Appendix 15 of BD5104

Peat carbon and hydrological modelling (MILLENNIA model)

The purpose of this Appendix is to further describe the methods and findings relating to the model predictions of peat carbon stocks, carbon fluxes and hydrological conditions which are described in sections 4.2.8, 4.5.5.2 and sections 4.6.1 to 4.6.3 of the main body of the report for project BD5104. The methods summaries, results and discussions are not repeated here but instead more details of the methods, some more detailed graphical results and information on the model assumptions are given.

MILLENNIA peat cohort model

The MILLENNIA model is based on concepts of litter decomposition models using basic, but well established environmental regressions to predict carbon (C) input and decomposition of litter and soil organic matter (SOM). The equations combine actual evapotranspiration (AET) derived net primary productivity (NPP) (Webb et al., 1978) and internal (e.g. litter quality) as well as external (e.g. AET or temperature) rate modifiers to predict litter decomposition rates (Minderman, 1968; Meentemeyer, 1978; Berg & McClaugherty, 2003). Litter decomposition models have been applied to simulate C accumulation in peatlands since the early work of Clymo (1984) using a litter cohort approach with increasing complexity, as summarized in Yu et al. (2001), sometimes considering climate response surfaces to determine peatland PFTs (Bauer et al., 2003; Gignac et al., 1991).

The MILLENNIA model was first developed as an annual model reflecting annual litter cohort accumulation (Heinemeyer et al., 2010), and was subsequently extended to allow monthly time steps reflecting the need to represent seasonal water table impacts in relation to ecological processes (Carroll et al., 2015).

Whilst there is no evapotranspiration from snow in the annual model (i.e. mean annual temperature ≤0°C), the monthly model included up to 27 mm water loss per month from likely snow cover (i.e. mean monthly temperature ≤0°C) according to measured average snow water loss evaporation rates of 0.036 inches per 24 hours Hutchison (1966). Further changes were implemented to improve hydrological and C flux process representation by calculating water filled pore space in the peat, bedrock drainage, plant mediated transport and methane oxidation (oxidation):

The available pore space in relation to the height above the water table depth (WTD) was based on data by Hayward and Clymo (1982; cf. Fig. 4, but ignoring the short term hysteresis effect); an exponential relationship is assumed between the distance to the water table and the available pore space ($0.2*EXP(1.6*WTD^2)$, such that available space increases with distance from the water table. Total space is then calculated by integrating the available pore space over the available unsaturated peat cohorts. By combining the water entering the system with the available space, a new WTD is calculated.

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

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

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

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

Spatial modelling:

To predict cranefly and subsequently bird numbers across our three focal landscapes (5 x 5 km squares containing our three field sites) water table depth (WTD) predictions were obtained for each 50 x 50 m square (considering varying aspect, slope and elevation effects on peat hydrology within each 5 x 5 km grid cell) from the adapted monthly version (Carroll et al., 2015) of the MILLENNIA peatland model (Heinemeyer et al., 2010). The below graphic (**Figure A15.1**) shows mean annual WTD predictions for the three sites in 2014 and in relation to the topography.

