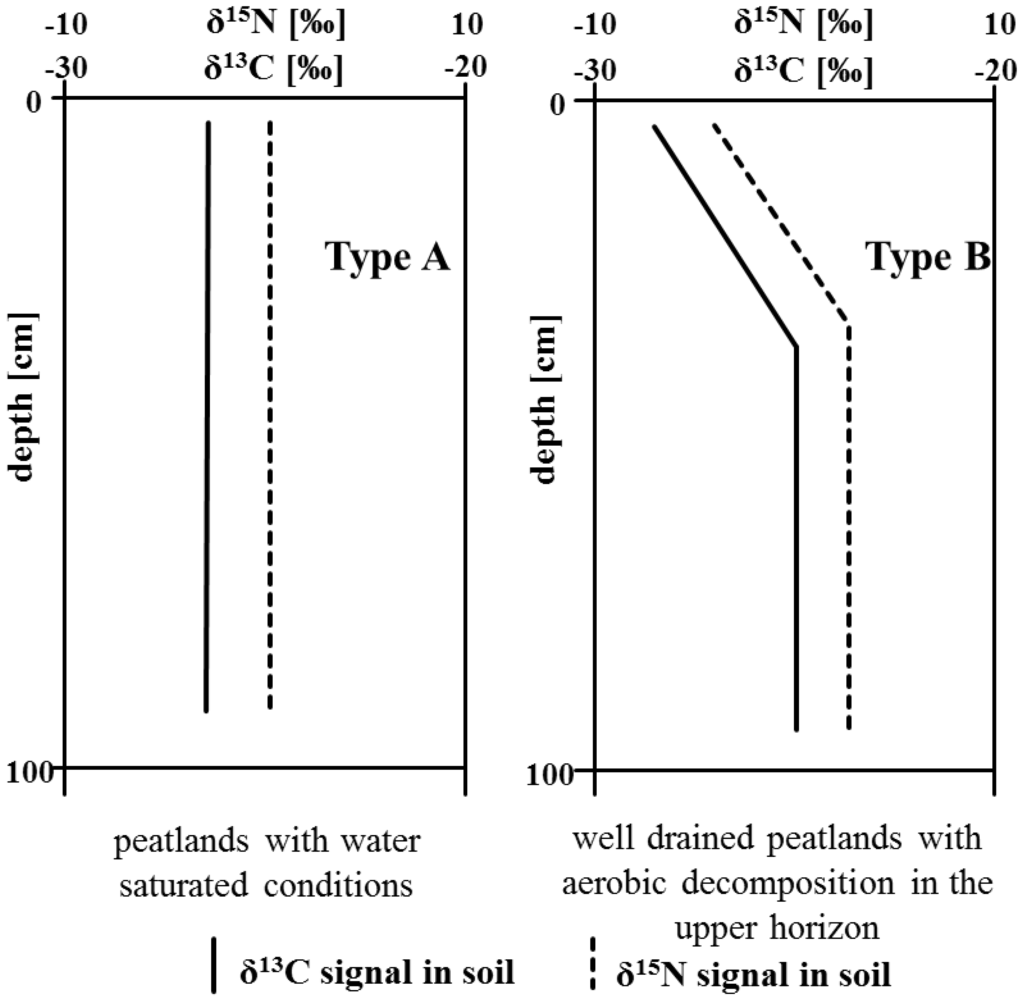
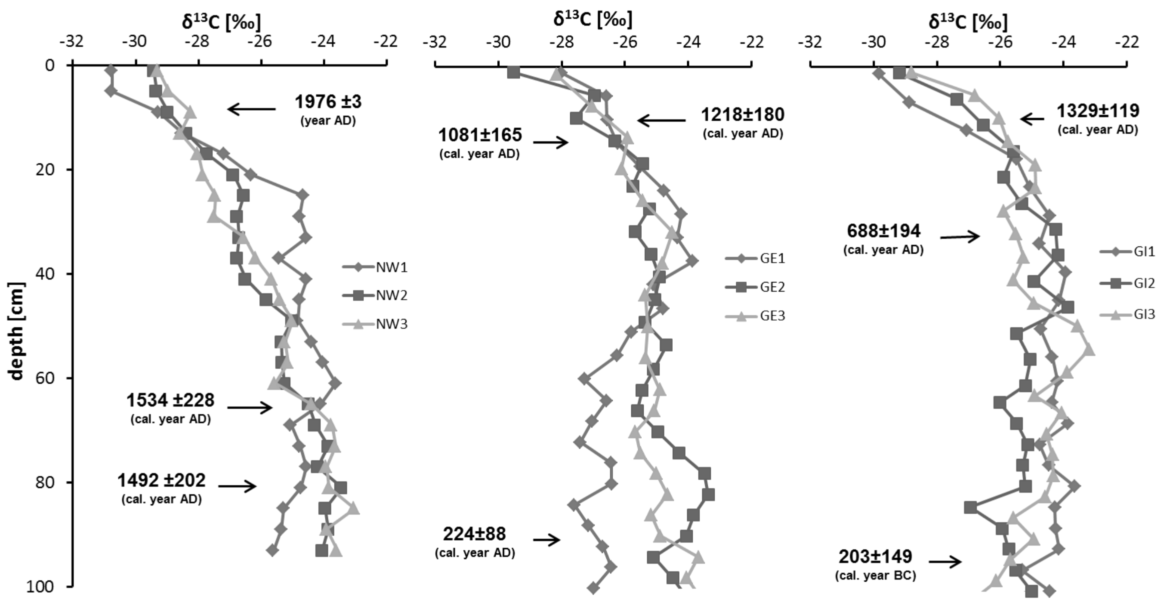


