Holocene environmental change: contributions from the peatland archive

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Abstract: Peatlands provide a widespread terrestrial archive of Holocene environmental change. The taphonomy of peat is relatively simple, the range of evidence and proxies is wide, and dating methods have become more accurate and precise, such that the potential temporal resolution of records is high. Although long established, the use of peatlands as archives of Holocene change has undergone phases of decline and resurgence. Here, the variable exploitation of the peat archive is explored, and recent developments in peatland science as applied to Holocene records are reviewed with reference to the collection of papers in this Special Issue of *The Holocene*, which are arranged in four key themes: (1) records of Holocene climatic change; (2) peatland dynamics; (3) carbon accumulation; and (4) implications for conservation and management. The changing acceptance of peatlands as archives of Holocene climatic change is attributed to developments in understanding of the peatland system and geographical differences in the history of Holocene research. Recent developments in biological and geochemical proxies combined with improvements in chronological techniques have resulted in renewed interest in peatland palaeoclimate records. Peatlands are an important global carbon pool and it is clear that climate has influenced the efficiency of long-term carbon sequestration by these systems. Climate has also had an impact on the biodiversity and condition of peatlands, which creates problems in discerning cause and effect in sites affected by human activities, and in targeting remedial management. It is concluded that particular strengths of the archive are the current diversity of peat-based palaeoenvironmental research and the potential for multiproxy analyses to be applied to a range of research issues. Mire-based investigations can complement research in other realms, and are deserving of greater attention from researchers of other archives.

Key words: Mires, peatland archives, proxy climate records, carbon cycling, climatic change, environmental change, environmental management, Holocene.

Introduction

Peatlands are areas of landscape that have a naturally accumulated layer of organic material at the surface. This accumulation, which is largely autochthonous and has relatively simple taphonomy, can be examined in detail for its palaeoenvironmental record. Gore (1983a) used the umbrella term 'mire' to encompass all ecosystems described in English usage as swamp, bog, fen, moor, muskeg and peatland, although others (e.g., Charman, 2002) reserve the term 'mire' for areas of active peat accumulation. The difference is largely immaterial for Holocene researchers, except to note that mires ('active peatlands') offer palaeoenvironmental records of recent as well as more ancient conditions.

Peatlands cover around 4×10^6 km^2 of the world's surface (Charman, 2002; Joosten and Clarke, 2002). Many are dispersed in relatively small patches, but there are extensive areas in the cooler climate areas of Canada, Scandinavia and northern Europe, including Russia and the Baltic states. Southern Hemisphere peatlands are more restricted, but notable peatland complexes exist in southern Argentina and Chile, the Falkland Islands, New Zealand and the Subantarctic islands, while tropical forested peatlands are extensive in Indonesia and peninsular Malaysia (see Gore, 1983a; 1983b; Lappalainen, 1996).

Peatlands possess several advantages for Holocene research: their terrestrial location makes them generally more accessible to researchers than ice sheets or oceans; they are more readily and economically cored than ice, ocean or lake bottoms; they have a greater range of proxy measures for climate than trees; and their autochthonous mode of production and accumulation renders them less susceptible to the redeposition that can bedevil some lake-sediment sequences. The ability of many mires to accumulate autochthonous material sequentially, to sequester carbon for thousands of years, and to contain within them a detailed archive of local and regional vegetation history makes peatlands amenable for study of environmental and climatic changes over Holocene and (occasionally) longer timescales (Blackford, 1993; Charman, 2002). For more than half a century, following the pioneering work of von Post (1916), Godwin (1940) and Jessen (1949) in

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Table 1 Main laboratory techniques used to investigate the palaeoenvironmental archive in peats, illustrating the range of examples presented in this issue