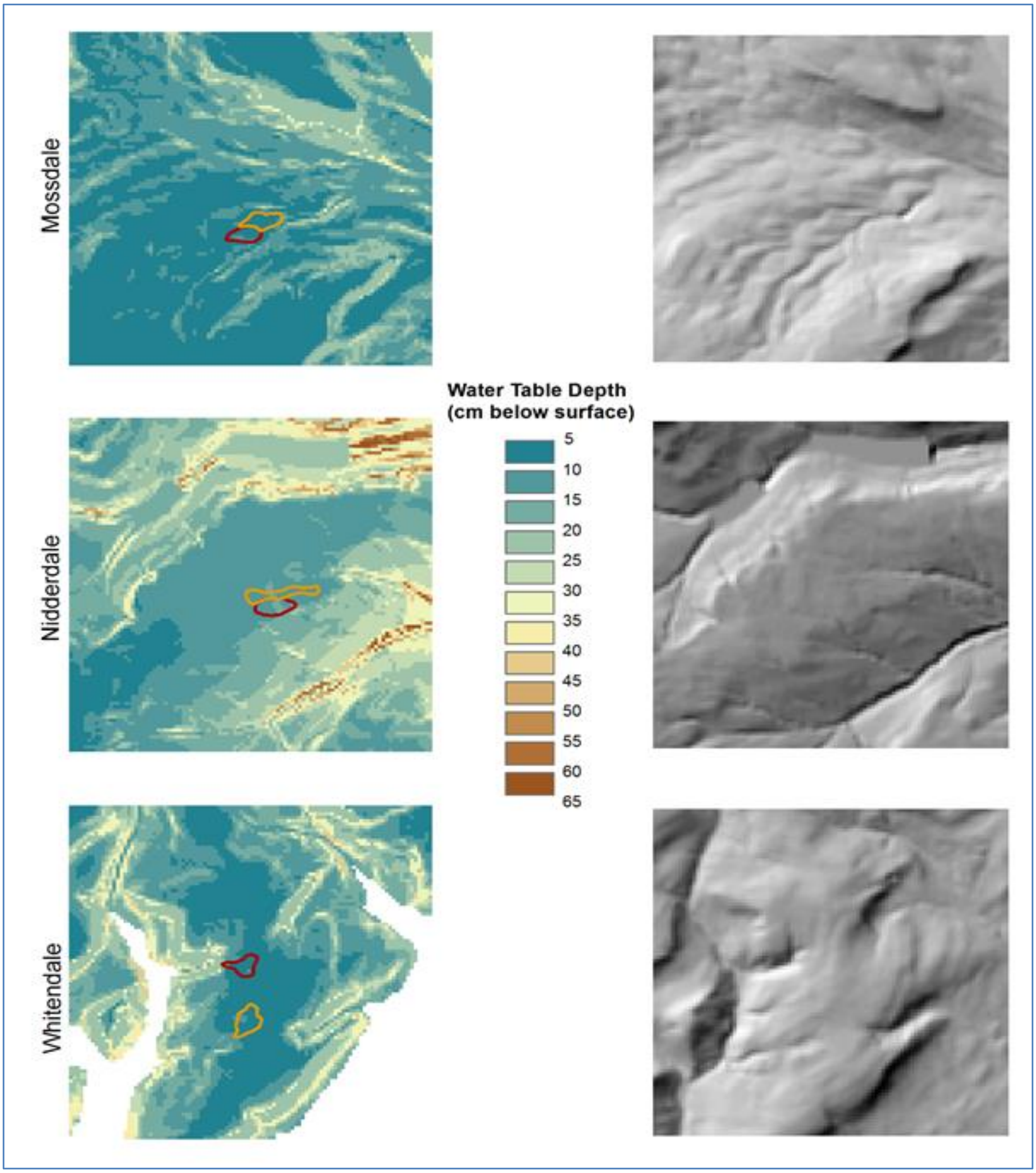


Figure A15.1 Mean annual water table (WTD) maps (based on monthly WTD predictions) for the three sites within the 5x5 km area surrounding the paired catchments (outlined) considering the water tables during the 2014 (as an average year) measurement period. Whitendale areas under 200 m a.s.l. were not included in the model as they do not support the blanket bog peatland habitat. Red outline shows burnt and orange outline shows mown sub-catchments. Figures on right give a representation of the topography of these sites (shaded slope and aspect) based on digital elevation models (DEMs) at 50 m resolution.

Specifically, summer WTD (July-September) was calculated, reflecting the observed cranefly desiccation period (Coulson, 1962). Two scenarios were considered: baseline climate (1961-1990) and a future (2051-2080) climate scenario (SRES emissions scenario A1B; UKCP09).

Model adjustments to drainage:

In addition to the previous model validation (Carroll et al., 2015), the three sites offered an independent validation based on plot-level WTD data. Since the previous publication, the model now also includes a bedrock drainage factor (see above), derived from information on specific yield (SY) and hydraulic conductivity (HC). This allows the model to reflect overall observed site differences, most likely reflecting drainage through the peat/bedrock interface, which also includes underground drainage via peat pipes. Slight adjustments to the default parameters were made based on iteration to obtain a better overall model fit (see **Figure 127** in the main report). The default parameters were HC = 5; SY = 0.05. The below graphic (**Figure A15.2**) compares measured (uncut plots) to modelled monthly WTD averages for the three study site based on the default SY and HC values.

