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Comment on "Soil CO_2, CH_4 and N_2O fluxes from an afforested lowland raised peatbog in Scotland: implications for drainage and restoration" by Yamulki et al. (2013)

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Abstract

Yamulki and co-authors address in their recent publication the important issue of net emissions of greenhouse gases (GHGs) from peatlands where land use conversion has taken place. In their case, they studied conversion to forestry versus peatland restoration after a first rotation of plantation forestry. They monitored soil-derived fluxes of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) using chamber measurements on planted and unplanted control treatments (with or without drainage), and an unplanted plot within a restored (felled) block on former lowland raised bog. They propose that their measurements of greenhouse gas (GHG) emissions at these sites suggest that the total net GHG emissions, in 100 yr carbon dioxide equivalents, of the restored peatbog would be higher than that of the peatbog with trees. We believe there are a number of issues with the measurement, calculation and comparison of these greenhouse budgets that may invalidate this conclusion.

1 Discussion

The study of Yamulki et al. (2013) presents valuable measurements of greenhouse gas emissions from two sites located on a former lowland raised bog in Scotland, UK. The first site includes experimental treatments of afforested or unplanted areas, in combination with or without drainage. The second site is a formerly unmanaged area, which is located within a block where a forestry rotation was felled and drains were blocked as part of a restoration treatment. They calculate estimates, based on a combination of measurements and literature data, of the greenhouse gas (GHG) balances at the experimental treatments on these two sites. Such data are of high policy relevance to national governments in the light of national GHG emissions accounting. Although lowland raised bogs constitute only a small proportion of the total peatland area in the UK, national GHG emissions are accounted for at the level of the overall peat resource that has been subject to management. In Scotland, 24 % of the land area is

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covered by peatlands (i.e. peat soils of more than 50 cm peat depth, Chapman et al., 2009). A sizeable proportion of the UK raised and blanket bogs were afforested in the 1970s and 1980s and the discussion of how to manage these forests or whether to restore such sites to peatland habitat brings with it potential implications for national accounting of GHG emissions from the land use sector. We recognise the need for measurements of GHG fluxes from afforested peatlands, especially in relation to emissions from restored peatlands, and towards which this publication has made a positive contribution. However, we believe that the conclusions drawn by Yamulki et al. (2013), regarding the relative GHG balance of their different study sites, are not robust. Here, we highlight two key areas in which we believe that their measurements, calculations and interpretation may be open to question, and in one case are demonstrably incorrect. In order to put the observed fluxes into context for further evaluation, it would be useful if further details about the study sites could be provided so that this work can contribute more effectively to future literature-based meta-analyses of the effects of different land use on GHG emissions from peatlands. We hope this comment also serves to open a wider discussion of the changing long-term dynamics of GHG emissions with land-use transitions, such as afforestation or restoration practices, on peatlands.

2 Static chamber methodology

Yamulki and co-authors present data from biweekly measurements of soil-derived trace gas emissions (CO_2, CH_4 and N_2O) using static, opaque (dark), chamber measurements on their four experimental treatments. These included 0.5 ha replicated plots of drained and planted (45 yr old trees) areas (DP), undrained and planted areas of the same stand age (uDP), and an undrained/unplanted control on the same site (uDuP). In addition, a number of pseudo-replicated measurements on a single 20 m × 30 m (0.06 ha) unmanaged plot were made within a nearby (7.5 km east) peatland. This plot was located within a previous plantation that was felled in 1998 and subsequently restored to active raised bog by blocking the drains. The abbreviation used for this

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plot in the text (n-pris) suggests that this site is in its original, near-pristine condition, implying minimal anthropogenic disturbance, which is most certainly not the case. The measured CO_2 flux was "derived from aerobic and anaerobic decomposition processes, respiration of other soil organisms, total dark respiration of ground vegetation and root respiration of trees". The statement by the authors as re-iterated above, in combination with the size of the chambers, implies that the measured respiratory fluxes on the unplanted sites (uDuP and n-pris) included autotrophic respiration (R_a) from the above-ground vegetation (*Sphagnum* moss and other bog vegetation) and hence represent net ecosystem respiration (R_{eco}). On the other hand, the fluxes from the forested sites must have excluded R_a from the canopy and other above-ground biomass of the trees. Ground vegetation below the tree canopy in these forestry plantations is typically minimal. While this is to some extent an unavoidable logistical issue, the implication is that the flux measured in the planted plots (DP and uDP) represents only soil respiration (R_{soil}). This term includes all of the heterotrophic components from litter and soil organic matter decomposition (R_h) but only some of the R_a components, because only root respiration, but not above-ground autotrophic respiration, is included in the measurements. This is reflected in the reported annual fluxes from the planted sites, which are much lower than from the unplanted sites (1.61 and 1.22 kg CO_2 m^{-2} yr^{-1} from drained and undrained planted sites, respectively, versus 2.58 and 1.84 kg CO_2 m^{-2} yr^{-1} in the non-drained nor planted peatland block and the nearby restored peatland area). In short, the presented data from the afforested sites, lacking the autotrophic flux from above-ground tree biomass, give an accurate estimation of the total soil CO_2 flux (R_{soil}) whereas the figures presented from the unplanted bog sites represent R_{eco}. The data presented in Tables 3 and 4 in Yamulki et al. (2013) therefore represent an erroneous comparison between R_{eco} from the uDuP and n-pris sites and R_{soil} from the DP and uDP. This introduces a bias, as is discussed further below.