Technique	Purpose	Example in this issue
Biological		
Palynology	Reconstruction of vegetational history: site and region	Bunting and Tipping; Roos-Barraclough *et al.*
Plant macrofossil analysis	Site vegetational history; proxy-climate study	Hughes and Barber; Langdon and Barber; Mauquoy *et al.*; Blaauw *et al.*, Davis and Wilkinson
Dendroecology and dendroclimatology	Reconstructing tree growth on mires; proxy-climate study	Mighall *et al.*
Charcoal analysis	Fire history	Bunting and Tipping
Insect analysis (esp. Coleoptera)	Ecological history and proxy-climate study	Whitehouse
Other non-pollen microfossils (NPMs)	Ecological conditions; fire and grazing history; proxy-climate study	Blaauw *et al.*
Testate amoebae analysis	Hydrology and proxy-climate study	Hendon and Charman; Davis and Wilkinson; Langdon and Barber
Physical and chemical		
Loss-on-ignition	To identify allochthonous input for site and land-use history	Bunting and Tipping
Carbon and C:N ratios	Carbon cycling	Karofeld; Malmer and Wallen; Mauquoy *et al.*
Magnetic susceptibility	To indicate allochthonous components; core correlation	–
X-ray	To identify mineral inwash and tephra layers	–
Bulk density	Accumulation rate; carbon studies	Karofeld; Malmer and Wallen; Roos-Barraclough *et al.*; Mauquoy *et al.*
Determination of peat humification	Proxy-climate study	Roos-Barraclough *et al.*; Langdon and Barber
Inorganic elemental chemistry	Pollution studies; land-use history; nutrient study	Mighall *et al.*
Organic biomolecules	Proxy-climate study; vegetational history in highly humified peats	–
Stable isotope analysis	Proxy-climate study, *inter alia*	
Dating		
Tephrostratigraphy; tephrochronology	Identifying isochrons for dating and inter-core correlation	Langdon and Barber
Radiocarbon – conventional	Dating various fractions of peats	Roos-Barraclough *et al.* (some); Whitehouse; Bunting and Tipping; Hughes and Barber
Radiocarbon – AMS	Dating peat components and for wiggle-match dating	Blaauw *et al.*; Mauquoy *et al.*; Roos-Barraclough *et al.*; Whitehouse (some); Bunting and Tipping (some)
Short-lived radionuclides (e.g., ^{210}Pb, ^{241}Am, ^{137}Cs)	Dating recent peat accumulation	Hendon and Charman; Roos-Barraclough *et al.*
Spheroidal carbonaceous particles (SCPs)	Dating recent peat accumulation in areas with documented industrial history	Hendon and Charman
Dendrochronology	Dating timbers and tree layers in peats; compiling site and regional chronologies	Mighall *et al.*
Recent plant incremental growth, e.g., moss or *Drosera*	Dating recent few years of peat growth in acrotelm	Karofeld

northwest Europe, palynologists have used them to chronicle vegetation history, and increasingly they have been used as 'off-site' records to provide the environmental setting for archaeological sites.

Peatland researchers can now draw upon a wide range of biological, physical and geochemical analyses and dating methods (Table 1), which can be combined in multiproxy studies of climate and environmental history at high resolution. For example, the increasing use of wiggle-matched AMS ^{14}C dates and tephrochronology means that the precision and accuracy now achievable in Holocene peat-based chronologies is much higher than in the pioneer studies. Indeed, temporal resolution of records can be sub-decadal, especially in recent peats (cf. van der Knapp and van Leeuwen, 2003).

Despite these apparent advantages, peatland archives have not yet attained the same global significance as those of ice cores, ocean cores, tree rings or even lake sediments. This Special Issue has therefore been compiled with a view to bringing some of the wide range of current palaeoenvironmental research on peatlands to a wider audience. Papers that exemplify recent developments in peatland research have been arranged here in four key themes: (1) records of Holocene climatic change; (2) peatland dynamics; (3) carbon accumulation; and (4) implications for conservation and management. Below, we highlight the potential contributions of peatland archives to Holocene science in these theme areas with reference to recent research and to the range of papers contained herein.

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(1) Records of Holocene climatic change

In northwest Europe it was peatlands that provided the evidence for the first systematic Holocene climatostratigraphy. This was based on the pioneering work of Blytt (1876) and Sernander (1908) in Scandinavia and became enshrined in the Blytt-Sernander scheme. Its notion of broad climate periods for the Holocene has since been acknowledged as too simplistic, although its terminology survives in a formal chronostratigraphy for parts of Scandinavia (Mangerud *et al.*, 1974) and less formally elsewhere in Europe. What is noteworthy is that it was a peatland stratigraphic record that first pointed to considerable climatic changes during the Holocene – features of the last 12 000 years that the first ice- and ocean-core records seemed to deny, but which more recent detailed records have since acknowledged.

