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Ecohydrological feedbacks confound peat-based climate reconstructions

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[1] Water-table reconstructions from Holocene peatlands are increasingly being used as indicators of terrestrial palaeoclimate in many regions of the world. However, the links between peatland water tables, climate, and long-term peatland development are poorly understood. Here we use a combination of high-resolution proxy climate data and a model of long-term peatland development to examine the relationship between rapid hydrological fluctuations in peatlands and climatic forcing. We show that changes in water-table depth can occur independently of climate forcing. Ecohydrological feedbacks inherent in peatland development can lead to a degree of homeostasis that partially disconnects peatland water-table behaviour from external climatic influences. We conclude by suggesting that further work needs to be done before peat-based climate reconstructions can be used to test climate models. **Citation:** Swindles, G. T., P. J. Morris, A. J. Baird, M. Blaauw, and G. Plunkett (2012), Ecohydrological feedbacks confound peat-based climate reconstructions, *Geophys. Res. Lett.*, *39*, L11401, doi:10.1029/2012GL051500.

1. Introduction

[2] There has been a proliferation of peat-based palaeoclimate studies in recent decades, and peat-based reconstructions have become one of the most common types of terrestrial palaeoclimate archive in some regions [e.g., *Charman et al.*, 2006]. This popularity attests to an increasing acceptance of peatlands as reliable archives of Holocene climate change [*Blackford*, 2000; *Chambers and Charman*, 2004], but also demands that the assumptions that underpin the methods involved are appraised critically.

[3] Recent work in NW Europe has suggested that reconstructions of peatland water tables from testate amoebae assemblages indicate changes in effective precipitation (precipitation minus evapotranspiration), relating primarily to the summer water deficit period [*Charman*, 2007; *Swindles et al.*, 2010]. The use of peat stratigraphy for palaeoclimatic reconstruction relies on two broad assumptions. Firstly, that measurements of plant macrofossil assemblages, peat humification, and testate amoebae provide reliable proxies for past water-table behaviour in peatlands. Secondly, that peatland water tables, particularly in ombrotrophic bogs, respond consistently and predictably to climatic conditions. While there is strong theoretical and observational evidence in support of the first assumption [*Woodland et al.*, 1998; *Väliranta et al.*, 2007], we question the validity of the second assumption, echoing earlier warnings [*Aaby*, 1976; *Barber*, 1981].

[4] Peat deposits are not static, inert receptacles of palaeoclimatic proxy information. Rather, peatlands and their constituent soils are dynamic ecohydrological systems, the behaviour of which is often complex and regulated by a network of cross-scale feedbacks between peat formation, decomposition, and drainage [*Belyea and Baird*, 2006; *Frolking et al.*, 2010; *Morris et al.*, 2011]. As such, hydrological transitions in peatlands can occur with weak climate forcing [*Belyea and Malmer*, 2004; *Belyea*, 2009]. It is also evident that, although there are some clear similarities between peat-based proxy climate records within a region, there are also marked differences (Figure 1). Such differences may be explained by i) internal peatland dynamics and feedbacks; ii) proxy responses that are non-linear, complacent, or related to non-climatic factors; and iii) chronological (dating) errors.

[5] While it seems that some shifts in reconstructed water tables do reflect climatic signals, this may not always be the case, and it is necessary to examine the scenarios leading to changes in peatland palaeo-water tables and the relative influence of autogenic (internal) and allogenic (external) processes. Here we present one such examination. Using well-dated proxy data from a typical northern peatland and a simple ecohydrological model of peatland development, we investigate whether shifts to both wetter and drier conditions in peat-based palaeohydrological records are caused by climatic change or internal ecohydrological mechanisms (or both) within a peatland.

2. Method

[6] Malham Tarn Moss (MTM) is a small (~30 ha) upland raised bog at an altitude of 377 m above sea level in North Yorkshire, England. Multiproxy palaeoecological data (testate amoebae and cladocera, plant macrofossils, pollen, spore and charcoal, loss-on-ignition, peat humification and $\delta^{13}C$) were used to examine the nature of stratigraphic changes in a visible peat section at MTM. We applied a transfer function based on weighted-averaging regression to the testate amoebae data to generate a quantitative water-table reconstruction, and used bootstrapping to calculate sample-specific errors [*Charman et al.*, 2007]. Bayesian modelling was used to produce an age-depth model with quantified chronological uncertainties [*Blaauw and Christen*, 2011]. We used Model 3 of *Morris et al.* [2011] to simulate a

