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1 **Unravelling past impacts of climate change and land management on historic peatland**  
2 **development using proxy-based reconstruction, monitoring data and process modelling**

3

4

5 Running head: Exploring historic peat development

6

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16

17

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20

21

22 Type of paper: Primary Research Article

23

24

1 **Abstract**

2 Peatlands represent globally significant soil carbon stores that have been accumulating for  
3 millennia under water-logged conditions. However, deepening water-table depths (WTD)  
4 from climate change or human-induced drainage could stimulate decomposition resulting in  
5 peatlands turning from carbon sinks to carbon sources. Contemporary WTD ranges of testate  
6 amoebae (TA) are commonly used to predict past WTD in peatlands using quantitative  
7 transfer function models. Here we present, for the first time, a study comparing TA-based  
8 WTD reconstructions to instrumentally-monitored WTD and hydrological model predictions  
9 using the MILLENNIA peatland model to examine past peatland responses to climate change  
10 and land management. Although there was very good agreement between monitored and  
11 modelled WTD, TA-reconstructed water table was consistently deeper. Predictions from a  
12 larger European TA transfer function data set were wetter, but the overall directional fit to  
13 observed WTD was better for a TA transfer function based on data from northern England.  
14 We applied a regression-based offset correction to the reconstructed WTD for the validation  
15 period (1931-2010). We then predicted WTD using available climate records as  
16 MILLENNIA model input and compared the offset-corrected TA reconstruction to  
17 MILLENNIA WTD predictions over an extended period (1750-1931) with available climate  
18 reconstructions. Although the comparison revealed striking similarities in predicted overall  
19 WTD patterns, particularly for a recent drier period (1965-1995), there were clear periods  
20 when TA-based WTD predictions underestimated (i.e. drier during 1830-1930) and  
21 overestimated (i.e. wetter during 1760-1830) past WTD compared to MILLENNIA model  
22 predictions. Importantly, simulated grouse moor management scenarios may explain the drier  
23 TA WTD predictions, resulting in considerable model predicted carbon losses and reduced  
24 methane emissions, mainly due to drainage. This study demonstrates the value of a site-  
25 specific and combined data-model validation step towards using TA-derived moisture

1 conditions to understand past climate-driven peatland development and carbon budgets  
2 alongside modelling likely management impacts.

3

4

## 5 **Introduction**

6

7 Globally, peatlands contain ~30% of all soil organic carbon (SOC), despite covering only 3%  
8 of the land surface (Parish *et al.*, 2008). They occur mainly in the Northern Hemisphere  
9 circumpolar region (henceforth NHCP), where low temperatures, high soil moisture and slow  
10 decay rates of litter input via net primary production (NPP) allow peat to form (i.e. a long-  
11 term positive balance between NPP and litter decay), often under conditions of high water-  
12 table depth (WTD). Crucially, this slow decay preserves an archive of peatland development  
13 (i.e. TA and plant remains) that can be dated and used to reconstruct past drivers of peatland  
14 growth, such as WTD and vegetation composition, providing key information on how  
15 peatlands respond to changes in climate.

16

17 Blanket bogs are a globally rare peatland habitat with the UK containing about 15% of this  
18 habitat (Tallis, 1998) but mostly in a degraded state (Natural England, 2008), largely due to  
19 past environment (e.g. N deposition) and management (e.g. drainage) impacts. In the UK  
20 blanket bogs represent about 90% of all peatlands (Bain *et al.*, 2011), which are often  
21 managed for grazing and grouse shooting, commonly supported by draining the peat and  
22 regular burning of vegetation. The consequence is dominance of heather (*Calluna vulgaris*),  
23 very low overall plant biodiversity, suppressed cover of peat-forming *Sphagnum* mosses  
24 (Lindsay, 2010), and often drier and eroding peat. In fact, only about 12% of protected  
25 blanket bog sites are classified as in favourable condition (Natural England, 2008). However,

1 little is known about management impacts on the long-term SOC accumulation and soil C  
2 emissions.  
3  
4 UK blanket bogs have accumulated peat since the start of the Holocene about 11.6 k years  
5 ago under varying climate, but current bioclimatic models highlight the threat by climate  
6 change to their natural range (Gallego-Salla *et al.*, 2010), suggesting that they might start to  
7 degrade as the climate warms (Gallego-Sala & Prentice, 2013) resulting in water-table  
8 drawdown and increased decomposition. However, existing bioclimatic models do not  
9 consider extremely important autogenic negative feedbacks within peatlands that may  
10 actually act as a 'buffer' to climate change (Swindles *et al.*, 2012). Such feedbacks include  
11 ecohydrological linkages between changes in WTD and shifts in vegetation communities  
12 (with different rooting depth and litter quality and thus affecting SOC inputs across depth and  
13 peat decomposition rates). A better process-level understanding of climate-peatland SOC  
14 feedbacks is clearly needed (Davidson & Janssens, 2006) since the mineralisation of peatland  
15 soil organic matter (SOM) has the potential to release vast amounts of previously locked-up  
16 C into the atmosphere. Depending on the water-table level, C emissions from decomposition  
17 are either as CO<sub>2</sub> (oxic acrotelm) or CH<sub>4</sub> (anoxic catotelm), the latter particularly responsible  
18 for exacerbating climate change and affecting the overall greenhouse gas (GHG) emissions.  
19 However, a key limiting issue in more accurate predictions of future climate is still the  
20 inadequate model representation of climate – terrestrial carbon (C) cycle feedbacks,  
21 particularly of peatland soil organic carbon (SOC; Limpens *et al.*, 2008). Several peatland  
22 models of varying complexity and feedback mechanisms have been developed (Clymo, 1984;  
23 Gignac *et al.*, 1991; Bauer *et al.*, 2003; Frohling *et al.*, 2010; Heinemeyer *et al.*, 2010; Baird  
24 *et al.*, 2012), which have often been compared to measured C stocks. However, there is a lack

1 of validating the C cycle underpinning hydrological model predictions against past palaeo  
2 records.

3

4 Peat archives from peat cores are also important for testing peatland development models,  
5 which predict peat layer accumulation and their associated chemical (e.g. carbon content) and  
6 physical (e.g. bulk density) properties, enabling comparison between the two. Data-model  
7 comparisons have revealed uncertainties in peat accumulation processes (Clark *et al.*, 2010),  
8 particularly considering hydrology, vegetation and NPP. Further, recent peat core studies  
9 (Charman *et al.*, 2013) indicate increased C accumulation during warmer periods due to  
10 increased NPP outweighing higher decomposition, which contradicts most global earth  
11 system model carbon cycle simulations (e.g. Friedlingstein *et al.*, 2006). Moreover, those  
12 global earth system models used by the Intergovernmental Panel on Climate Change (IPCC)  
13 do not yet adequately include peatland SOC dynamics, limiting global predictions on future  
14 climate C-cycle feedbacks and resulting GHG emissions. Latest attempts to include peatlands  
15 in global dynamic vegetation models (e.g. LPX; Spahni *et al.*, 2013) are promising, yet still  
16 show major process-level uncertainties.

17

18 Testate amoebae (TA) are commonly used to reconstruct peatland hydrological changes over  
19 the Holocene, as indicator species are aligned across a gradient of wet to dry conditions based  
20 on present-day associations (Amesbury *et al.*, 2016; Turner *et al.*, 2014). Peat cores provide a  
21 stratigraphic (i.e. temporal) archive of past TA species composition, thus allowing to predict  
22 past moisture (and likely water-table) conditions from understanding of contemporary  
23 ecology. Quantitative transfer functions are used to establish a relationship between present-  
24 day species composition and hydrological data and then applied to subfossil data from cores  
25 (Amesbury *et al.*, 2016).