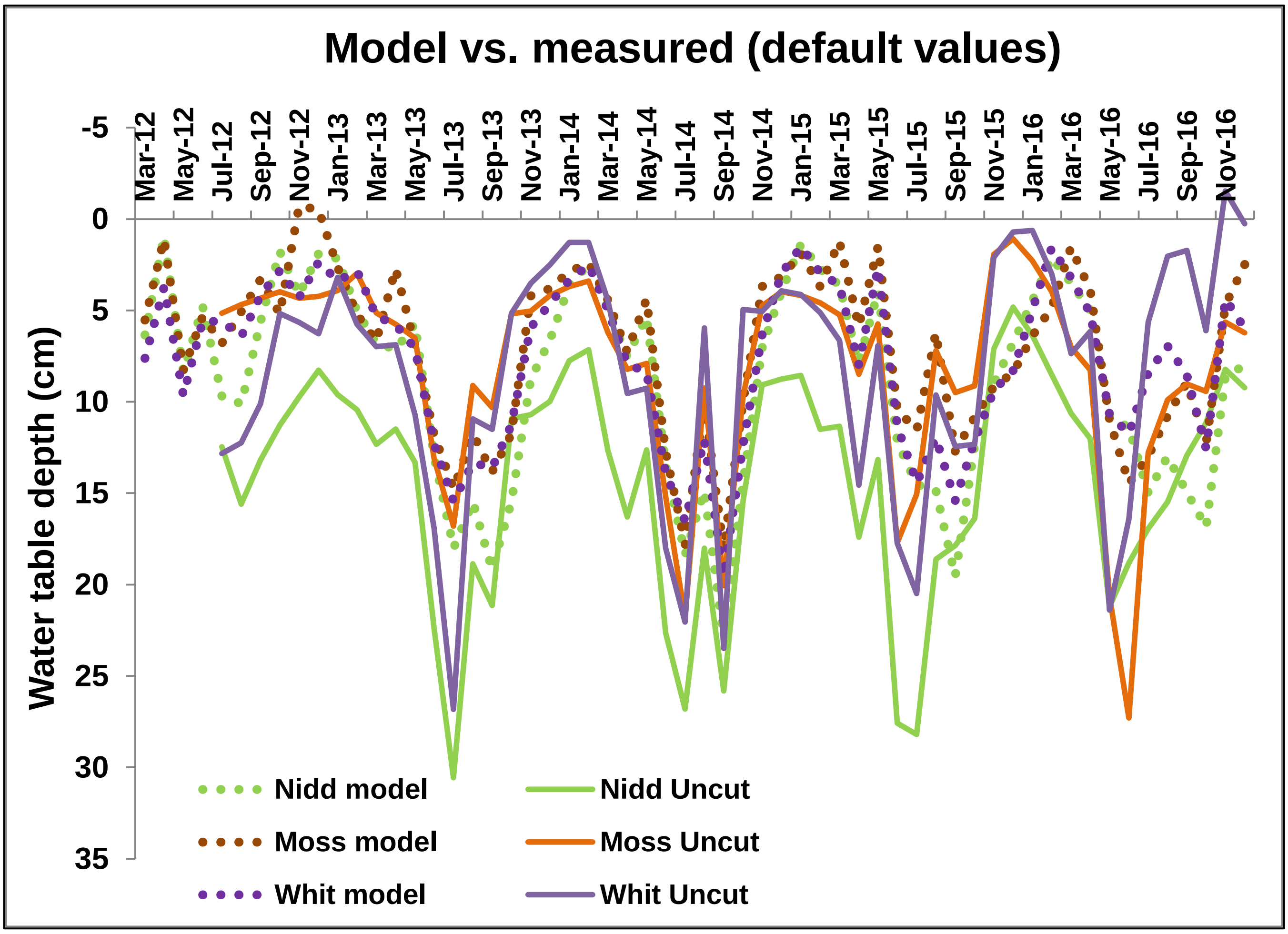


Figure A15.2 Site averages versus model predicted mean monthly water table depths for the three sites for the uncut management with the model default drainage parameters for hydraulic conductivity (HC) and specific yield (SY). The default model parameter values were: HC = 5; SY = 0.05.

Comparison of model water table predictions to paleo-records of *testate amoebae*:

Whereas in the short-term site measurements of WTD can be used for model validations, longer-time scales rely on comparing model predictions to WTD reconstructions, for example based on testate amoebae (TA). Peat cores provide a stratigraphic (i.e. temporal) archive of past TA species composition, thus allowing to predict past moisture conditions from understanding of contemporary ecology (Amesbury et al., 2016). The MILLENNIA peatland model predicts peat hydrological conditions (i.e. water table) based on climatic conditions either for annual or monthly time steps. Here we used the annual MILLENNIA version (Heinemeyer et al., 2010) for the long term peat accumulation during the Holocene and for the period until 1914, and either the annual or monthly version (Carroll et al., 2015) until 2012 (reflecting model application and climate data availability). We used available reconstructed Holocene climate data (based on a combination of recent instrumental data and a variety of existing multiproxy reconstructions, see Morris et al., 2015) to model long-term peat accumulation, Met Office 5 km gridded data (Perry & Hollis, 2005) for recent past (1914-1991) and ECN data (ECN Data Centre: http://data.ecn.ac.uk accessed in 2013) for the more recent period (1992-2012). Met Office data were adjusted for the Moor House site (for elevation) to achieve the same long-term average temperature and rainfall amounts as the ECN data (see Carroll et al., 2015). The model predicted WTDs allowed comparison to TA-based WTD reconstructions for a peat core at Moor House (Swindles, unpublished) using the transfer function of Turner et al. (2014). Section 4.6.1 in the main report provides more results.