Although there is a century-long history to peatland proxy climate research, peat-based records do not feature in the second edition of Bradley's (2001) otherwise excellent *Paleoclimatology* text, nor do they appear prominently in Ruddiman's (2001) compendium of Earth's climate. Within palaeoclimatology, therefore, peatlands receive no or rather little attention compared to other archives. Given their widespread distribution, it is remarkable that peatlands do not figure more prominently as global archives of Holocene environmental change. That peatlands have not been at the forefront of global palaeoclimatology is, we suspect, fourfold: (1) most peat stratigraphers from the second half of the twentieth century served their apprenticeship in palynology, which is a region-specific science and so not one that immediately promotes palynologists onto the world stage; (2) the bulk of proxy climate work from peatlands has been conducted in northwest Europe, and until relatively recently other regions of the world had been ignored; (3) in the USA particularly, the primary Holocene continental palaeoenvironmental archive has been lakes, rather than peats, and peat-based research has been a minority interest in a nation where some of the leading palaeoclimatologists reside; (4) study of the climate history from peatlands was largely in abeyance for 50 years in the mid-twentieth century, allegedly owing to a misconception as to how peat bogs grow (Backeus, 1990).

To claim a 50-year lacuna in peat-climate science may overstate the case somewhat, but there has nevertheless been a long-held view that mires grow primarily through autogenic processes rather than being controlled by allogenic climate – a view that was challenged and falsified by Barber (1981) in Britain, and examined quizzically by Frenzel (1983) in continental Europe. In Scandinavia, an early emphasis on autogenic succession (Osvald, 1923) has long influenced research, and the internal dynamics of peatlands pose challenging questions (see Seppä, 2002) for those who maintain that the dominant control on peat accumulation is climate. Nevertheless, since the mid-1970s, methods of peat humification (Aaby and Tauber, 1975; Blackford and Chambers, 1993) and quantitative macro- and microfossil analysis (Haslam, 1987; Hughes *et al.*, 2000; Charman and Warner, 1997) have been used to reconstruct past climate in northwest Europe at the site (Nilssen and Vorren, 1991; Barber *et al.*, 1994; Chambers *et al.*, 1997; Charman *et al.*, 1999; Charman and Hendon, 2000; Mitchell *et al.*, 2001), inter-site (Aaby, 1976; Barber *et al.*, 1998; Blackford and Chambers, 1995; Mauquoy and Barber, 1999; Hendon *et al.*, 2001; Mauquoy *et al.*, 2002) and regional (Blackford and Chambers, 1991; Barber *et al.*, 1999; 2000; Chambers and Blackford, 2001) scales. The quantity of northwest European work has yet to be matched elsewhere.

The range of techniques (Table 1) has grown in recent decades, such that investigations can now be multiproxy. Although the chemical derivation of peat humification data is not fully understood (see Caseldine *et al.*, 2000), and some of the proxy climate data sets may not be independent of each other – for example, there is the possibility of a plant-species signal within peat-humification data (Chambers *et al.*, 1997) – they can nevertheless be obtained at high resolution and interpreted through comparison with contemporary mire communities. For example, detailed ecological data have allowed development of transfer functions to infer past mean annual water-table depths from fossil assemblages of testate amoebae (Woodland *et al.*, 1998).