1  
2 Model predictions of peat carbon stock and flux changes rely on capturing seasonal and inter-  
3 annual WTD changes. Whereas in the short-term site measurements can be used for model  
4 validations, validation over longer-time scales relies on comparing model predictions to  
5 WTD reconstructions, for example based on TA taxa found within the peat core. In addition  
6 to other dating tools such as radiocarbon (Turner et al., 2014), the use of Spheroidal  
7 Carbonaceous Particles (SCPs; Swindles, 2010) allows the generation of temporally-  
8 constrained records of palaeo-hydrological conditions in the recent past. Together with dating  
9 tools, palaeo-reconstructions thus offer crucial insights into peatland development, (i)  
10 understanding baseline trajectories in peatland development, and (ii) assessing long-term  
11 resilience and recovery rates of peatlands to climate or management impacts (Swindles *et al.*,  
12 2016). TA based reconstructions of past WTDs can then be compared to process model  
13 predictions, providing an important hydrological model validation tool. A good fit between  
14 TA and model predicted WTDs supports applying model scenarios to explore past  
15 management impacts on peatland functioning and carbon storage. The MILLENNIA peatland  
16 model predicts peat hydrological conditions (i.e. water-table depth) based on climatic  
17 conditions and long-term peat column growth either for annual or monthly time steps. Here  
18 we used the annual MILLENNIA version (Heinemeyer *et al.*, 2010) for long-term peat  
19 accumulation during the Holocene until 1914, and then either the annual or monthly version  
20 (Carroll *et al.*, 2015) until 2012. This choice of model application reflected the availability of  
21 climate data. The WTDs predicted by the MILLENNIA model allowed comparison to TA-  
22 based WTD reconstructions from ca. 1760 onwards for a peat core at Moor House National  
23 Nature Reserve (NNR) using TA transfer functions. The WTDs from different management  
24 model scenarios were then compared to the TA-based WTD, and related to C accumulation  
25 and C emissions affecting the GHG balance.

## 1 **Materials and Methods**

2

### 3 **Site location and environmental conditions**

4 The study site, Moor House National Nature Reserve (NNR), covers about 75 km<sup>2</sup> of a  
5 typical UK blanket bog with much known about its ecology (Garnett *et al.*, 2001; Heal &  
6 Perkins, 1978) together with detailed meteorological (i.e. weather station) and hydrological  
7 (i.e. water-table) data collected by the Environmental Change Network (ECN). It is located in  
8 the northern Pennines across an elevation range of 290 - 850 m (a.s.l.) and is characterised by  
9 a sub-arctic–oceanic climate with an average long-term mean annual temperature (MAT) and  
10 precipitation (MAP) at 550 m altitude of about 5.1°C (1931-1997) and around 2000 mm (last  
11 20 years), respectively (cf. Garnett, 1998). Peat formation at the study site started about 9,000  
12 years ago (see Heinemeyer *et al.*, 2010 for more site information). This study focuses on a  
13 square kilometre around the ECN meteorological station at 550 m (NY757328; 54° 68' N, 2°  
14 37' W), a site with mostly deep (>1 m) peat (histosol), supporting dominant vegetation of  
15 *Calluna vulgaris* L. [Hull] and *Eriophorum* spp. with some *Sphagnum* spp., and classified as  
16 a *Calluna vulgaris*–*Eriophorum* blanket mire (for more information on vegetation and peat  
17 depth see Garnett *et al.*, 2000 and Heinemeyer *et al.*, 2010). Typically the peatland site has a  
18 pH of generally between 3.0 – 4.2 and a high mean annual WTD of within 5 cm of the peat  
19 surface for >80% during the year (Evans *et al.*, 1999).

20

### 21 **Peatland model predictions**

22 The MILLENNIA peatland model (Heinemeyer *et al.*, 2010) predicts peat hydrological  
23 conditions (i.e. water-table) based on climatic conditions either for annual or monthly time  
24 steps. The hydrological conditions, in connection with internal factors (e.g. litter quality) and  
25 external modifiers (e.g. temperature and oxygen availability), then determine decomposition



1 rates of old and new carbon fractions (as in Bauer, 2004) across the peat profile based on  
2 litter inputs via NPP as a function of potential evapotranspiration (PET) based on Lieth &  
3 Box (1972). Detailed model explanations are provided in Heinemeyer *et al.* (2010; annual  
4 model) and Carroll *et al.* (2015; monthly model). Here we used the annual version for the  
5 long-term peat accumulation during the Holocene and for the period until 1914, and either the  
6 annual or monthly version until 2012 (reflecting model application and climate data  
7 availability). However, model outputs are only provided as annual averages in relation to  
8 average TA predictions. The main model driver is climate with either monthly or annual  
9 temperature and rainfall amounts as inputs. Both versions consider topography (e.g. slope  
10 affecting temperature, runoff and erosion), vegetation (e.g. affecting NPP, litter quality and  
11 transpiration losses) and preceding hydrological conditions (e.g. high water-tables leading to  
12 higher runoff) to predict a new water-table, vegetation (based on the preceding five-year  
13 average water-table) and corresponding changes in soil carbon fluxes (i.e. CO<sub>2</sub> and CH<sub>4</sub> from  
14 decomposition), peat depth increments (i.e. accumulation) and soil C budgets (change in soil  
15 C stock in relation to input from NPP and losses from soil C fluxes and erosion).

16

17 Further changes were implemented to improve hydrological and C flux process  
18 representation by calculating water filled pore space in the peat, bedrock drainage, plant-  
19 mediated transport and methane oxidation (oxidation):

20

21 *The available pore space* in relation to the height above the water-table depth (WTD)  
22 was based on data by Hayward & Clymo (1982; see Fig. 4, but ignoring the short  
23 term hysteresis effect); an exponential relationship is assumed between the distance  
24 to the water-table and the available pore space ( $0.2 \cdot \text{EXP}(1.6 \cdot \text{WTD}^2)$ ), such that  
25 available space increases with distance from the water-table. Total space is then

1 calculated by integrating the available pore space over the available unsaturated peat  
2 cohorts. By combining the water entering the system with the available space, a new  
3 WTD is calculated.

4  
5 *To simulate drainage* of the peat column into the bedrock, two drainage factors are  
6 included, specific yield (SY) (0.1) and hydraulic conductivity (HC). These are set to  
7 default values of 0.02 (SY in %) and 0.1 (HC in cm/year) reflecting average values  
8 for clay reported by Johnson (1967) for SY (2%) and for unweathered clay based on  
9 Bear (1972) for HC (10-5 feet/day). However, SY and HC can be altered as a user  
10 input.

11 *The plant functional type* (vegetation) composition of shrub, sedge, rush, grass, herb,  
12 *Sphagnum*, other moss) is based on a moving average of five years of previous  
13 water-tables, allowing representing a more stable/resilient vegetation in the case of  
14 only a few very dry or wet years.

15  
16 *The anoxic ratio* is set to 0.035, similar to values reported in previous literature (Bauer,  
17 2004) ranging from 0.025 to 0.0625.

18  
19 *Methane oxidation* is set to 0.05 g C/g/yr and reflects the range of the very scarce data  
20 available on methane oxidation in relation to dry peat and/or on a carbon (mass)  
21 basis, i.e. McDonald *et al.* (1996) provided incubation values at 20°C for UK peat of  
22 around 0.08 g C/g/yr, Watson *et al.* (1997) quoting 0.012 g C/g/yr (i.e. 0.001021  
23 molC/g/yr equal to 1.021e-3 molC/g/yr), but Yrjala *et al.* (2010) quoted only 0.0009  
24 g C/g/yr (0.2 µmol/gDW/d) and Whaalen & Reeburg (2010) measured around 0.002  
25 g C/g/yr.

1

2 We used available reconstructed Holocene climate data (based on a combination of recent  
3 instrumental data and a variety of existing multiproxy climate reconstructions, see Morris et  
4 al., 2015) to model long-term peat accumulation, Met Office 5 km gridded data (Perry &  
5 Hollis, 2015) for the recent past (1914-1991) and ECN data (ECN Data Centre:  
6 <http://data.ecn.ac.uk>) for recent present periods (1992-2012). Met Office data were adjusted  
7 for elevation for the Moor House site in order to achieve the same long-term average  
8 temperature and rainfall amounts as the Moor House ECN data (see Carroll *et al.*, 2015).  
9 Model predictions of monthly water-table depth could be compared to averaged ECN hourly  
10 automated dipwell data (UK grid location: NY 75072 33425; missing data were gap-filled by  
11 interpolation of manual data) for the period of 1999 - 2012. Water-table depth standard  
12 deviation for a Moor House model evaluation (see supplementary data in Carroll *et al.*, 2015)  
13 was predicted to within 0.32 cm (linear  $R^2 = 0.57$ ).