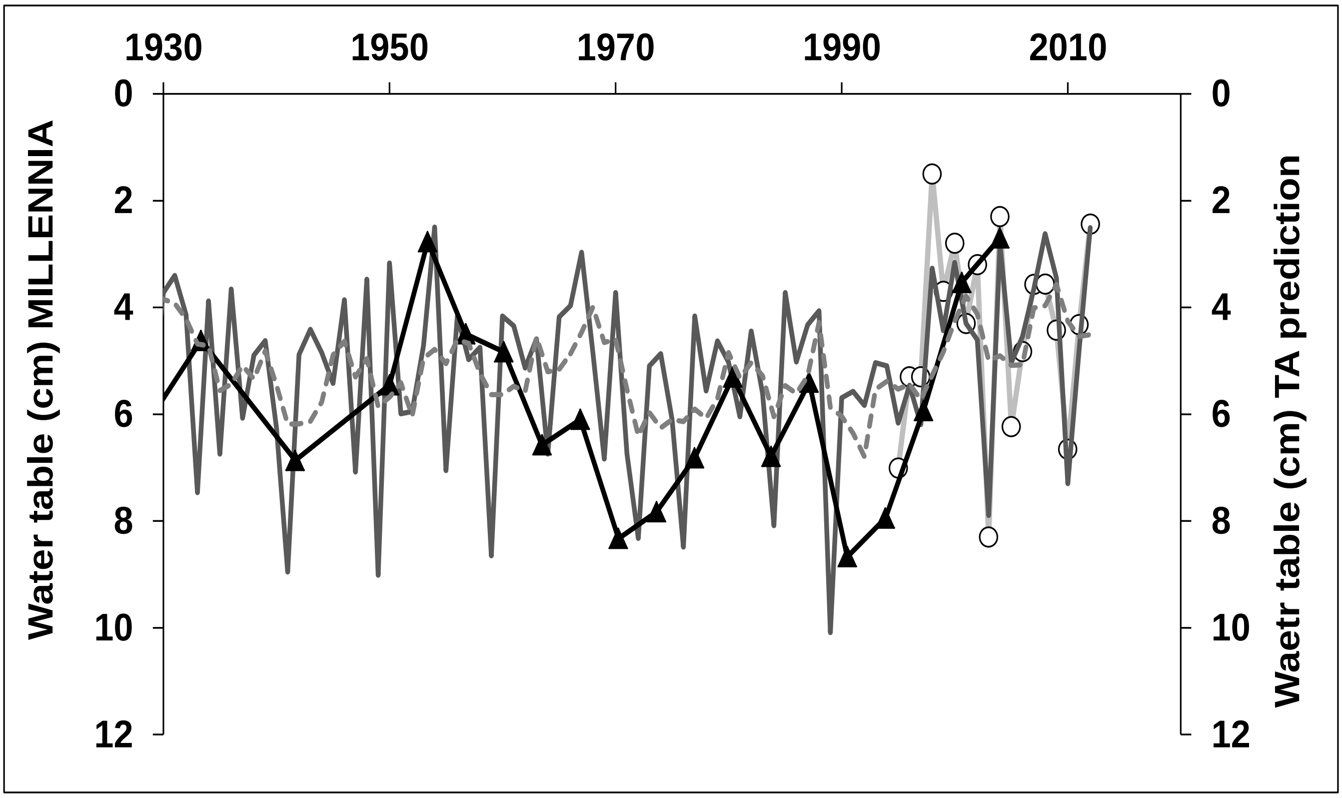


Figure A15.3 Annual water table (WTD) predictions (in the peat profile) for the Moor House NNR site since 1930 from the MILLENNIA model (dark grey lines, with 4-year average as dashed line) *versus* 4-yearly *testate amoebae* (TA) based predictions (black line) and actual annual site averages (white circles and light grey line) based on available continuous WTD readings (1995-2012) obtained from the ECN site (licence: ECN:AH2/14).

Using the available long-term climate data for a nearby Northern England peatland site (Morris et al., 2015) adjusted for Moor House (i.e. absolute for the long-term mean temperature and percentage for the total rainfall) together with ECN climate data since 1931 allowed comparing MILLENNIA model predicted WTD over an extended range (1750s till 2012) for which TA WTD reconstructions were available. The above graphic (**Figure A15.3**) shows the comparison between TA and model predicted WTD during the period of declining or no active management for grouse shooting (drainage or burning) for which reliable climatic records were available (i.e. ECN data).

Implementing grouse management (burning and drainage):

In order to highlight the importance of site history in determining current C sink strength a further model study was conducted for Moor House, which was a former shooting estate during 1942-1951 and grouse moor management scenarios reflected available site information (Rob Rose, CEH; personal communication), indicating a 20 year burn rotation with assumed associated drainage since 1850 (assumed first burn) till the 1950s. Burning was assumed to reduce net primary productivity (NPP) to 1% in the burnt year (with charcoal adding about 5% to an inert carbon pool; section 4.4.4 in the main report), subsequently recovering in a sigmoidal shape to 100% by either 5 or 10 years after burning (based on Heinemeyer et al., unpublished data). Drainage was assumed to reduce water tables on average by 5 cm, based on field evidence by Wilson et al. (2010), and to have started in 1830, before intensification of grouse shooting, to enable enhanced heather growth and drier access conditions for gamekeepers. Reduced WTDs were assumed to enhance decomposition and increase CO_2 but decrease CH_4 emissions similarly to model impacts of natural WTD changes (Heinemeyer et al., 2010). Drainage (grip) effectiveness was assumed to be at optimum for 25 years (renewed once in 1871 and then maintained at optimum until 1905, reflecting intense grouse shooting), declining to 60% over the subsequent 15 years and to 0% by 1955. Grazing pressure was assumed to be insignificant above 450 m (i.e. no reduction in NPP at the modelled altitude of 550 m a.s.l.).