Fig. 1: Theoretical concept of $\delta^{13}C$ and $\delta^{15}N$ depth profiles in natural (left) and degraded (right) peatlands.



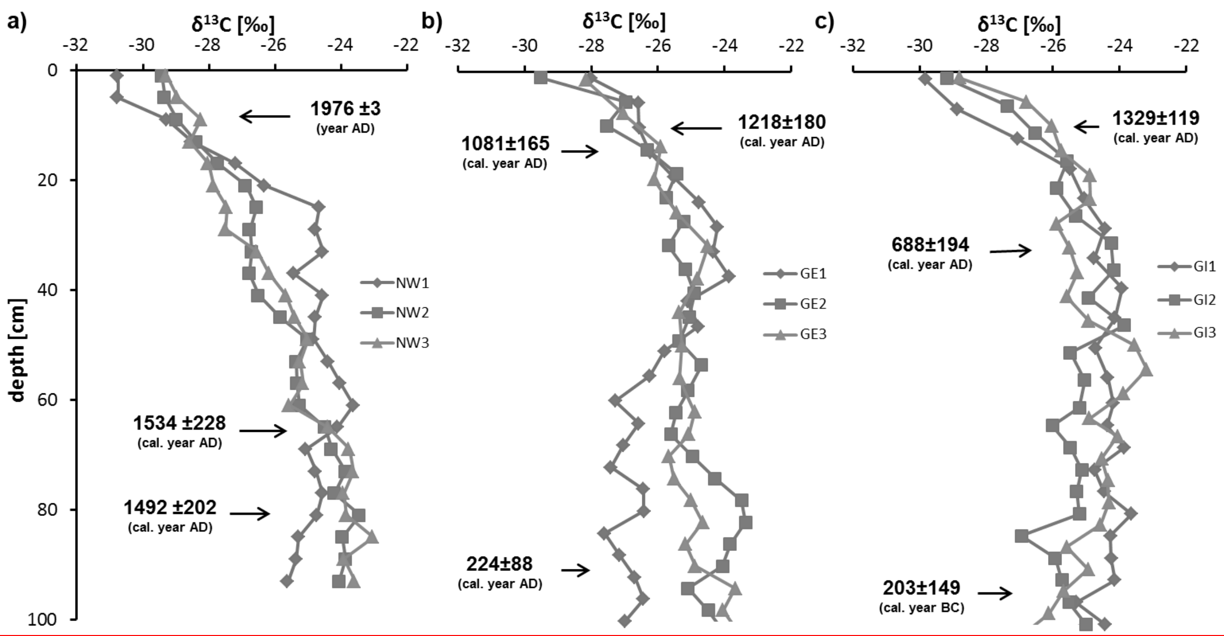
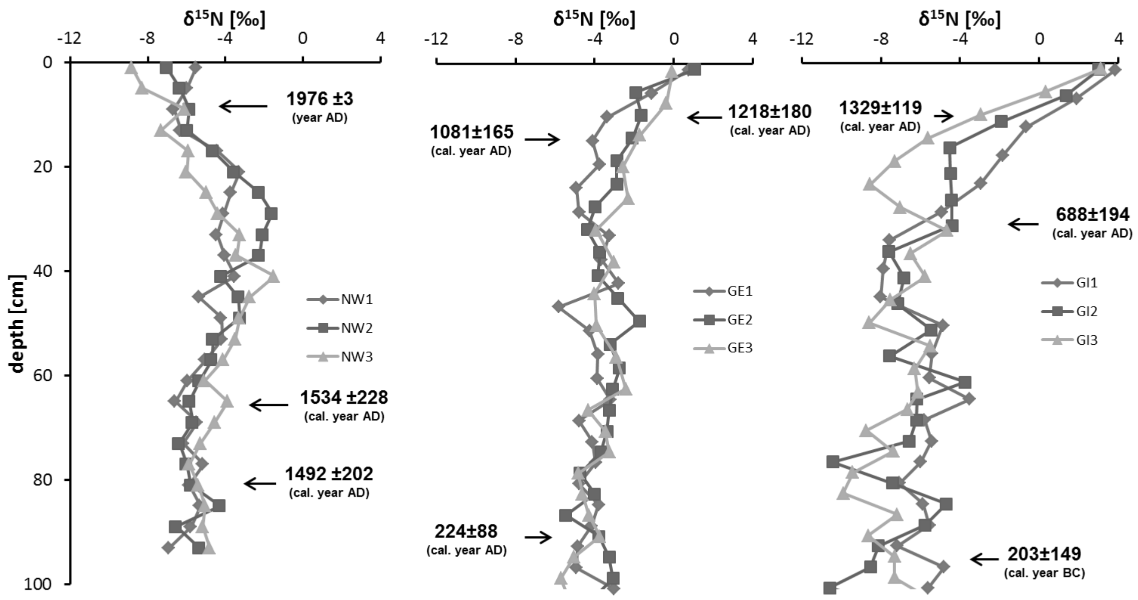