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3 Calculations of net CO_2 fluxes

The second issue we identify relates to the calculation of both the "net ecosystem CO_2 exchange" and the overall "net GHG flux" (Table 4) for their study sites. Here, we believe that the calculation of net GHG flux for their near-pristine site (n-pris) is demonstrably incorrect. In general, the net flux of CO_2 between the land-surface and the atmosphere is termed the Net Ecosystem Exchange (NEE-CO_2), which represents the (typically small) balance between gross photosynthetic productivity or gross primary productivity (IPCC definition) (GPP) and total ecosystem respiration (R_{eco}-CO_2). As noted above, Yamulki and co-workers measured R_{eco} rather than R_{soil} in the unplanted sites where non-forest vegetation was present. Thus, the missing term in the estimation of NEE-CO_2 for these sites is GPP. However, for the unplanted sites, Yamulki and co-workers used literature values of NEE from other semi-natural bogs in place of GPP as their input term (see Table 4). Although they correctly label this term "net ecosystem CO_2 exchange" in their Table 4, they added the sum of all soil-derived trace gas emissions in terms of CO_2 equivalents (CO_2e) ("total soil GHG emission", = R_{eco} of all 3 GHGs) to this value to calculate the "net GHG flux" (Table 4). We have clarified the values presented in Table 4 against the cited literature to confirm that these indeed represent net ecosystem CO_2 exchange. The values are based on chamber (Billett et al., 2004) and eddy covariance measurements at Auchencorth Moss (Dinsmore et al., 2010; both incorporated into the cited review of Billett et al., 2010). This confirms our interpretation that R_{eco} was effectively double-counted in the "net GHG flux" calculations for the n-pris site, leading to the incorrect inclusion of a CO_2 emission of 1821 $g\,CO_2e\,m^{-2}\,yr^{-1}$ in the total estimated GHG emission of 1993–2303 $g\,CO_2e\,m^{-2}\,yr^{-1}$ for this site. Correctly omitting this flux would put the net GHG flux figure closer to a small net GHG source in CO_2 equivalents. For the restored site of Yamulki et al., if this is as "near-pristine" as the authors suggest, we would have expected it to be similarly close to equilibrium, at least in terms of carbon balance. If the reported rate of CO_2 emission were correct (on a per hectare basis, the reported flux represents a massive net loss of 19.9 to 23 tonnes of

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$CO_2e\,ha^{-1}\,yr^{-1}$), we would expect this site to be subject to subsidence approaching the 1–2 $cm\,yr^{-1}$ observed in peatlands drained for intensive arable use.

In the most climatically similar year in relation to the Yamulki study, the Dinsmore et al. (2010) figures for Auchencorth Moss in 2007–2008 reported a net ecosystem exchange of CO_2 of $-420\,g\,CO_2e\,m^{-2}\,yr^{-1}$. Adding the observed methane and nitrous oxide losses to this assumed net fixation of CO_2 would result in a net GHG flux of $172\,g\,CO_2e\,m^{-2}\,yr^{-1}$ rather than the stated, 10 times higher, range. Of course, a more ideal scenario would have been the inclusion of measured GPP data for the n-pris site, such that the R_{eco}-CO_2 loss could be balanced against a measure of GPP on site. This brings the estimates for the net CO_2 and GHG balance more into line with previous studies performed on near-natural peatlands (e.g. Billett et al., 2010; Koehler et al., 2011) which consistently suggest that these systems are net CO_2 sinks. Following the inclusion of CH_4 and N_2O emissions they may be either small net GHG sinks or small net GHG sources (e.g. Billett et al., 2010; Koehler et al., 2011), although the recent review of Yu (2012) concluded that the majority of natural peatlands have a net cooling effect on a 100 yr time horizon. The n-pris site in Yamulki et al., of course is not a truly near-pristine site. As stated, this is a very small plot that had not been drained or planted, but is located within a formerly afforested plot, which had subsequently been restored by felling the trees 10 yr prior to the start of the GHG flux measurements. The implications of this recent management event on estimates of the likely GHG balance will be discussed further below, but first we examine the calculations of the net GHG flux for the planted sites.