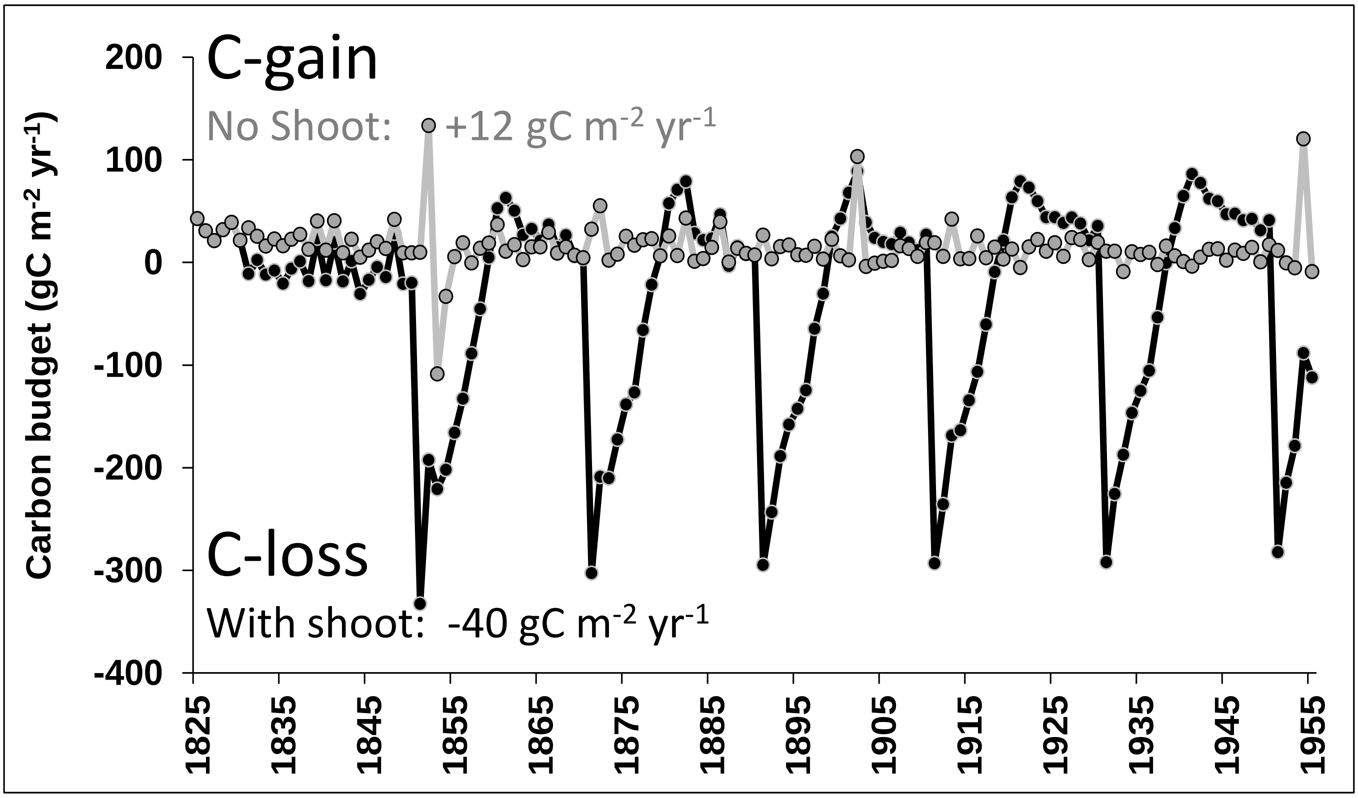


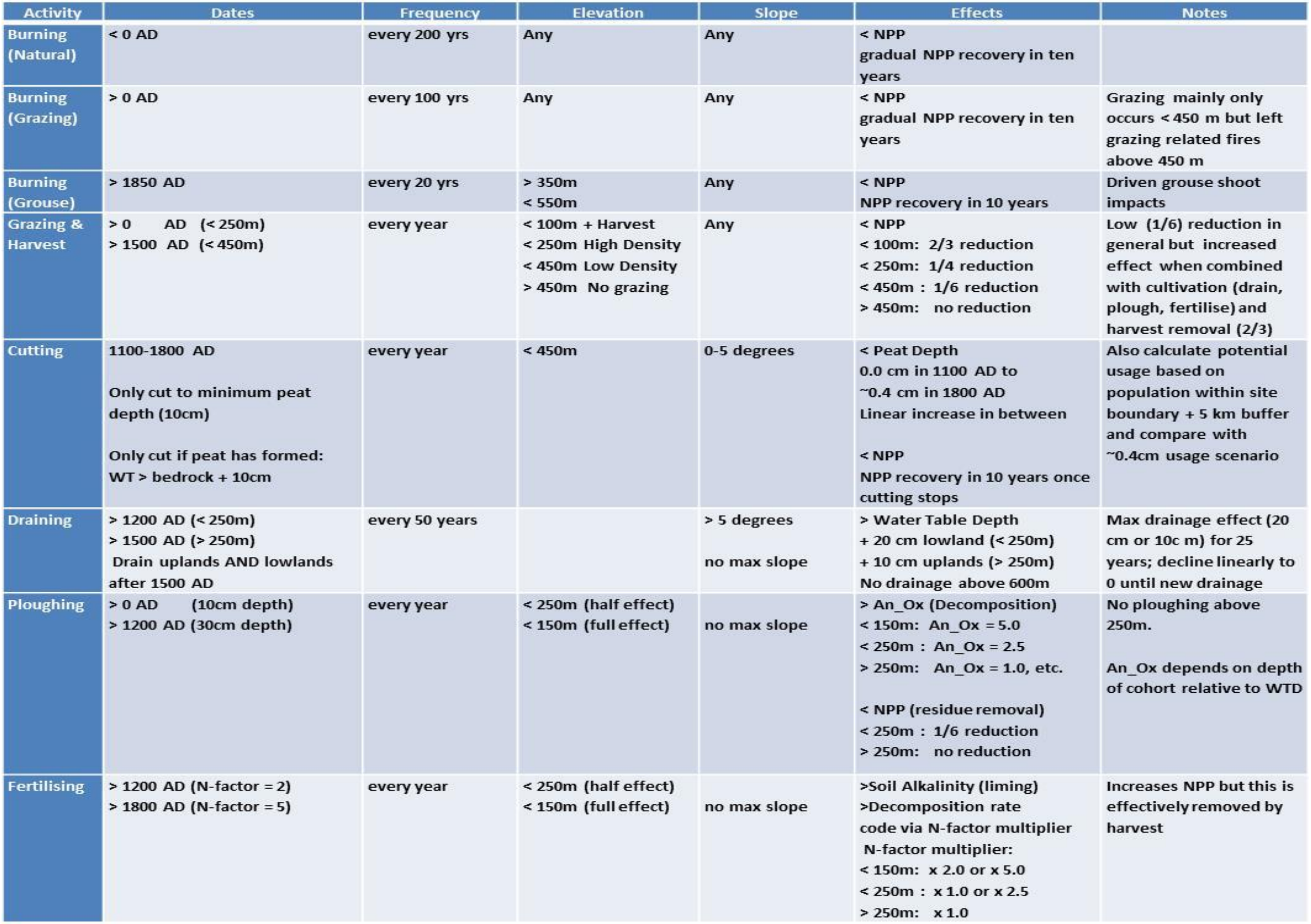
Figure A15.4 Predicted carbon budgets from the MILLENNIA model for the two management scenarios (no shoot vs. shoot) at Moor House NNR, considering drainage (~5 cm lower WTD) and over 10 years reduced net primary productivity (NPP) after burning (every 20 years) under grouse moor management during 1850s – 1920s. The mean annual C-gain (-shoot) or C-loss (+shoot) is indicated for the two scenarios.