14

15 Moor House was a formal shooting estate during 1842-1951 and grouse moor management  
16 scenarios reflected available site information (Rob Rose, CEH; personal communication),  
17 which indicated a 20 year burn rotation. The associated drainage was assumed to last from  
18 1831, before intensification of grouse shooting (to enable enhanced heather growth and drier  
19 access conditions for gamekeepers), until the late 1950s. Burning was anticipated to have  
20 started in 1851 and to reduce NPP to 1% in the burnt year (and charcoal adding about 5% to  
21 an inert carbon pool), subsequently recovering in a sigmoidal shape to 100% by either 5 or 10  
22 years after burning (based on field observations by Heinemeyer et al., unpublished data).  
23 Drainage was expected to reduce WTD on average by 5 cm, based on the field evidence of  
24 Wilson et al. (2010). Reduced WTD were linked to enhanced decomposition and increased  
25 the associated CO<sub>2</sub> but decreased CH<sub>4</sub> emissions similarly to modelled impacts of natural

1 WTD changes (Heinemeyer *et al.*, 2010). Drainage (grip) effectiveness was assumed to be at  
2 optimum for 25 years and declining to 60% over the subsequent 15 years (renewed once in  
3 1871 and then maintained at optimum until 1905, reflecting intense grouse shooting), finally  
4 declining to 0% by 1955. Grazing pressure was anticipated to be insignificant above 450 m  
5 (i.e. no reduction in NPP at the modelled altitude of 550 m a.s.l.). Further model scenarios  
6 considered a no management option (no shoot).

7

### 8 **Water-table reconstructions**

9

10 A Russian peat core was taken from the top 50 cm of peat beside the Moor House ECN  
11 station (Lat. 54.695500; Lon. -2.387400) following De Vleeschouwer *et al.* (2010). The core  
12 was returned to the laboratory and stored at 4°C before analysis. The top 20 cm of the core  
13 was sampled at 0.5 cm resolution and testate amoebae were prepared using the standard  
14 method of Booth *et al.* (2010). We applied the Northern England and pan-European transfer  
15 functions to the subfossil TA data to reconstruct water-table depth (Turner *et al.*, 2013;  
16 Amesbury *et al.*, 2016). In both cases weighted-averaging tolerance downweighted regression  
17 with inverse deshrinking was used as it yielded the best performance statistics. The water-  
18 table reconstructions were standardised following Swindles *et al.* (2015). There is some  
19 variation in predicted water-tables between the two transfer functions which is caused by  
20 inter-model differences in WTD optima of key taxa. Some drier taxa (e.g. *Nebela militaris*,  
21 *Trigonopyxis arcuata* type) have drier optima in the Northern England model owing to the  
22 inclusion of some very dry peatlands affected by fire and drainage from this region. Sample-  
23 specific standard errors for the TA transfer function reconstructions were based on 1000  
24 bootstrapping cycles (e.g. Amesbury *et al.*, 2016). The resulting WTD predictions could then

1 be paired with mean annual WTD predictions for years obtained from the MILLENNIA  
2 model based on establishing a peat age-depth profile based on a SCP profile.

3

#### 4 **Peat core age-depth profile**

5 SCPs have been deemed to provide reliable age information from peatlands in Northern  
6 Britain and Ireland for the last ~150 years (Swindles, 2010; Swindles *et al.*, 2010; Turner *et*  
7 *al.*, 2014). Three unambiguous features can be used as age-equivalent stratigraphic markers:  
8 (i) the start of the record (c. 1850), (ii) the rapid increase in SCPs (c. 1950) and (iii) the peak  
9 (c. 1978). These represent (i) the start of high temperature combustion and power generation;  
10 (ii) the post-WW2 increase in power generation and fossil fuel burning and (iii) the peak of  
11 SCP production before reliance on other methods of power generation and the advent of clean  
12 fuel technologies (e.g. Rose *et al.*, 1995). We used the method of Swindles (2010) to prepare  
13 SCPs from the peat. Linear interpolation was used to generate a simple age-depth model  
14 between the three SCP age-equivalent stratigraphic markers and the date of core sampling  
15 (2011) as the uppermost time point; dates before the start of the SCPs are an extrapolation  
16 based on accumulation rate.

17

18

#### 19 **Results**

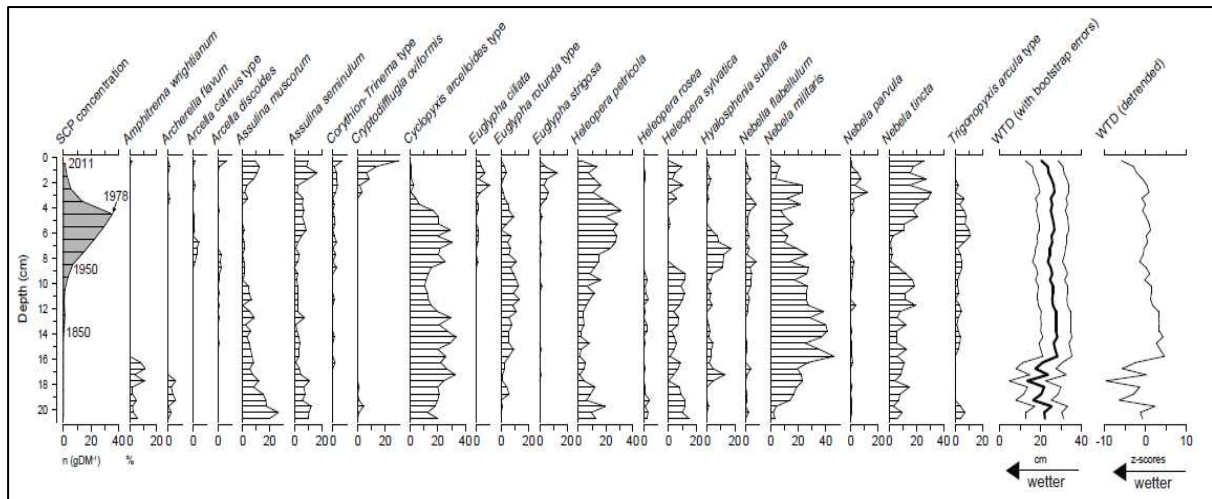
20

#### 21 **Water table reconstructions**

22 The testate amoebae data from Moor House (Fig. 1) along with the SCP concentrations and  
23 water-table reconstructions show periods of changes in wetness across the peat depth profile.

24

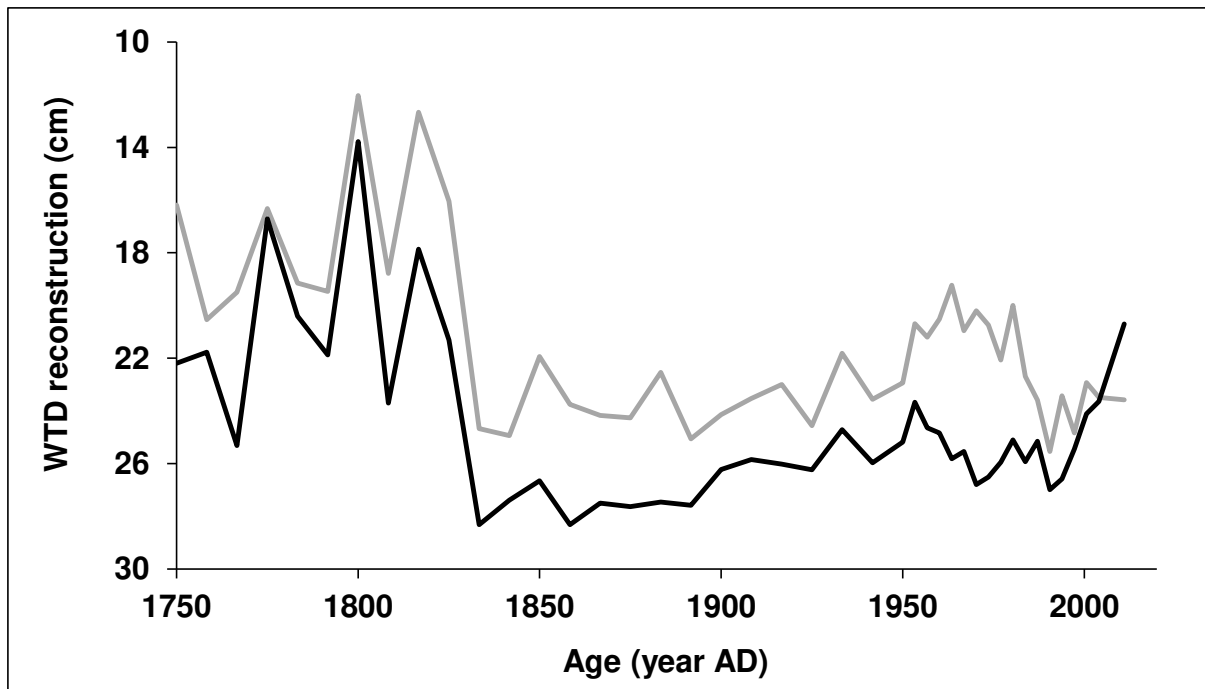
25



1  
 2 **Fig. 1** Testate amoebae record (%) from the Moor House blanket bog, Northern Britain  
 3 alongside the SCP concentration data with chronological assignments marked (i.e. 1978 at  
 4 ~4.5 cm; 1950 at ~9.0 cm; 1850 at ~14.0 cm). The water-table depth reconstruction using the  
 5 transfer function of Turner *et al.* (2014) is illustrated with standard errors derived from  
 6 bootstrapping (1000 cycles). The standardised water-table reconstruction in relation to z-  
 7 scores (following Swindles *et al.*, 2015) is also shown.