Fig. 2: δ^{13}C depth profiles at (a) the near-natural site (NW), (b) extensive used grassland site (GE) and (c) intensive used grassland site (GI) at the Ahlen-Falkenberger peatland. Calibrated radiocarbon ages are displayed as mean calendar ages with 1 standard deviation (n=3) at their corresponding depth.



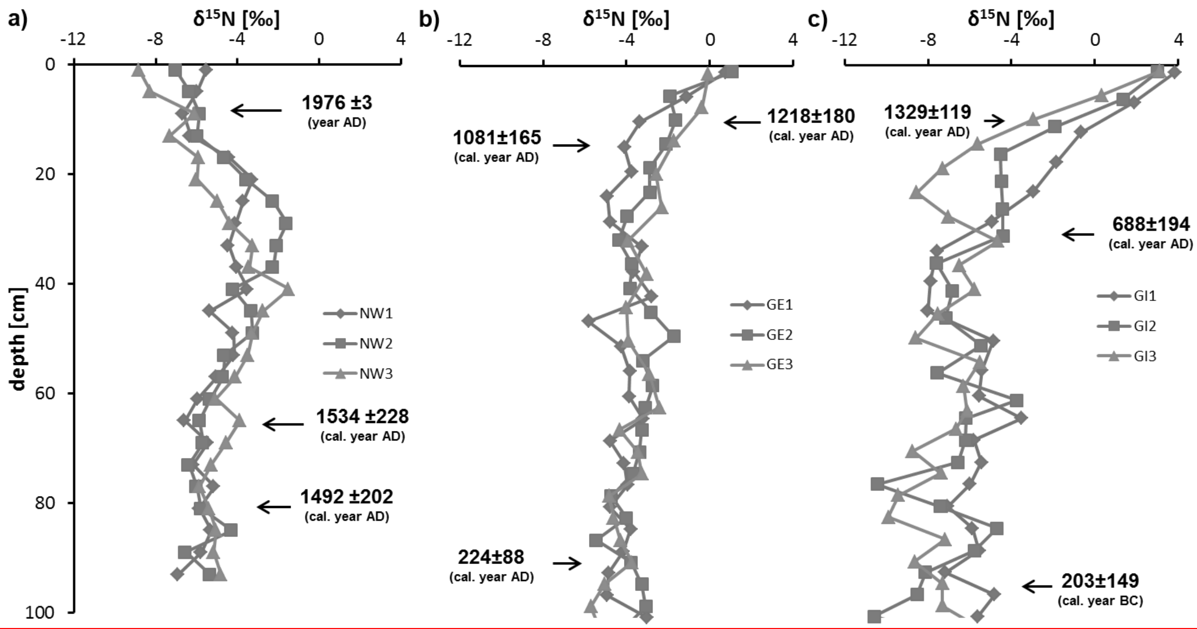
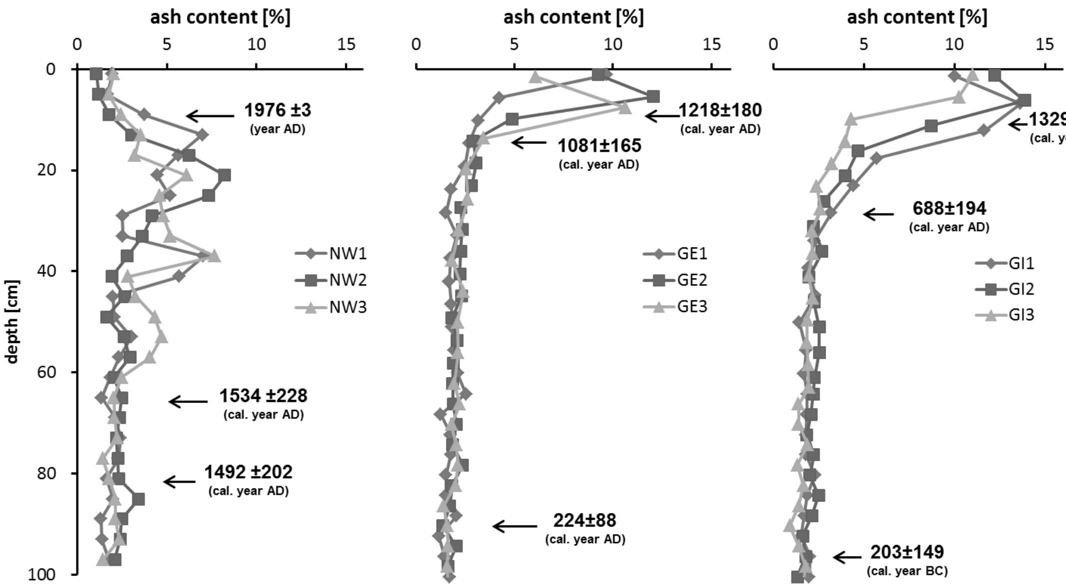