The above graphic (**Figure A15.4**) shows the predicted C budgets during the grouse management period between the 1830s and the 1950s (with shoot, i.e. drainage and burning) compared to an unmanaged scenario (no shoot). Model predictions clearly indicate reduced C gain under a shoot scenario. However, this does not include any possible charcoal sequestration or impacts on decomposition processes (see Sections 4.3.3 and 4.4.2 in the main report).

Implementing potential past human impacts as land management scenarios:
A final model study was performed to consider the potential grouse moor management (burn and mow) impact on C storage in a wider land use management context, with potential further relevance for C storage across wider catchment areas including organo-mineral soils, some under current burning regime and most likely some of which were past peatlands (i.e. peat was lost due to human activity). Although peatland model predictions of potential peat depth would only apply to peatland areas and would become meaningless elsewhere, the litter decomposition based C stock predictions should still apply. Therefore, the MILLENNIA model was adapted to represent various management impacts on predicted C cycle processes and the resulting C stocks. This allowed comparing an unmanaged scenario predicting potential soil (peat) C accumulation to a likely managed scenario in relation to what could likely be observed today.

The following table (**Table A15.1**) provides an overview of the different human managements (i.e. burning, grazing, harvest, peat cutting, ploughing, fertilising) and their assumed impacts on specific model processes. Scenarios (**Table A15.1**) reflected population increase and improvements in agriculture with low intensity management before 1200 and increasingly upward management from 1500 onwards and general intensification in agriculture. Scenarios also considered elevation and slope conditions limiting the activity of certain managements to realistic/suitable areas. In addition some natural disturbance was assumed for natural fires (every 200 years).

Table A15.1 Outline of management scenario dates (period), frequencies and topographic limitations (elevation and slope ranges), together with the main effects (in relation to carbon accumulation) and general explanatory notes.



Activity	Dates	Frequency	Elevation	Slope	Effects	Notes
Burning (Natural)	< 0 AD	every 200 yrs	Any	Any	< NPP gradual NPP recovery in ten years	
Burning (Grazing)	> 0 AD	every 100 yrs	Any	Any	< NPP gradual NPP recovery in ten years	Grazing mainly only occurs < 450 m but left grazing related fires above 450 m
Burning (Grouse)	> 1850 AD	every 20 yrs	> 350m < 550m	Any	< NPP NPP recovery in 10 years	Driven grouse shoot impacts
Grazing & Harvest	> 0 AD (< 250m) > 1500 AD (< 450m)	every year	< 100m + Harvest < 250m High Density < 450m Low Density > 450m No grazing	Any	< NPP < 100m: 2/3 reduction < 250m: 1/4 reduction < 450m : 1/6 reduction > 450m: no reduction	Low (1/6) reduction in general but increased effect when combined with cultivation (drain, plough, fertilise) and harvest removal (2/3)
Cutting	1100-1800 AD Only cut to minimum peat depth (10cm) Only cut if peat has formed: WT > bedrock + 10cm	every year	< 450m	0-5 degrees	< Peat Depth 0.0 cm in 1100 AD to ~0.4 cm in 1800 AD Linear increase in between < NPP NPP recovery in 10 years once cutting stops	Also calculate potential usage based on population within site boundary + 5 km buffer and compare with ~0.4cm usage scenario
Draining	> 1200 AD (< 250m) > 1500 AD (> 250m) Drain uplands AND lowlands after 1500 AD	every 50 years		> 5 degrees no max slope	> Water Table Depth + 20 cm lowland (< 250m) + 10 cm uplands (> 250m) No drainage above 600m	Max drainage effect (20 cm or 10c m) for 25 years; decline linearly to 0 until new drainage
Ploughing	> 0 AD (10cm depth) > 1200 AD (30cm depth)	every year	< 250m (half effect) < 150m (full effect)	no max slope	> An_Ox (Decomposition) < 150m: An_Ox = 5.0 < 250m : An_Ox = 2.5 > 250m: An_Ox = 1.0, etc. < NPP (residue removal) < 250m : 1/6 reduction > 250m: no reduction	No ploughing above 250m. An_Ox depends on depth of cohort relative to WTD
Fertilising	> 1200 AD (N-factor = 2) > 1800 AD (N-factor = 5)	every year	< 250m (half effect) < 150m (full effect)	no max slope	>Soil Alkalinity (liming) >Decomposition rate code via N-factor multiplier N-factor multiplier: < 150m: x 2.0 or x 5.0 < 250m : x 1.0 or x 2.5 > 250m: x 1.0	Increases NPP but this is effectively removed by harvest

Moreover, a usual peat cutting depth of 40 cm was translated into an average annual long-term cutting depth impact across the landscape of about 0.4 cm (depending on total peat area available and overall demand for fuel) – otherwise, detailed spatial modelling would be needed to represent local peat cutting areas. Finally, burning, grazing and harvest as well as peat cutting reduced NPP inputs with a subsequent recovery period. The below graphic output (**Figure A15.5** and **Figure A15.6**) displays the impact of the assumed management/disturbance on the peat accumulation (carbon stocks).