8  
 9 The earliest part of the record (before 1850) is very wet owing to the presence of wet-  
 10 indicator species such as *Amphitrema wrightianum* and *Archerella flavum*. After this, the  
 11 assemblage suggests quite a dry peatland surface with the abundance of *Nebela militaris*,  
 12 *Cyclopyxis arcelloides* type (mostly comprised of *Phryganella acropodia*) and *Heleopera*  
 13 *petricola*. All testate amoeba taxa identified in fossil samples were present in the modern  
 14 training sets of the two transfer functions. The comparison of the Northern England and pan-  
 15 European modelled water-tables (Fig. 2) illustrates that the WTD optima of TA species from  
 16 the wider European area are wetter than those for Northern England (for the regression  
 17 equation see Fig. 2 legend).

18



1

2 **Fig. 2** Water-table depth (WTD) reconstructions for the Moor House blanket bog peat core  
 3 based on alternative testate amoebae transfer functions: Europe, EU (grey) (Amesbury *et al.*,  
 4 2016) *versus* Northern England, NE (black) (Turner *et al.*, 2013). Note, a lower WTD value  
 5 means wetter conditions. The linear regression for the reconstructed WTD comparison is  
 6  $y_{[NE]} = 0.79x_{[EU]} + 7.58$ ;  $R^2 = 0.65$ .

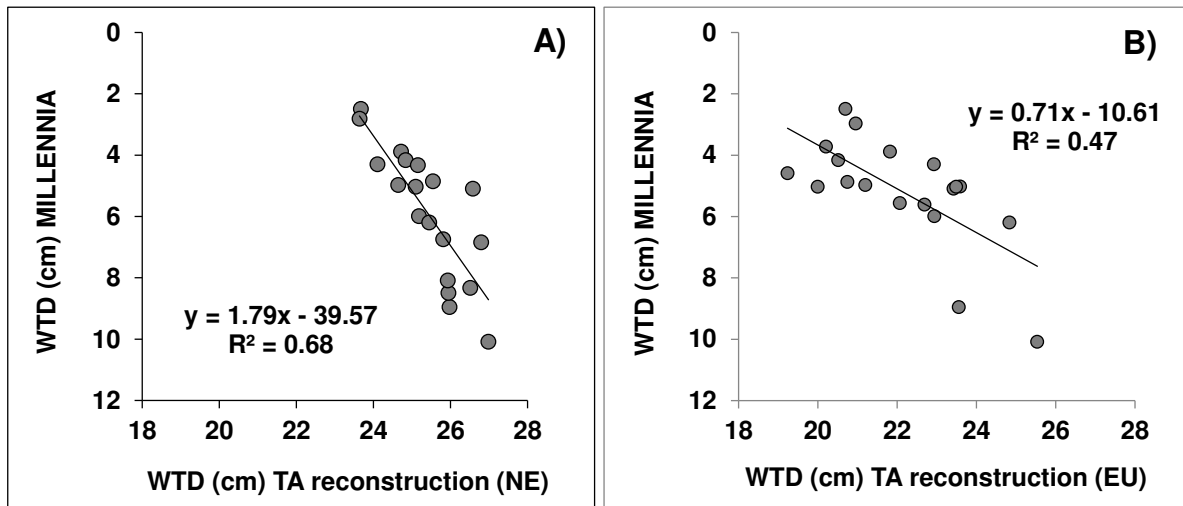
7

8 **TA-derived *versus* MILLENNIA model water-table predictions and site records**

9

10 Water-table reconstructions for the Moor House core based on the Northern England transfer  
 11 function ( $WTD_{TA\_NE}$ ) showed an overall good correlation with the MILLENNIA modelled  
 12 WTD during the period of high quality climate records available for modelling (i.e. 1933-  
 13 2004; see Fig. 3a) but TA-predictions were consistently drier ( $WTD = 1.79 * WTD_{TA\_NE} -$   
 14  $39.57$ ;  $r^2 = 0.68$ ). A comparison with the EU TA transfer function (Fig. 3b) indicated slightly  
 15 wetter conditions but with a less good fit to the measured data ( $WTD = 0.714 * WTD_{TA\_EU} -$   
 16  $10.613$ ;  $R^2 = 0.47$ ). The reason behind this difference in TA-predicted WTD likely reflects

1 different WTD optima of key testate amoebae species in the different geographical areas.  
 2 Therefore, we decided to use the  $WTD_{TA\_NE}$  model for subsequent analysis because of the  
 3 better directional fit in addition to closer geographical location of the TA records.  
 4



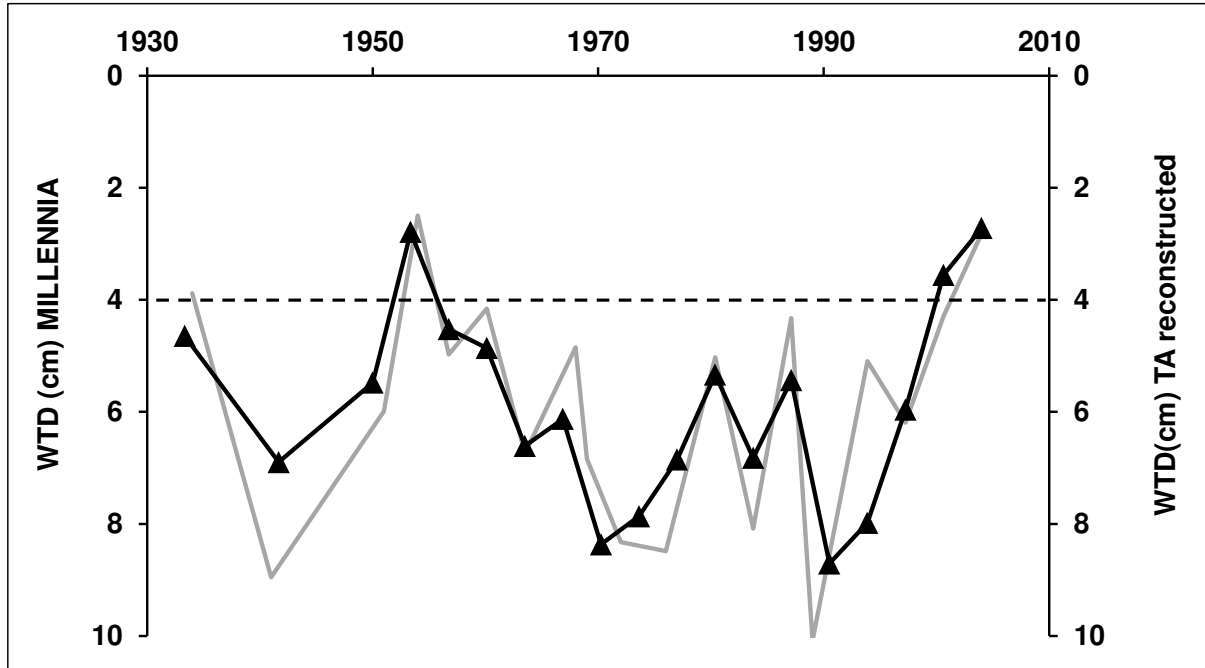
5  
 6 **Fig. 3** Linear regression of MILLENNIA model predicted mean annual water-table depth  
 7 (WTD in cm) for 19 years during 1933-2004 *versus* the corresponding years for the two  
 8 testate amoebae (TA) reconstructions (see Fig. 2) based on the **A**) uncorrected transfer  
 9 function derived for northern England (NE) as in Turner *et al.* (2013), and **B**) the uncorrected  
 10 European (EU) transfer function (Amesbury *et al.*, 2016). The corresponding regression  
 11 equations are shown.