For the planted sites, Yamulki et al. (2013), use an estimated value of "net ecosystem CO_2 exchange" in Table 4 that is based on total tree biomass calculated from whole site tree mensuration data and to which they add their combined soil-derived trace gas emissions ("total soil GHG emissions") to determine the net GHG flux for these sites. We challenge that the "net ecosystem CO_2 exchange" value presented here is in fact a representation of net primary productivity (NPP), i.e. GPP minus the amount of carbon respired by the trees through autotrophic respiration (R_a). Net Ecosystem Ex-

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change, as already described above, represents the balance between GPP and R_{eco}, or, alternatively expressed, the balance between net primary productivity (NPP, which equals GPP $-R_a$) and heterotrophic soil respiration (R_h). Firstly, the authors state that it "does not include accumulation of leaf, branch and root litter", although it presumably does include living root and needle biomass. Hence, this figure may be an underestimate of NPP and likely ranges of annual litter production could perhaps been provided as the soil-based GHG fluxes would have included respiration of some of this litter pool as well as turnover of more decomposed soil organic matter. To this NPP value, the total sum of all soil-based trace gas losses measured (Table 4) are added to calculate the net GHG flux. Although this would seem a valid approach as NEE = NPP $+R_h$, the soil respiratory fluxes measured included autotrophic respiration from the tree roots. In other words, some components of the net respiratory losses are double-counted in the net GHG flux calculation. The authors do state that this calculation "is slightly overestimating net CO_2 losses as tree root respiration is included". However, the proportional input from autotrophic respiration to the soil respiratory fluxes has often been shown to approximate 50 % (Högberg et al., 2005; Saiz et al., 2006) so this is not an inconsiderable flux. Therefore, depending on the proportion of root autotrophic respiration to the overall R_{soil}, and the fate of any annual litter inputs compared to the contribution of litter decomposition to R_h, the net GHG flux at the afforested sites may be significantly different to the value calculated in Table 4 and could be substantially lower.

One might also question the use of a value of NPP derived from the linear interpolation of biomass accumulation as forest growth models generally adopt a more sigmoidal shape and as such the productivity and carbon sink strength of an older forest may in theory be lower at the time of the measurements than the value presented here. The authors also state, citing the work of Minkkinen and Laine (1998), that productivity in the drained and afforested area is likely to have been higher than in the undrained site, yet this is not taken into consideration when calculating the net ecosystem GHG budget. In any of the above scenarios, the net GHG flux estimates for the planted sites are also likely to be compromised.

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We would welcome further clarification from the authors as to the assumptions made in the calculation of the net ecosystem CO_2 exchange and net GHG flux at these sites. Irrespective of this, the highlighted calculation errors markedly alter the final conclusions of the paper regarding the relative GHG balance of forested and unforested peatlands as the n-pris site, although still a net source in CO_2 equivalents, is likely to be much less of a net source than presented, and the afforested sites, for entirely different reasons, may also be much less of a net source. Based on the data presented in the paper, however, it is impossible to establish the likely net GHG flux at any of the sites correctly, and hence a comparison between the planted and n-pris sites should not be a part of the discussion of the data.

4 Methane measurements

Our final area of concern in relation to the GHG balances reported for the sites at Flanders Moss is the significant emission of methane (22.6 g CH_4 m^{-2} yr^{-1}) reported from the restored (n-pris) site. This exceeds the range given by Levy et al. (2012) for methane emissions from a wide range of UK soils, including many peatlands, which tend to have values at the upper end of the −0.15 to 13.8 g m^{-2} yr^{-1} range observed. In the recent Couwenberg and Fritz (2012) synthesis, the highest emissions published from temperate raised bogs with plant communities including aerenchymatous species (which can transport methane through their roots and stems) were approx. 50 g CH_4 m^{-2} yr^{-1}, as opposed to 25 g CH_4 m^{-2} yr^{-1} where no aerenchymatous plants were present. While the methane emissions published in this paper appear reasonable in this context, it does indicate that they are in the upper range of all previously published work or that there would have to be a significant contribution through plant mediated transport, an issue that is not considered in this paper as a potentially contributing factor. The high values observed may also represent an artefact of the location of this small, unplanted, 0.06 ha plot, in the middle of a previous plantation forest. Often such areas were never planted as they were too wet even following drainage and

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the authors state that the site "became extremely wet" following the restoration activities surrounding it. The chamber size suggests that the measurements at this site may not represent an accurate assessment of the heterogeneity of these ecosystems, which are comprised of a wider suite of microform features (e.g. hummocks, hollows and lawns) and which need to be considered when making ecosystem scale GHG assessments. It would therefore be useful for future literature-based assessments if the authors were able to comment in more detail on the vegetation characteristics (e.g. presence of aerenchymous species) on this site, as well as on the location of their chambers and the observed trace gas emissions in relation to peatland microforms.