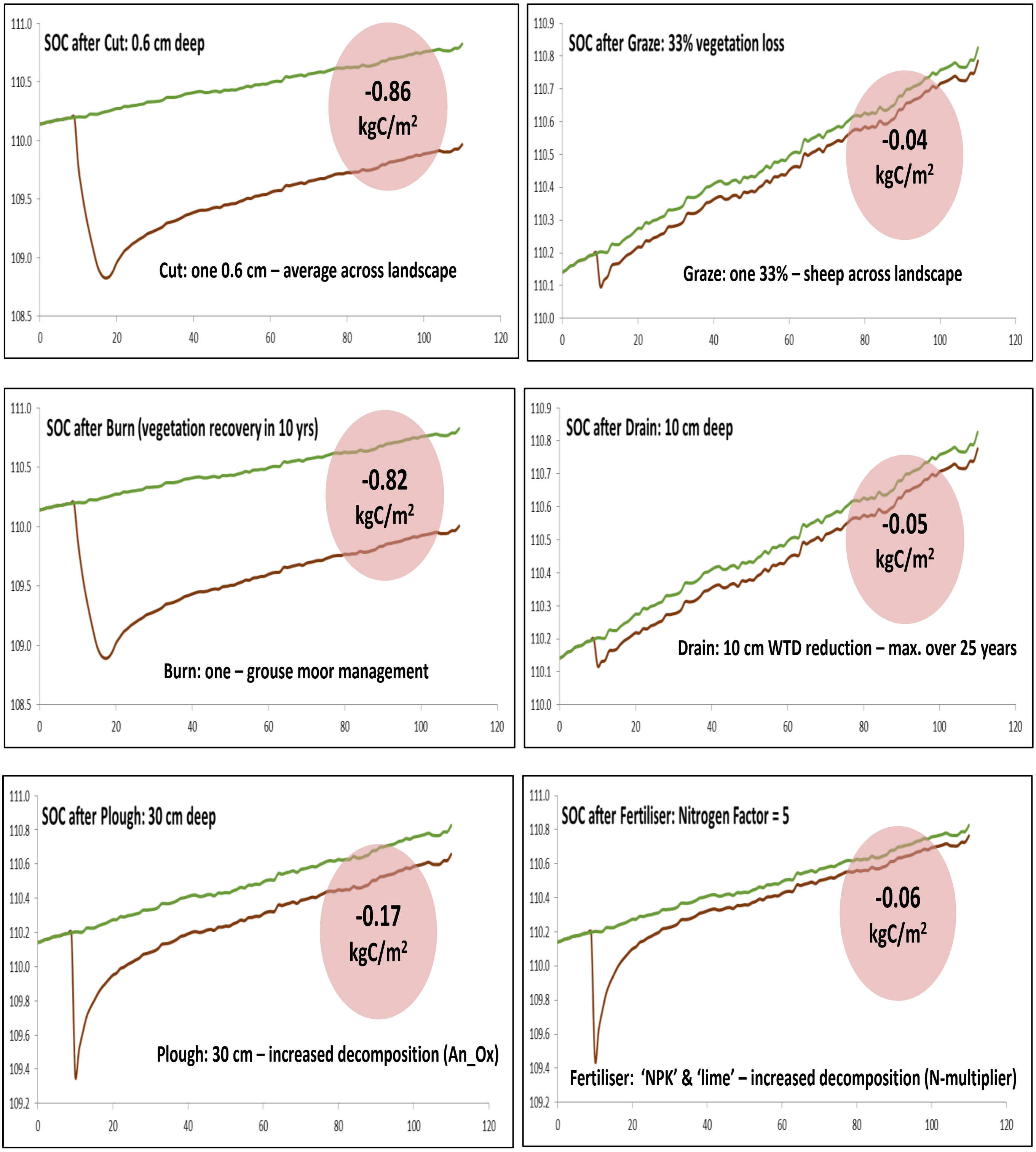


Figure A15.5 MILLENNIA model predictions of soil organic carbon (SOC) stocks at Moor House over time (years) for the main six individual management scenarios (**Table A15.1**) outlining the onset and its one-off effect on SOC compared to the unmanaged scenarios. Note the average (across a larger upland area) peat cutting scenario is equivalent to cutting 40 cm at one location. The overall one-off impact on carbon stocks over the entire peat accumulation period is shown inside the red circles. Note the slightly different y-axis scales.