12  
 13 The available ECN site climate data (1931-2010) for Moor House were used to make  
 14 comparisons between annual mean WTD predicted by the MILLENNIA model to the paired  
 15 years ( $\pm 1$  year) with the offset corrected available TA-derived  $WTD_{TA\_NE}$  from the Moor  
 16 House core (Fig. 4). Not only did the WTD range predicted by the model agree with the TA-  
 17 derived WTD, but it also reproduced the general pattern of dry *versus* wet years  
 18 (MILLENNIA WTD =  $WTD_{TA\_NE} + 0.004$ ;  $r^2 = 0.68$ ). Both WTD predictions indicated that  
 19 the years between 1965 and 1995 were an extended period of fairly dry conditions compared



1 to the long-term WTD average of  $4.4 \pm 1.8$  cm (based on annual averages of ECN dipwell  
2 data for 1995-2012).

3



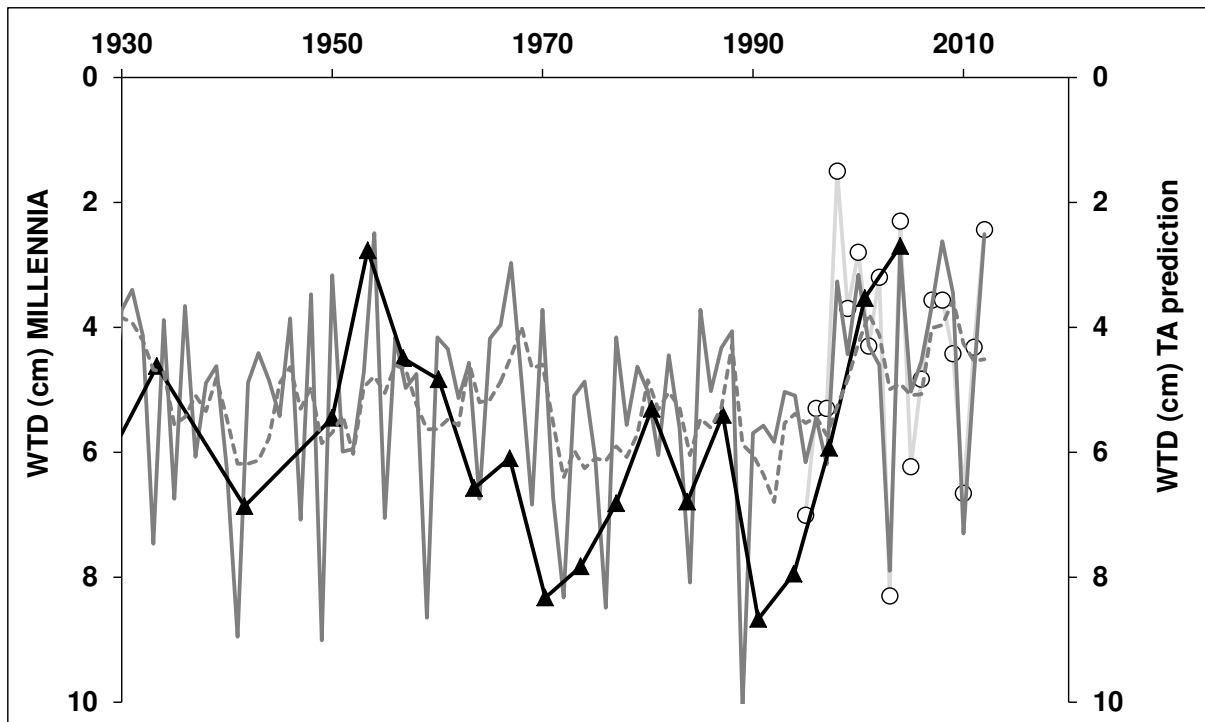
4

5 **Fig. 4** Selected years for mean annual water-table depth (WTD in cm) predictions (in the peat  
6 profile) between 1931-2004 from the MILLENNIA model (grey line) paired with years  
7 (triangles) of available testate amoebae (TA) based predictions (black line) using the offset  
8 regression (Fig. 3A). The dashed line indicates the long-term (1995-2012) mean annual WTD  
9 at Moor House (ECN data).

10

11 The annual MILLENNIA model prediction of WTD during 1931-2012 also showed very  
12 good agreement with the paired years of available offset corrected TA-derived WTD,  
13 capturing peaks and troughs as well as the average trend (Fig. 5). Moreover, the model  
14 predicted WTD ( $WTD_{Mod}$ ) followed the available annual ECN site WTD ( $WTD_{ECN}$ ) data  
15 very well ( $WTD_{ECN} = WTD_{Mod} * 0.813 + 0.595$ ,  $r^2 = 0.57$ ; see Carroll *et al.*, 2015).

16



1

2 **Fig. 5** Annual water-table depth (WTD in cm) predictions (in the peat profile) since 1930  
 3 from the MILLENNIA model (dark grey lines, with 4-year average as dashed line) *versus* the  
 4 4-yearly predictions (black line) from testate amoebae (TA) based on the offset regression  
 5 (Fig. 3A) and actual annual site WTD averages (white circles and light grey line) based on  
 6 available continuous WTD data (1995-2012).

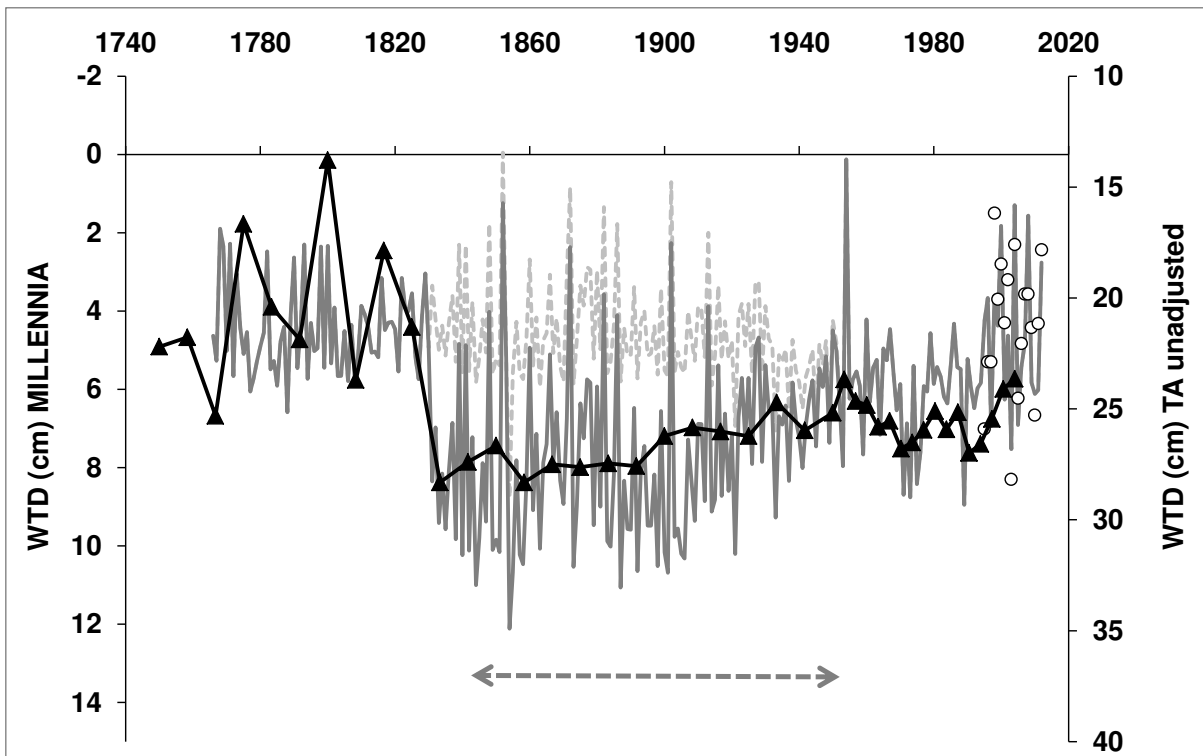
7

8 **Comparison of predicted water-tables for management scenarios and site records**

