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Late Holocene ecohydrological and carbon dynamics of a UK raised bog: impact of human activity and climate change

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ABSTRACT

Understanding the ecohydrological responses of peatlands to climate change is particularly challenging over the late Holocene owing to the confounding influence of anthropogenic activity. To address this, a core spanning the last ~2400 years from a raised bog in northern England was analysed using a comprehensive suite of proxy methods in an attempt to elucidate the drivers of change. A testate amoebae-based transfer function was used to quantitatively reconstruct changes in water table depth, supported by humification analysis and a plant macrofossil-derived hydroclimatic index. Pollen and plant macrofossil data were used to examine regional and local vegetation change, and human impacts were inferred from charcoal and geochemistry. Chronological control was achieved through a Bayesian age-depth model based on AMS radiocarbon dates and spheroidal carbonaceous particles, from which peat and carbon accumulation rates were calculated. Phases of both increased and decreased bog surface wetness (inferred effective precipitation) are present, with dry phases at *c.* AD 320–830, AD 920–1190 and AD 1850–present, and a marked period of increased effective precipitation at *c.* AD 1460–1850. Coherence with other records from across Northern Europe suggests that these episodes are primarily driven by allogenic climatic change. Periods of high bog surface wetness correspond to the Wolf, Spörer and Maunder sunspot activity minima, suggesting solar forcing was a significant driver of climate change over the last ~1000 years. Following the intensification of agriculture and industry over the last two centuries, the combined climatic and anthropogenic forcing effects become increasingly difficult to separate due to increases in atmospheric deposition of anthropogenically derived pollutants, fertilising compounds, and additions of wind-blown soil dust. We illustrate the need for multiproxy approaches based on high-resolution palaeoecology and geochemistry to examine the recent trajectories of peatlands.

1. Introduction

Peat-based hydrological reconstructions provide an important insight into climatic changes during the Holocene (Aaby, 1976; Blackford, 2000; Chambers and Charman, 2004; Barber, 2007; Chambers et al., 2012). Ombrotrophic peatlands represent very useful ecosystems for the investigation of past climate as precipitation is the sole source of water, thus surface hydrology is a function of effective precipitation (precipitation − evapotranspiration). There has been debate over whether the primary driver of bog surface wetness (BSW) is temperature (Schoning et al., 2005; Barber and Langdon, 2007) or summer water deficit (Charman et al., 2004; Charman, 2007). However, it has been suggested recently that climatic context has a major influence on drivers of BSW, temperature having more influence in a continental setting whereas summer water deficit has the strongest relationship with water table depth in oceanic regions (Lamentowicz et al., 2008). Charman et al. (2009) propose that UK peatland BSW is driven by variations in precipitation, relating primarily to the warm-season water deficit period.

Surface vegetation and microbiota are responsive to changes in effective precipitation, and a wide range of biological remains and geochemical signals are often preserved *in situ* within accumulating peat. Radiocarbon dating of above-ground plant remains in peat (e.g. *Sphagnum*) is also comparatively straightforward, allowing well-constrained reconstructions of Holocene palaeoenvironmental change (Aaby, 1976; Mauquoy et al., 2002). Good chronological control is an essential pre-requisite for meaningful reconstructions, allowing comparison of peat-based records with lacustrine, speleothem and ice core records (Barber, 2007; Swindles et al., 2010). However, separating climatic signals from the effects of human influence in ombrotrophic peatlands is a persistent problem

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(Chambers, 1993; Rydin and Jeglum, 2006). Direct anthropogenic impacts such as drainage, peat cutting, grazing, burning, or indirect influences such as surrounding land-use changes and atmospheric deposition can heavily influence the ecohydrology of peatland ecosystems (Blackford, 2000; Charman, 2002). For example, the landscape of the UK has been subject to increasing levels of anthropogenic influence since Mesolithic hunter–gatherers initiated landscape change as early as *c.* 7000 BC (Bush, 1988), as evidenced by charcoal layers found in early Holocene peats and lake deposits throughout the British uplands (Simmons and Innes, 1996). Thus, many peatlands have been influenced by climate change and human impacts for much of the Holocene.

Established methods for palaeohydrological reconstruction include testate amoebae-based transfer functions, plant macrofossil and humification analysis. Each proxy has specific strengths and weaknesses; for example, testate amoebae are particularly effective where peat stratigraphy is dominated by a single eurytypic *Sphagnum* species rendering the interpretation of humification and macrofossil analysis unreliable, and humification is useful where peat is highly decomposed (Blackford and Chambers, 1993; Caseldine et al., 2000; Barber et al., 2003; Langdon and Barber, 2005). Combining several proxies potentially gives more robust reconstructions, particularly when combined with proxies of human activities such as geochemical data and pollen analysis (e.g. Lomas-Clarke and Barber, 2007; Coombes et al., 2009; Lamentowicz et al., 2009; Schofield et al., 2010). However, studies of recent environmental change that utilise a comprehensive array of biological, geochemical and physical proxies in ombrotrophic peatlands are relatively uncommon (De Vleeschouwer et al., 2009; van der Knaap et al., 2011; De Vleeschouwer et al., 2012).