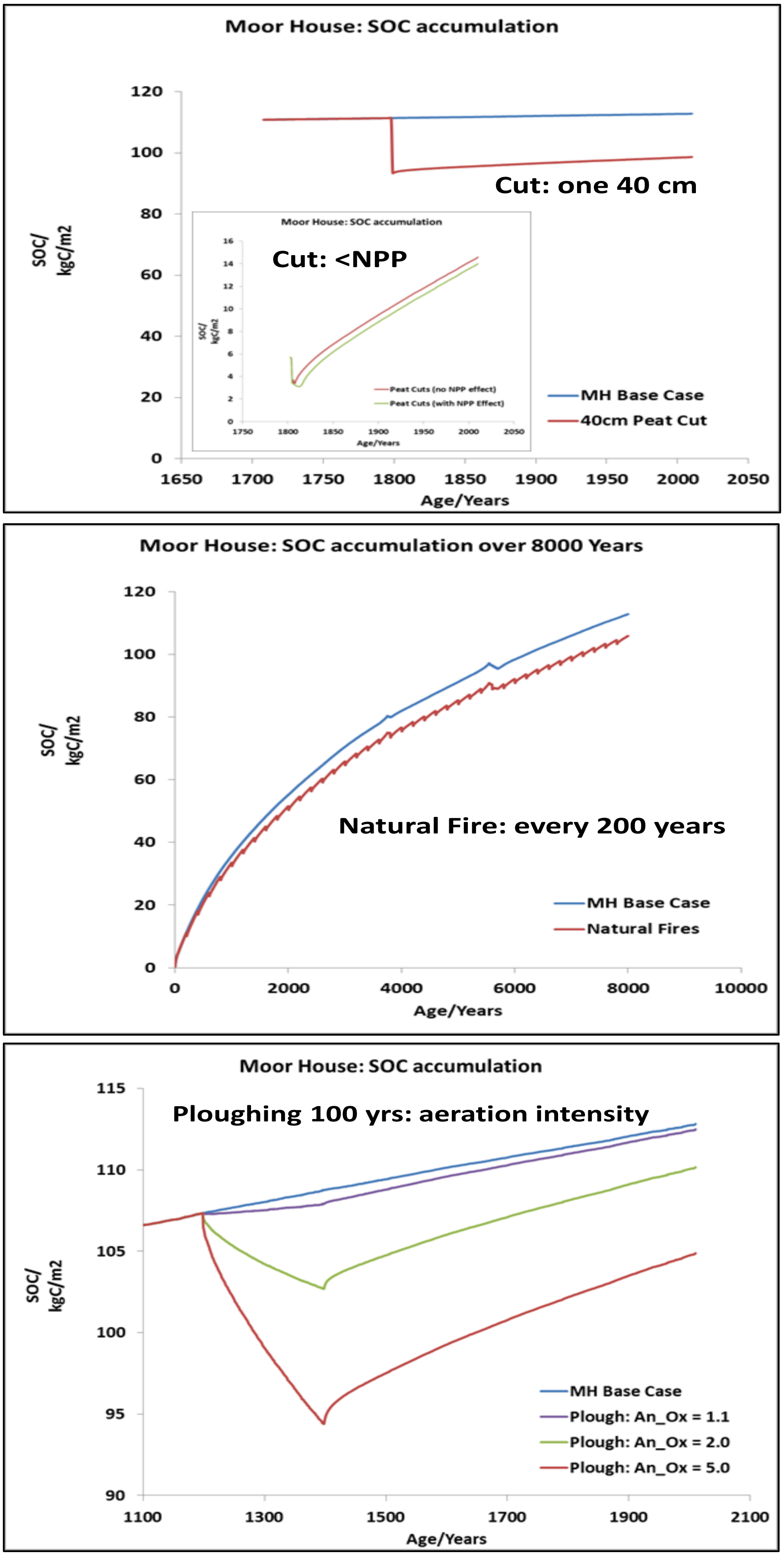


Figure A15.6 MILLENNIA model predictions of soil organic carbon (SOC) for three of the main six individual management scenarios at various degrees of implication (i.e. **TOP**: one-off cutting depth of 40 cm per location vs. no cutting; inset shows considering the impact of reduced net primary productivity (NPP) after cutting vs. no effect), occurrence (i.e. **MIDDLE**: natural fire of every 200 years vs. no fires), or intensity (i.e. **BOTTOM**: three levels of ploughing aeration impact – note the truncated y-axis) compared to the unmanaged scenarios (blue lines).

Whereas for some aspects, literature data were available, mostly impact estimates were based on non-peer-reviewed “grey” literature provided by Prof. Ian Rotherham (see reference list) and P.A. Ardron’s (1977) PhD thesis on the Peak District (UK) area and best estimates (for examples, no data was found on the general impact of grazing and harvest removal on NPP). However, the model scenarios are intended to only provide a first attempt in testing the hypothesis that potential past soil (peat) C stocks are much larger than anticipated by current stocks. This would then help to place any current peatland management effects on soil C stocks into the context of past and potential future changes across peatland areas and elsewhere.

Model scenarios were run over 8,000 years, reflecting a general onset of significant soil C accumulation in peatlands across the UK (e.g. Tallis, 1991). Adjusted climate data were used as in the previous section for Moor House but were adjusted for the respective site location’s long-term average climate (obtained from the UK’s MetOffice website). An unmanaged and managed scenario was run for each site (from South to North: Poundsgate, York, Hawes, Moor House, Otterburn, Kinnbrace; see **Figure 141** in the main report) for a 5 x 5 km area covering a range of combination of elevation, slope and aspect at a 50 x 50 m resolution.

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