9

10 Use of the available long-term climate data for a nearby Northern England peatland site  
 11 (Morris *et al.*, 2015), adjusted to the long-term mean temperature and total rainfall for Moor  
 12 House, together with Moor House ECN climate data since 1931, provided a basis for a  
 13 comparison of the WTD predicted by the MILLENNIA model over an extended time period  
 14 (1750s till 2012), for which TA WTD reconstructions were available (Fig. 6). Although the  
 15 general WTD patterns agreed very well between the two predictions, the (unadjusted) TA  
 16 WTD predictions were much drier than the MILLENNIA predictions. Whilst MILLENNIA

1 model predictions indicated mean annual WTD conditions during 1760-1830 of between 2-6  
 2 cm, the unadjusted TA predictions of WTDs were around 15 to 25 cm. Adjusting for the  
 3 1931-2004 determined TA-WTD offset (Fig. 3a) increased the TA-based WTD predictions to  
 4 above the peat surface ( $-2.92 \pm 6.16$  cm; data not shown). However, whereas MILLENNIA  
 5 model predictions of the unmanaged (no shoot) scenario remained very wet during 1830-  
 6 1940, unadjusted TA-predictions showed much lower WTD during that period, but  
 7 overlapped again with the MILLENNIA model predictions from the 1940s onwards (Fig. 6).  
 8



9  
 10 **Fig. 6** Water-table depth (WTD in cm) predictions from the MILLENNIA model (grey lines)  
 11 *versus* 4-yearly testate amoebae (TA) based predictions (black line) and actual annual site  
 12 WTD averages (white circles) based on available continuous site WTD data (1995-2012).  
 13 Light dashed grey line indicates model scenario without any management, whereas dark solid  
 14 grey line indicates a grouse moor management scenario during 1842-1951 (dashed arrow)  
 15 with a period of active drainage (1831-1920). Note the different y-axis scales (i.e. unadjusted  
 16 TA WTD predictions).

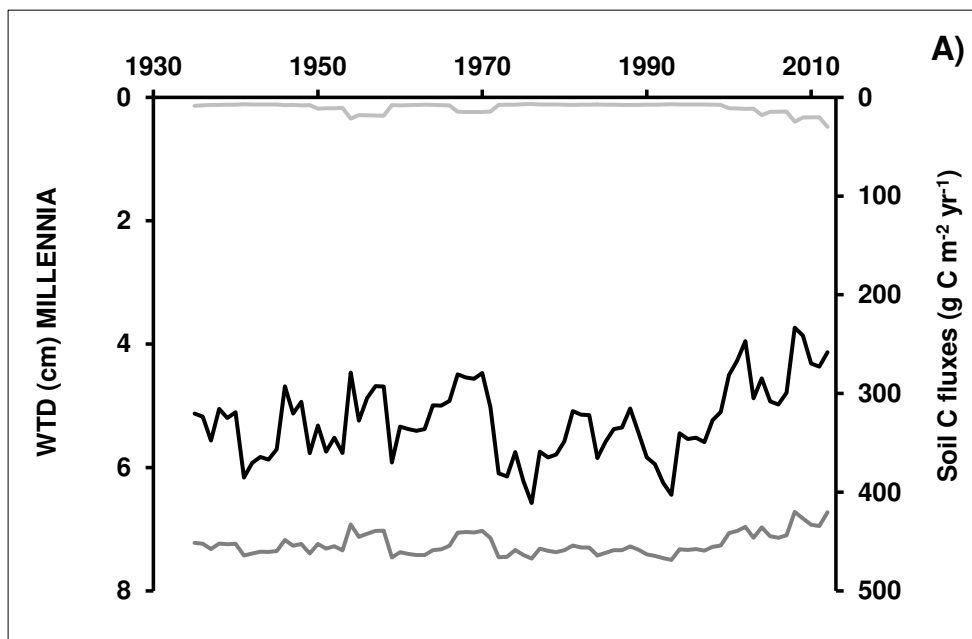
1

## 2 Predicted impacts on soil C emissions, peat C budgets and peat accumulation rates

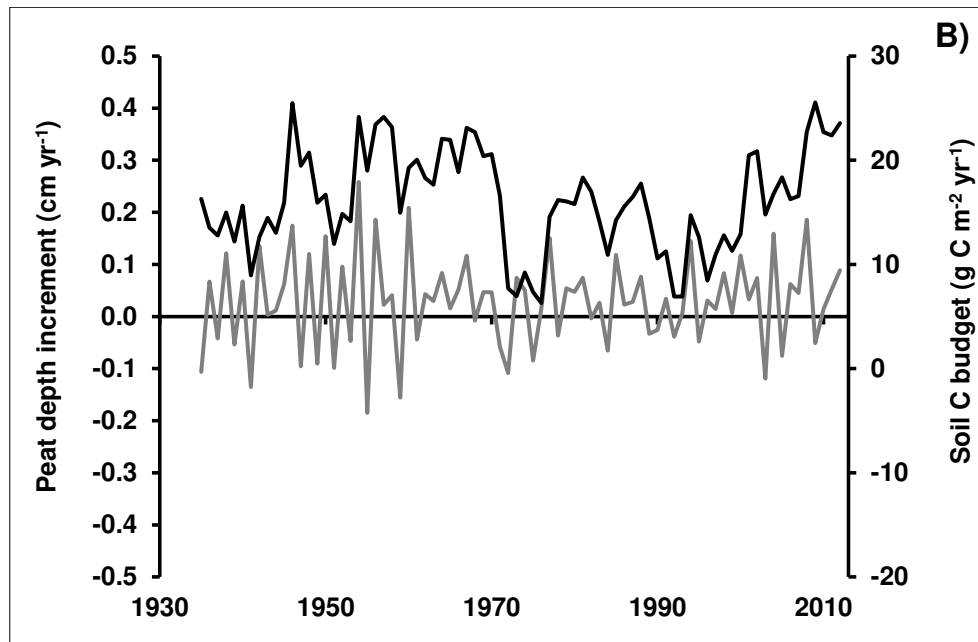
3

4 The observed drier than average mean annual WTD predictions from the MILLENNIA  
5 model during 1965-1995 (Fig. 4) corresponded to 5.2 g C m<sup>-2</sup> yr<sup>-1</sup> lower net methane (CH<sub>4</sub>)  
6 but 13.4 g C m<sup>-2</sup> yr<sup>-1</sup> higher CO<sub>2</sub> emissions (Fig. 7a) than during the remaining period of  
7 1931-2012. This change in soil C fluxes to the atmosphere reflected the increased aerobic  
8 decomposition processes under a lower WTD, which resulted in near zero mean peat depth  
9 increment (reduced by 0.041 cm yr<sup>-1</sup>) and a lower mean soil C budget (reduced by 6.2 g C m<sup>-2</sup>  
10 yr<sup>-1</sup>) (Fig. 7b) during the drier 1965-1995 period.

11



12



1

2 **Fig. 7** MILLENNIA model predictions (five year running means) of climatic impacts during  
 3 1931 to 2012 on A) annual water-table depth (WTD in cm; black line) and carbon (C) fluxes  
 4 of CO<sub>2</sub> (dark grey line) and CH<sub>4</sub> (light grey line), and B) annual peat depth increments (grey  
 5 line) and soil C budget (black line) with positive numbers representing C gains.