Most of the proxy climate indicators have a strong hydrological component, but some may be indicative of temperature changes. Early work in Europe (Brenninkmeijer *et al.*, 1982; Dupont and Brenninkmeijer, 1984; Dupont, 1985) showed the potential for bulk stable-isotope measures from ombrotrophic mires to yield proxy climate data. However, the complex signals incorporated in peats of mixed botanical composition meant that these early attempts were not immediately pursued in northwest Europe. In other regions, such as China (Hong *et al.*, 2000; 2001) and South America (White *et al.*, 1994; Pendall *et al.*, 2001), isotopic records with less complex signals have been derived from monospecific fractions of peat. In the more complex peat types of Europe, chemical biomarkers have been sought that might reflect changes in plant communities and so could enable detection of vegetational change in highly decayed peats. Although early work to derive proxy climate biomarkers was not immediately successful (Ficken *et al.*, 1998), subsequent attempts (Nott *et al.*, 2000; Pancost *et al.*, 2000) have shown more promise. Recently, Xie *et al.* (2000) showed that stable isotopes of biomolecules are strongly correlated to instrumental temperature data, offering the possibility of a new, independent continuous temperature record from peatlands.

The recent emphasis being placed by peatland researchers on proxy climate records is manifest not just for Europe but also for Asia (Sukumar *et al.*, 1993; Rajagopalan *et al.*, 1997; 1999; Hong *et al.*, 2000), Australasia (McGlone and Wilmshurst, 1999; Wilmshurst *et al.*, 2003), North America (Halsey *et al.*, 1998; Campbell *et al.*, 2000) and South America (Pendall *et al.*, 2001). Indeed, van Geel *et al.* (2000) hypothesize evidence for global teleconnections using peat-based and other palaeoenvironmental archives.

Four papers in this issue illustrate aspects of developments in the dating of peat palaeoclimate records. Roos-Barraclough *et al.* present results of a lengthy peat humification record from Switzerland. The record is at high resolution (approximately 20 cal. yrs per sample), well dated by both conventional and AMS ^{14}C techniques and by short-lived radioisotopes, and the results are compared with proxies from other archives and proxies from other peatlands in the same region. Langdon and Barber take chronological precision a stage further by focusing on particular periods where tephra layers facilitate geographical comparisons between sites. Their multiproxy analyses indicate regional differences in climatic change over a north–south axis within Scotland, a relatively small region. Finally, Blaauw *et al.* and Mauquoy *et al.* use wiggle-matched ^{14}C dates to provide a precise chronology for proxy surface-wetness data from mires over recent centuries. These two papers provide further evidence of solar forcing of climatic change in the mid- and late Holocene.

(2) Peatland dynamics

The dynamics of peat-bog growth has long been of interest to researchers (e.g., Osvald, 1923; Clymo, 1984; Svensson, 1988; Belyea and Clymo, 2001). Early work on peat stratigraphy in mainland Europe (Weber, 1902; Granlund, 1932) was succeeded by an emphasis on recurrence horizons (e.g., Lundqvist, 1962), and later the use of radiocarbon dating to determine peat initiation and spread (e.g., Korhola, 1992). However, the spread of mires may itself create consequences for peatland palynologists. Here, Bunting and Tipping show how the changing pollen-source area

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of a mire varies considerably during the development of the peatland, thus altering the way the palynological record should be viewed at different times. Changes in taphonomic processes may also affect other records, such as those of heavy-metal deposition (e.g., Shotyk *et al.*, 1998).

One of the key issues in understanding the growth of peatlands concerns the way in which some mires undergo a fundamental hydrological change from a minerotrophic system fed by groundwater to an ombrotrophic system fed only by precipitation. Here, Hughes and Barber show that there may be different pathways to ombrotrophy. One route requires the prevalence of very wet oceanic conditions, but another may involve first a drying of the peatland creating a more impermeable surface and eventually greater waterlogging through changes in hydraulic conductivity.

One area of Holocene peatland palaeoecology in which there has been relatively little work is that of palaeoentomology. Here, however, Whitehouse demonstrates how analyses of beetle remains can provide a complementary source of data to palynology. In particular, the dynamics of an equivocal *Pinus* pollen record at a site in eastern England are illuminated by the beetle evidence, which shows quite clearly that local populations of the tree survived. It appears from this study that Coleopteran data from Holocene peat sequences primarily reflect local edaphic factors (see also Lavoie *et al.*, 1997), and this contrasts with the well-established use of Coleoptera from sediments of Lateglacial age to provide data on regional climatic change (e.g., Atkinson *et al.*, 1987).