5 Towards assessments of GHG benefits of afforestation or restoration of peatlands

We believe that any realistic assessment of the GHG benefits or costs of afforestation or restoration of peatlands needs to take into account the long term, whole life cycle, carbon budget. To establish the carbon sink strength of near natural peatlands, Yu (2012) conducted a meta-analysis of full C budget data collected for a minimum of two and maximum of six years at five peatland sites in the Northern Hemisphere. The study showed that only one of the five sites (a minerotrophic site) exhibited methane emissions that, in carbon dioxide equivalents, would negate the strong net fixation through net ecosystem exchange of carbon dioxide. The geographically closest of the cases in Yu (2012) to the sites used by Yamulki et al. (2013), is Auchencorth Moss, which is the site they derive some of their literature values from. As referred to earlier, in the most climatically similar year in relation to the Yamulki study, the Dinsmore et al. (2010) figures for Auchencorth Moss in 2007–2008 reported a net ecosystem exchange of CO_2 of $-420\,g\,CO_2e\,m^{-2}\,yr^{-1}$. This NEE value, plus a net loss of 9.75–11.5 g of $CO_2e\,m^{-2}\,yr^{-1}$ as methane and similar values for N_2O emissions, together with the other relevant carbon budgets such as aqueous losses from the system, still resulted in a net carbon sink as well as net global cooling effect for the whole Auchencorth site (Drewer et al.,

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2010). The Auchencorth site, however, might not represent a suitable comparison, as it is on relatively shallow peat and has been affected by past drainage and nearby peat extraction, which has lowered the water table at this site. Overall, though, the sequestering function of an established peatland, as in any biological system, is likely to be dependent on its relative maturity. Productivity in forest ecosystems is highest in the initial growth phase and declines with the stand age of forests. Reports of GHG flux measurements from restored peatland areas suggest strong growth of the recolonizing vegetation, which can lead to NEE in excess of that observed in natural peatlands in their mature phases (Bortoluzzi et al., 2006; Samaritani et al., 2011).

Restored peatlands, especially in the early phases of recovery, will inevitably present a different carbon budget to pristine or near-natural sites, and this carbon budget will be a function of the initial condition of the peatland prior to restoration, the hydrological conditions achieved through restoration and the stage of the restoration trajectory. The limited studies published to date on this topic have included examples of previously industrially harvested peatlands (Yli-Petays et al., 2007) as well as peatlands subjected to limited disturbance through domestic peat cutting or moderate drainage (Bortoluzzi et al., 2006; Samaritani et al., 2011). Yli-Petays et al. (2007) reported losses of up to 38.4 g CH_4 m^{-2} yr^{-1} in a rewetted (periodically flooded) poor fen peatland 50 yr after abandonment following mechanical peat extraction. These high methane emissions, together with a net ecosystem CO_2 exchange of between 30–83 g C m^{-2} yr^{-1} due to the still patchy vegetation, suggested that these sites were still strongly net C emitting despite restoration management. In contrast, Bortoluzzi et al. (2006) and Samaritani et al. (2011) reported potential strong net GHG sinks in peatlands recovering from less severe damage. Bortoluzzi et al. (2006) observed CH_4 emissions in the range of 6–130 CO_2e m^{-2} yr^{-1} in vegetated areas in a site last cut and drained 20 yr previously, but these emissions were more than offset by a NEE-CO_2 of −200 to −600 g CO_2 m^{-2} yr^{-1}. The exceptions were bare patches where CH_4 fluxes outweighed NEE-CO_2 due to a combination of lack of vegetation and a high watertable. Samaritani et al. (2011) reported their early-stage restoration site (29 yr since the last distur-

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bance) to be a net source of 40 g CO_2e m^{-2} yr^{-1}, compounded by an additional loss of at least 46 g CO_2e m^{-2} yr^{-1} as methane. However, both of their older restoration sites were net GHG sinks, with observed balances of −220 g CO_2 m^{-2} yr^{-1}, slightly offset by 57 g CO_2e m^{-2} yr^{-1} as methane in a 42 yr old site, and −209 g CO_2 m^{-2} yr^{-1} partially offset by 150 g CO_2e m^{-2} yr^{-1} methane in a 51 yr old site. In both their studies, the site hydrology was relatively stable, with few flooding events.