6

7 The MILLENNIA model scenario period of 1851-1950 (Fig. 8) showed a positive (C gain)  
 8 annual soil C budget (Fig. 8b) of  $12.7 \pm 22.7 \text{ g C m}^{-2}$  for the unmanaged scenario (with a  
 9 mean WTD of  $4.7 \pm 1.5 \text{ cm}$ ; Fig. 8a) compared to a negative (C loss) budget of  $-38.6 \pm 110.1$   
 10  $\text{g C m}^{-2}$  for the grouse managed scenario with drainage (mean WTD of  $7.7 \pm 2.1 \text{ cm}$ )  
 11 assuming a 10-year NPP recovery time after burning (resulting in  $51.3 \text{ g C m}^{-2} \text{ yr}^{-1}$  less soil  
 12 carbon gain under grouse management). The corresponding peat depth increments predicted  
 13 by the MILLENNIA model during 1851-1950 showed a mean peat accumulation of  $0.03 \pm$   
 14  $0.59 \text{ cm}$  for the unmanaged (no shoot) *versus* a loss of  $-0.06 \pm 0.61 \text{ cm}$  for the grouse  
 15 managed scenario (i.e.  $0.09 \text{ cm yr}^{-1}$  less peat depth increment). Moreover, the 5-year NPP re-  
 16 growth scenario (data not shown) resulted in about 45% lower mean annual soil C budget  
 17 loss ( $-21.6 \pm 93.7 \text{ g C m}^{-2}$ ) and half the peat increment loss ( $-0.03 \pm 0.63 \text{ cm}$ ) compared to the

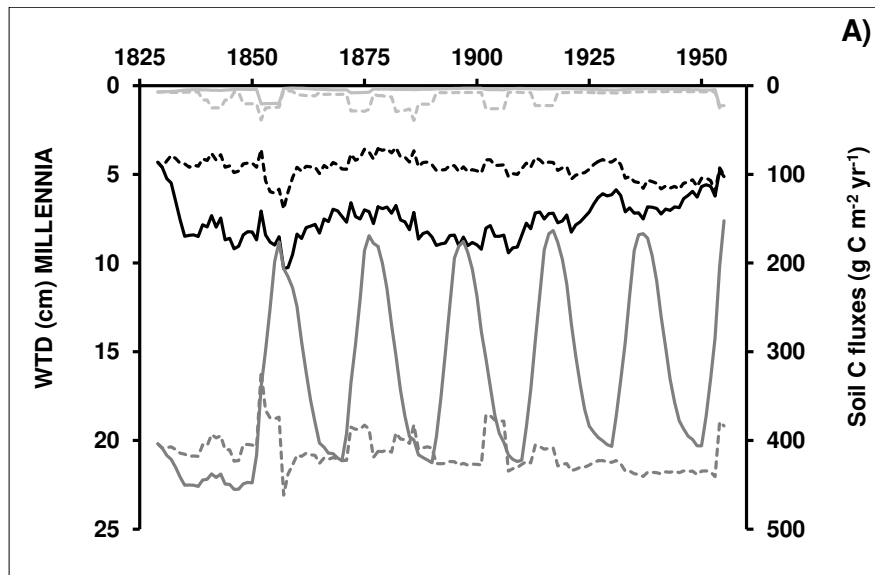
1 10-year NPP recovery scenario. In comparison to the default burn and drain scenario, the  
2 burn but no drain 10-year NPP re-growth scenario (data not shown) resulted in about 30%  
3 lower C and peat accumulation losses with a mean annual soil C budget of  $-28.4 \pm 108.7 \text{ g C}$   
4  $\text{m}^{-2}$  and  $-0.04 \pm 0.63 \text{ cm}$  mean annual peat depth increment (with a mean WTD of  $4.8 \pm 1.9$   
5 cm). The burn but no drain 5-year NPP re-growth scenario reduced this further (i.e. 80%  
6 lower soil C and peat increment losses with a mean annual soil C budget of  $-10.9 \pm 92.6 \text{ g C}$   
7  $\text{m}^{-2}$  and a mean annual peat depth increment of  $-0.01 \pm 0.64 \text{ cm}$ .

8

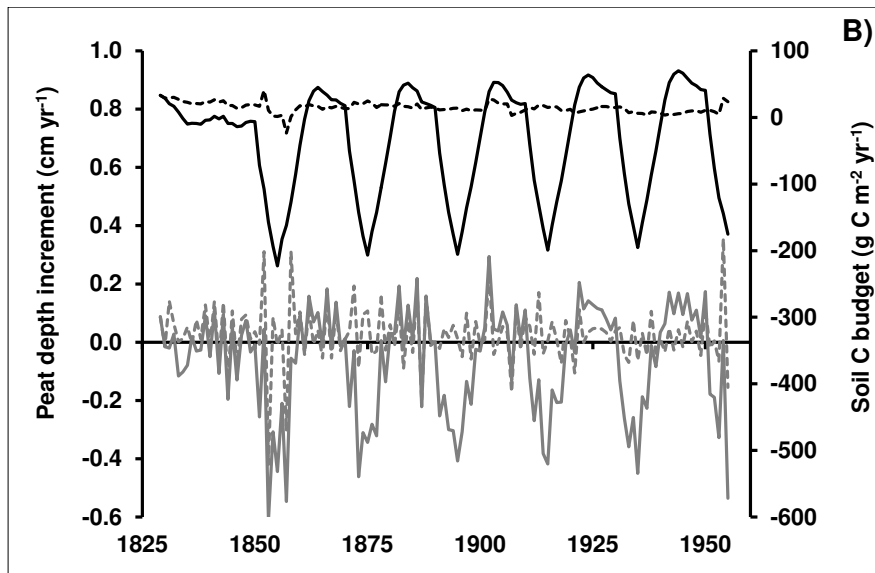
9 During 1831-1850, the period of drainage only (i.e. no burning), the managed scenario  
10 reduced the mean annual soil C budget by  $27.8 \text{ g C m}^{-2}$  to  $-7.2 \pm 15.8 \text{ g C m}^{-2}$ , which  
11 reflected an average reduction in mean annual WTD by  $3.9 \text{ cm}$  to  $8.3 \text{ cm}$  (Fig. 8a). These  
12 changes in soil C budget under drainage only corresponded to an annual peat depth increment  
13 reduction by  $0.06 \text{ cm}$  to  $-0.02 \pm 0.63 \text{ cm}$  compared to the unmanaged scenario (Fig. 8b).

14

15 The grouse moor management (i.e. 1851-1950) not only impacted C dynamics via reduced  
16 water-tables from drainage (Fig. 8a), it also altered C inputs and thus C dynamics via reduced  
17 NPP following burning. Overall, drained and 10-year NPP recovery scenarios reduced both  
18 mean annual C losses from soil  $\text{CO}_2$  fluxes ( $308 \pm 106 \text{ g C}$ ) and annual  $\text{CH}_4$  emissions ( $4.9 \pm$   
19  $8.3 \text{ g C}$ ) compared to the unmanaged scenario for which mean annual values were  $417 \pm 60 \text{ g}$   
20  $\text{C}$  for  $\text{CO}_2$  and  $13.2 \pm 20.4 \text{ g C}$  for  $\text{CH}_4$  net emissions (i.e. including methane oxidation,  
21 ebullition and plant-mediated transfer (PMT) processes via sedge leaves and stems).  
22 However, whereas the no drain 10-year NPP burn scenario decreased  $\text{CO}_2$  ( $292 \pm 110 \text{ g C}$ )  
23 and increased  $\text{CH}_4$  ( $9.8 \pm 18.0 \text{ g C}$ ) emissions (Fig. 8a), the 5-year NPP scenario (data not  
24 shown) increased both  $\text{CO}_2$  fluxes ( $348 \pm 92 \text{ g C}$ ) and net  $\text{CH}_4$  emissions ( $11.2 \pm 18.8 \text{ g C}$ )  
25 emissions, reflecting quicker vegetation re-growth and thus NPP and PMT recovery.



1



2

3 **Fig. 8** MILLENNIA model predictions (five year running means) of management impacts  
 4 during 1825 until 1945 on **A**) annual water-table depth (WTD; black line) and carbon (C)  
 5 fluxes of CO<sub>2</sub> (dark grey line) and CH<sub>4</sub> (light grey line), and **B**) annual peat depth increments  
 6 (grey line) and the soil C budget (black line) with positive numbers representing net C gains.  
 7 Unbroken lines represent the unmanaged (no shoot) 'natural state', whereas dashed lines  
 8 represent predictions for grouse moor management (1842-1951) including active drainage  
 9 (1931-1920); drainage efficiency 25 years at maximum plus 15 years reduction to 60% and  
 10 0% by 1955) and burning (20 year cycles; with an exponential 10-year re-grow period to full  
 11 net primary productivity) during 1850 till 1950.

## 1 Discussion

2

3 This study provided novel insights into ecological applications of using TA-derived water-  
4 table depth reconstructions in a site-specific model validation context. The findings highlight  
5 the value of combining palaeo-ecological records with process level modelling to allow better  
6 understanding of the effects of climate and management on peat development and C cycling.  
7 This combination shows promising potential in allowing to understand the contributions of  
8 past environmental (e.g. climate) and human-induced (e.g. grouse management) changes in  
9 peatland development over time, C stocks and corresponding C fluxes.