A different approach to investigating ancient pine populations on mires is provided by Mighall *et al.*, who suggest that the demise of pine at a site in western Ireland was occasioned by an increase in mire surface wetness, coupled with a period of associated nutrient deficiency, which prevented seedling establishment.

(3) Carbon accumulation

In recent years, spurred by the emphasis on contemporary 'global warming', a particular focus has been on calculation of the carbon balance of peatlands by various means e.g., Gorham, 1991; Martikainen *et al.*, 1995; Korhola *et al.*, 1996; Mäkilä, 1997; Clymo *et al.*, 1998; Alm *et al.*, 1999; Kuder and Kruge, 2001). From southern Sweden, Malmer and Wallen report a decline in net carbon accumulation over the past millennium, in contrast to subalpine mires where carbon-accumulation rates have remained constant. An example of a small-scale phenomenon with a potentially large influence on mire carbon accumulation is that explored by Karofeld. His work on Estonian mires indicates that mud-bottom hollows are microhabitats where net carbon loss is occurring at a surprising rate. The cumulative losses from such features may be important in calculating mire carbon balance. In addition to reviewing the peatland records of climatic change and solar variability in sequences dated by wiggle-matched radiocarbon dates, Mauquoy *et al.* provide new information on carbon-accumulation rates in relation to 'Little Ice Age' climatic deterioration. At the sites studied in England and Denmark, carbon-accumulation rates apparently declined during this period.

(4) Implications for conservation and management

Peatland conservation has received much attention in recent years. This is partly in direct response to the increased rate of destruction of peatlands by human agency, but it also reflects an acknowledgement that mires are important pools of specialized species and plant communities. The value of peatlands extends beyond this to aesthetic and functional qualities (Joosten and Clarke, 2002) but much of the conservation effort is presently directed to preserving biodiversity of species, communities and sites. To conserve an ecosystem requires an understanding of all influencing factors. In the case of peatlands in northwest Europe, much attention has been focused not simply on conserving existing sites but also on restoring damaged sites (Stoneman and Brooks, 1997; Heathwaite *et al.*, 1993). Most of these efforts are designed to mitigate the obvious damage of drainage, peat harvesting or afforestation, and it has been assumed that climate plays only a minor role in the timescales involved. However, evidence is now emerging that some peatlands have undergone significant change in the last century that is more likely to be caused by climate than human perturbation. Here, Hendon and Charman provide the first detailed hydrological reconstruction for this period to test hypotheses of direct (non-climatic) human impacts on peatlands in northern England. Their findings demonstrate that water tables declined before the suggested human impacts began, and that climatic change may be the one remaining factor than can satisfactorily explain the observations.

An issue to emerge from much palaeoecological research is the extent to which ecosystems can ever be considered 'natural'. For example, Segerström *et al.* (1994) show that 'ancient' swamp forest in Sweden was under cultivation only 500 years ago. The concept of 'naturalness' has important implications for establishing the targeted end-point in attempts at habitat restoration or creation. Here, Davis and Wilkinson argue from their work on damaged lowland mires in northwest England that some sites have been sufficiently variable in the past to imply that a greater variety of end-points should be acceptable, as compared with those of 'undamaged' systems. Similar ecosystem dynamism is displayed in other peatland habitats when long-term perspectives are taken (cf. Chambers *et al.*, 1999), which shows the value of peatland palaeoecological studies for informing the site-management process.

Conclusions

Palaeoenvironmental evidence from peatlands testifies both to autogenic change within wetlands and to externally driven changes, including abrupt climatic shifts in the Holocene. Particular strengths are the current diversity of peat-based palaeoenvironmental research, the widespread and relatively accessible range of sites, improvements in applicable dating methods, and the capacity for multiproxy analyses of peat components. For Holocene climate reconstruction, peatland archives can complement others by giving different perspectives on the magnitude, rate, frequency and causes of past and contemporary climatic change. They deserve greater attention from researchers of those other archives. In addition, studies of peatlands provide data on the role of mires as global carbon pools and as reservoirs of biodiversity. Palaeoecological studies of peatlands also provide insights into the development of mires and so can also be used to broaden the management vision for conservation objectives for wetland habitats.

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