Fig. 3: $\delta^{15}N$ depth profiles at (a) the near-natural site (NW), (b) extensive used grassland site (GE) and (c) intensive used grassland site (GI) at the Ahlen-Falkenberger peatland. Calibrated radiocarbon ages are displayed as mean calendar ages with 1 standard deviation (n=3) at their corresponding depth.



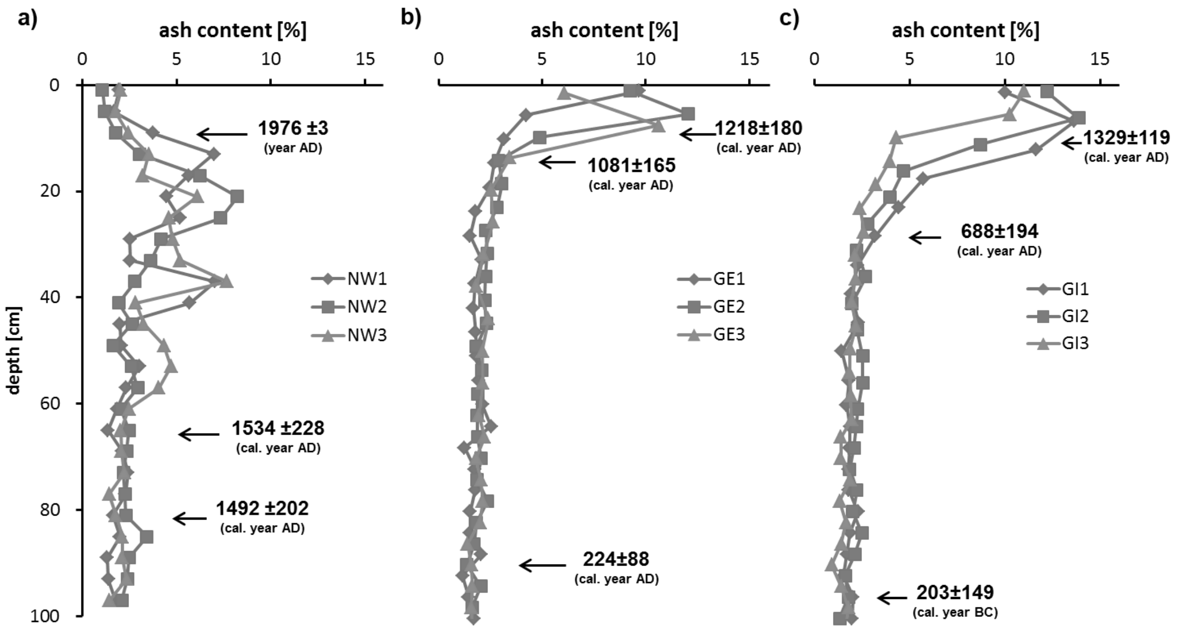


Fig. 4: Ash content depth profiles at (a) the near-natural site (NW), (b) extensive used grassland site (GE) and (c) intensive used grassland site (GI) at the Ahlen-Falkenberger peatland. Calibrated radiocarbon ages are displayed as mean calendar ages with 1 standard deviation (n=3) at their corresponding depth.