10

11 Although the EU transfer function predictions (as used in Amesbury *et al.*, 2016) showed  
12 wetter conditions overall (Fig. 2), the model fit to the MILLENNIA predictions was not  
13 improved, indicating a better overall fit using the geographically closer NE transfer function,  
14 possibly applying across the wider UK context, which has yet to be tested. Previous work  
15 comparing TA to recent short-term monitored WTD by Amesbury *et al.* (2016) was based  
16 around a collection of samples from several sites and did not compare TA-derived  
17 reconstructions to site-specific long-term modelled hydrological time series. Moreover,  
18 whereas Amesbury provided a WTD reconstruction based on comparing two different TA  
19 transfer functions, we identified and adjusted for a generic transfer function offset based on a  
20 site-specific validation period (Fig. 3) to allow a context-dependent (i.e. NE blanket bog at  
21 Moor House) model comparison over several centuries. The fairly constant offset could well  
22 reflect a TA sample bias of summer sampling and thus drier conditions overall (i.e. during  
23 contemporary sampling to obtain TA calibration data on moisture or WTD relationships);  
24 water-tables at Moor House frequently drop to 20 - 30 cm during July and August (Carroll *et al.*,  
25 *et al.*, 2015). With fairly constant water-table drawdown during drier periods (unpublished data



1 by Heinemeyer et al.), a general offset can be expected (i.e. wetter sites are always wetter and  
2 vice-versa).

3

4 Notwithstanding the overall good fit from the offset corrected TA-derived *versus* model  
5 predicted water-tables (Fig. 4), some resulting TA-derived water-table predictions such as the  
6 very wet period between 1730-1830 (as shown in Fig. 6) might seem questionable. However,  
7 the predicted standing water conditions of up to -10 cm when applying the offset adjusted TA  
8 functions (using the offset corrected NE transfer function as shown in Fig. 3a) fall within the  
9 tolerance and optima values (i.e. Turner et al., 2013) of two wet to aquatic TA indicator taxa  
10 (see Fig. 5 in Amesbury *et al.*, 2016), *Amphitrema wrightianum* type ( $2 \pm 6$  cm mean WTD)  
11 and *Archerella flavum* ( $8 \pm 7$  cm mean WTD). This coincides with documented wet bog  
12 conditions across Ireland (Swindles *et al.*, 2013) and Northern Britain (Mauquoy *et al.*, 2002)  
13 during this period (i.e. the Little Ice Age) with potentially standing water for most of the year  
14 or water pools in hollows. Such conditions of standing water are not specifically captured by  
15 either the model or TA WTD predictions, which are relatively insensitive to water-tables  
16 above the surface. Moreover, the climate data used in the model become less reliable before  
17 the 1850s, and this period might well have been wetter than the by Morris *et al.* (2015)  
18 reconstructed climate record suggests. Therefore, MILLENNIA predicted WTD during 1730-  
19 1830 might be under predicting the WTD in relation to uncertain climate input data.

20

21 Most interesting was the period between 1840s and 1940s, an unexpectedly drier period  
22 based on TA predicted hydrological conditions compared to the wetter conditions predicted  
23 by the MILLENNIA model based on climate only (Figure 6). Moor House was a formal  
24 shooting estate throughout exactly this period (i.e. 1842-1951), based on grouse bags and  
25 predator control information (ECN data provided by Rob Rose from the Centre for Ecology

1 and Hydrology (CEH) Lancaster, personal communication). Grazing intensity on true blanket  
2 bogs such as Moor House is low (0.5 sheep/ha according to Rawes & Heal, 1978), except  
3 perhaps for recently burnt areas; historically grazing was probably low overall because  
4 farmers were unable to grow sufficient feed to maintain their stock over the winter,  
5 particularly at altitudes above 500 m. Therefore, burning in connection with drainage seems  
6 to be the most likely factor explaining the water-table lowering. The available anecdotal  
7 evidence (R. Rose (CEH), personal communication) from some of the game keepers in the  
8 latter part of the period suggest that an average of 250 acres were burnt each year out of a  
9 total area of about 5000 acres (i.e. averaging a 20 year burn cycle) and drainage ditches were  
10 maintained to aid the heather management. Such intense grouse moor management would  
11 have most likely resulted in a lowering of the water-table by around 5 cm, as has been  
12 observed in a grip blocking study by Wilson *et al.* (2010). Interestingly, the MILLENNIA  
13 scenarios simulating such grouse moor management resulted in the modelled WTD capturing  
14 this drier period as inferred from the TA record, which in the model scenario was mainly a  
15 result of drainage.

16

17 Moreover, the managed model scenario indicated considerable losses in the soil C budget and  
18 decreased peat accumulation rates. Up-scaled to an intense grouse moor management period  
19 of 100 years these accumulated C losses (i.e. 1850-1950) relate to around 5 kg C m<sup>-2</sup> less soil  
20 carbon or 10 cm lower peat depth accumulation than predicted for the unmanaged scenario.  
21 Notably, burning and drainage contributed equally to the carbon loss, via reduced NPP (i.e.  
22 less litter input) and enhancing decomposition (i.e. lower WTD). Garnett *et al.* (2001)  
23 indicated a carbon loss and lower peat accumulation on burn management at Moor House  
24 (based on experimental burn plots) of around 73 g C m<sup>-2</sup> yr<sup>-1</sup>, slightly higher but very similar  
25 to our model predictions of 51 g C m<sup>-2</sup> yr<sup>-1</sup>. However, the Garnett *et al.* study contained some

1 methodological uncertainties in relation to calculating C stocks (Clay *et al.*, 2010) and the  
2 MILLENNIA model did not account for any potential charcoal impacts on hydrology and  
3 decomposition. In particular, impacts on peat bulk density (i.e. charcoal pieces entering peat  
4 pores) with possibly changes in water holding capacity and charcoal inputs representing an  
5 inert C pool (i.e. biomass partly by-passing decomposition; see Clay *et al.*, 2010) with  
6 possible additional effects on decomposition rates (e.g. negative priming; see Lu *et al.*, 2014)  
7 might need to be considered in future model developments. Notably, the Garnett *et al.* (2001)  
8 study has been highlighted by Evans *et al.* (2014) as the only substantial study assessing  
9 burning impacts on UK blanket bogs. Therefore, burn management implications on the long-  
10 term peat C stock remain uncertain.

11

12 Whilst the estimated mean annual soil CO<sub>2</sub> fluxes of around 300-400 g C m<sup>-2</sup> yr<sup>-1</sup> (i.e. range  
13 of managed vs. unmanaged scenario, respectively) are within the same order of magnitude  
14 reported for a study at Moor House (Clay *et al.* 2010), the CH<sub>4</sub> emissions of around 5-10 g C  
15 m<sup>-2</sup> yr<sup>-1</sup> were slightly higher compared to published values for the Flow Country (4.3 g C m<sup>-2</sup>  
16 yr<sup>-1</sup>; Levey & Gray, 2015) and Moor House (3.9 g C m<sup>-2</sup> yr<sup>-1</sup>; Worrall *et al.*, 2007, and 6.4 g  
17 C m<sup>-2</sup> yr<sup>-1</sup>; Worrall *et al.*, 2009). However, the existing data on net CH<sub>4</sub> emissions from  
18 peatlands are very uncertain, with many older studies using inadequate methodologies (i.e.  
19 long chamber incubation periods and inaccurate analyser techniques such as gas  
20 chromatographs). Moreover, recent data from Moor House during two wet and warm years  
21 (2015-2016) measured much higher than previous average annual CH<sub>4</sub> emissions from peat  
22 decomposition of 2 to 400 g C m<sup>-2</sup> yr<sup>-1</sup> (unpublished; pers. comm. Rob Rose at CEH).  
23 However, the largest uncertainty for field measurements is likely related to manual chamber  
24 measurements often not capturing plant-mediated transfer rates and ebullition, bypassing  
25 methane oxidation and thus leading to an overall underestimation of 'true' methane fluxes.

1 Due to both model and measurement uncertainties, the presented CH<sub>4</sub> emissions should thus  
2 not be taken as real flux predictions but rather be seen as indicators of possible differences to  
3 be assessed by future monitoring.

4

5 Peat cores provide a valuable archive for reconstructing peat development in relation to past  
6 climate, particularly TA-based water-table reconstructions as a driver of peat and carbon  
7 accumulation. We have shown here that combining this peatland archive with actual site  
8 measurements and model scenarios of past water-tables can provide additional information  
9 on likely impacts of land management, which are not easily detectable otherwise, but are  
10 crucial for explaining observed peat accumulation not explained by climate alone.

11

12

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22

23

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