The drivers of ecohydrological change in peatlands during the late Holocene become increasingly convoluted as abrupt climatic changes occur contemporaneously with elevated levels of human impact, resulting in complex palaeoenvironmental signals. Therefore a need for a fully integrated approach to palaeoenvironmental reconstructions using multiple proxy methods and empirical evidence is apparent. This study presents a ~2400 year multiproxy surface wetness reconstruction from an ombrotrophic raised bog in northern England, UK. The palaeohydrological data is supplemented by a record of past regional and local vegetation changes, geochemical and physical/sedimentological data. The aim of this study is to present comprehensive multiproxy data from a north-western European raised bog so that drivers of change can be elucidated. The specific aims are to 1) reconstruct local and regional palaeoenvironmental changes for the last *c.* 2000 years; 2) identify major changes in bog surface wetness and compare the records inferred from three proxies; 3) determine the source and level of anthropogenic influence; 4) determine whether shifts in bog surface wetness and vegetation correlate with anthropogenic factors or climatic events.

2. Study site

Malham Tarn Moss (MTM) (Fig. 1) is a coalescence of three distinct ombrotrophic raised bogs (covering around 40 ha) that forms the major part of a diverse mire complex adjacent to Malham Tarn, a shallow marl lake in the Yorkshire Dales National Park, England (54°05′47″N, 002°10′30″W, 380 m asl.). MTM represents a suitable site for this investigation, as detailed historical records and archaeological data provide evidence of human activity around the area from the Mesolithic period onwards. High-quality climate data from local instrumentation and historical records of land management and agrarian activities are also available. In addition, there are several other palaeoenvironmental reconstructions from raised bogs in the north of England (and therefore within a similar climatic context) with which comparisons can be made.

The underlying geology is impermeable Silurian slates mostly covered by undulating glacio-fluvial deposits, with Carboniferous limestone surrounding the area. It is bordered by a broad belt of calcareous fen to the north/north-west and a narrower ‘lagg’ to the south/south-west that separate MTM from the surrounding agricultural rough pasture. The fens are fed by strongly calcareous waters draining from the surrounding limestone rocks. To the east, MTM borders directly onto the tarn. The bog stratigraphy indicates that marl sediments, deposited in open water, were succeeded by fen vegetation, evident in highly humified peat containing *Phragmites* and woody remains above the mineral substrate (Pigott and Pigott, 1959). The switch to bog vegetation occurred around 8000 years ago, as shown by subsequent *Sphagnum* peat. Ombrotrophic *Sphagnum austinii*-rich peat then accumulated up to a depth of 5–6 m over much of the bog (Pigott and Pigott, 1959; Piggott and Piggott, 1963).

In terms of human impact on Tarn Moss, archaeological artefacts attest to the regular presence of Mesolithic hunter-gathers around Malham Tarn, and settlement during the Bronze Age (Raistrick and Holmes, 1962). The pollen record of Pigott and Pigott (1959) indicates regional woodland clearance from the late Neolithic/early Bronze Age period onwards. It is likely that animals were grazed on and around MTM throughout most of the historical period, and an estate book of the 1780s shows the fen areas divided into agricultural compartments (Cooper and Proctor, 1998). The level of the tarn was raised in 1791 by around 1.3 m (Holmes, 1965) causing rapid erosion of the peat rand, resulting in a vertical exposed peat face several metres high. Peat rand erosion rates have been estimated at ~0.07 m y^{-1} (Pentecost, 2000). Surface patterns on MTM suggest part of the mire has been drained and cut for peat, though no written records have yet been found (Pentecost, 2000).

3. Methods

3.1. Field sampling

A 100 cm-long peat sequence was extracted from Malham Tarn Moss using a Russian-type D section corer (Jowsey, 1966) with a 50 × 5 cm chamber, using the parallel hole method and 20 cm overlap. Cores were extracted from a lawn microform (De Vleeschouwer et al., 2010) on the eastern cupola. Cores were placed in plastic guttering of a similar diameter to prevent movement in transit, wrapped in cling film, and stored at 4 °C prior to laboratory analysis. A description of the core lithostratigraphy was carried out before sub-sampling following Tröels-Smith (1955).

3.2. Dating and age-depth model

Spheroidal Carbonaceous Particles (SCPs) are a component of fly-ash generated during high temperature combustion of fossil fuels, and therefore represent a stratigraphic age-equivalent marker in recent (post industrial revolution) peat profiles (Rose, 1990). Contiguous 1 cm sub-samples were taken from the top 20 cm of the profile for SCP analysis and prepared using acid digestion (Swindles, 2010). A known mass of material was slide mounted in Naphrax and the number of SCPs counted at 400× magnification. The resulting count is expressed as the number of SCPs per gram of dry peat. Calendar ages were assigned to the start of SCPs in the profile, the rapid rise, and peak concentration using established comparative data from UK lake profiles dated by radiometric methods (Rose et al., 1995; Rose and Appleby, 2005).

Twelve samples from the rest of the peat profile were selected for Accelerator Mass Spectrometry ^{14}C dating at the Queen’s University Belfast ^{14}CHRONO laboratory. Sample preparation followed the recommendations of Piotrowska et al. (2011). Where present,