There are very few examples of GHG fluxes of afforested peatlands where all the component terms have been measured concurrently, or over a longer timeframe. Whole site NEE reports from a naturally afforested peatland in Finland (subjected to additional drainage 34 yr previously to aid timber growth) concluded that the site, at that point in its life cycle, acted as a net carbon sink of between 870–1000 g CO_2 m^{-2} yr^{-1}, of which the tree biomass accumulation accounted for 585–645 g CO_2 m^{-2} yr^{-1} (Ojanen et al., 2012). Hence, in that example, the relatively sparse tree density as well as the remaining peatland vegetation cover, both contributed to net C sequestration. In other peatland forest sites, such as reported by Lohila et al. (2007), where drainage was more effective and active planting took place (resulting in greater tree density) a net annual loss of CO_2 from the system was reported due to large soil respiratory losses. In their study, the plantation was a 30 yr old Sitka spruce plantation, which, over the course of a year, only served as a net carbon sink for CO_2 during warm and dry spells in the summer months. On cold or damp summer days, the system was a net source, with net emissions in the same range as reported by Yamulki et al. (2013). In a UK setting, the only comparable study is Hargreaves et al., (2003), who studied NEE-CO_2 using eddy covariance techniques on a variety of peatlands ranging from near-natural (Auchencorth Moss) to sites with 26 yr old plantation forestry stands. They reported a moderate net CO_2 sink within the same range as reported by Billett et al. (2004) for subsequent years at the control (Auchencorth Moss) site, followed by net emissions after site preparations for two years. A net uptake in excess of that at Auchencorth Moss was observed for all afforested sites of more than 4 yr of growth up to 26 yr old stands. However, most of the reported fluxes were based on extrapolations from periods of 3–

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4 weeks, based on the diurnal variation observed at the Auchencorth Moss site, where data were collected over a year and 9 months.

On a greater temporal scale, any plantation forest will eventually be harvested and the C sequestered in tree biomass will be effectively lost from the system, although longevity off-site is dependent on the timber products derived and the rates of decomposition of remaining stems, brash, stumps and roots. In addition, the disturbance effect from harvesting and replanting will also release a large gaseous and dissolved C pulse. The Yamulki et al. (2013) study contrasted drained/undrained sites in a plantation forest on peat soil at a late growth phase (i.e. at the end of the phase where C is strongly sequestered in tree biomass) with sites that were either likely to be confounded by the drying effect of nearby forestry, or part of a restoration site recovering from a relatively recent, large disturbance event, through the felling of the surrounding plantation 10 yr before the GHG flux measurements. The comparison of "snapshot" images at different times in the systems' growth cycle, regardless of any inherent bias in the calculations, can be problematic particularly when extrapolating to wider areas for use as a policy-development tool. To give an accurate assessment, such comparisons need to be made on the basis of the total GHG budget over, or normalised for, the whole life cycle of plantation forestry versus restored peatlands. The current knowledge base in relation to the ability of restored peatlands to eventually become net C sequestering ecosystems again is insufficient, yet our best understanding is that natural peatlands predominantly act as net cooling ecosystems, even under current climatic constraints (Yu, 2012). As long as restoration can achieve a reversion to a "near-natural" state, the preservation of carbon sequestered in peatland ecosystems is likely to represent a more effective carbon store when compared to plantation forests over the very long term (> 100 yr).

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6 Summary

Yamulki et al. (2013) present a detailed, comprehensive set of measurements of GHG fluxes from peatland sites subject to contrasting management. Such measurements are sparse at both a national and a global scale, and are urgently needed to support policy on peatland management for climate mitigation, and in a wider ecosystem services context. We believe that the conclusion presented by Yamulki et al. (2013) that that the total net GHG emission of a restored peat bog exceeds that of an adjacent afforested site at Flanders Moss, is erroneous and based on a number of flawed assumptions made during the analysis of their results. Although Yamulki et al. (2013) did not extrapolate their findings to a wider landscape or political context, in an era where it has become a necessity to reduce global GHG emissions, the scientific knowledge base that helps to answer the question of where and how to achieve the national emissions reductions targets must not present confused scenarios. We would therefore welcome any clarifications the authors are able to make on our interpretation of their study.

We would like to state that we contacted the authors of the publication with a previous draft of this Comment, to avoid factual errors on our part and to facilitate an open discussion.

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