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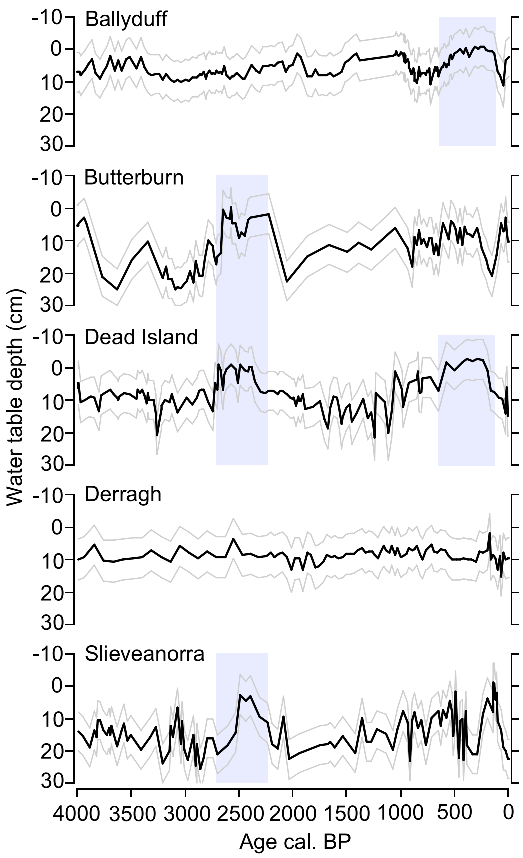

Figure 1. Quantitative 4,000-year water-table reconstructions from five peatlands in the UK and Ireland. The sites comprise: Ballyduff - County Tipperary, Ireland (D. Charman et al., unpublished data, 2012); Butterburn - Cumbria, England [*Mauquoy et al.*, 2008]; Dead Island - County Londonderry, Northern Ireland [*Swindles et al.*, 2010]; Derragh – County Longford, Ireland [*Langdon et al.*, 2012]; Slieveanorra - County Antrim, Northern Ireland [*Swindles et al.*, 2010]. All reconstructions are based on a European testate amoebae-hydrology transfer function [*Charman et al.*, 2007]. Sample-specific errors were generated through 1,000 bootstrap cycles. The chronologies are based mostly on radiocarbon dating, although tephra layers were also used to constrain the records from Dead Island and Slieveanorra. The records from Dead Island and Slieveanorra have a modified chronology based on Bayesian modelling [*Swindles et al.*, 2012]. The blue-shaded boxes illustrate clear phases of similarity between records – namely a hydrological response to a major climatic event beginning at ~2700 cal. BP [*Swindles et al.*, 2007] and the Little Ice Age at c. 600–150 cal. BP [*Barber et al.*, 2000]. It is obvious that there is not always coherence between the records outside these boxes.

virtual bog (an artificial ecology) with similar properties to MTM. The virtual bog had the same initiation date and diameter as MTM. We chose decay-rate and peat permeability parameters that were plausible (within measured ranges) for raised bogs. Likewise, the relationship between rate of litter production and water-table depth was based on measurements from a UK raised bog with similar plant assemblages to MTM [*Belyea and Clymo*, 2001]. The virtual bog allowed us to perform numerical experiments to investigate how peatland water tables respond to climatic changes. We refer the reader to Text S1 in the auxiliary material for further details.[1]

3. Results and Discussion

[7] The multiproxy paleoenvironmental data clearly show that the stratigraphic changes were driven by peatland water-table fluctuations (Figures 2 and S1–S6 and Tables S1 and S2). Two periods of abrupt water-table rise are evident from decreased peat humification and replacement of palaeoecological indicators of deep water tables (e.g., Ericaceae macrofossils and pollen; the testate amoeba *Hyalosphenia subflava*) by indicators of near-surface water tables (e.g., *Sphagnum cuspidatum* macrofossils; *Sphagnum* spores; the testate amoeba *Amphitrema wrightianum*) (Figure 2). The dataset clearly shows that there were four rapid, high-magnitude water-table fluctuations over a relatively short timescale (~500 years) within this peatland, forming a sawtooth pattern with respect to time. Two major wet shifts (water-table rise) occurred at c. 2210–2170 calibrated years before present (cal. BP where BP is AD 1950) and c. 2000–1975 cal. BP with changes in mean reconstructed water table of ~23 and ~17 cm respectively. These wet shifts were followed by wet phases of ~70 and ~90 years before the peatland returned rapidly to a drier state (deeper water table). Phases of deep water tables are present in the record at c. 2301–2210 cal. BP, c. 2050–2010 cal. BP and c. 1875–1840 cal. BP (Figure 3). The presence of the Glen Garry tephra layer (2210–1966 cal. BP) in this sequence allows precise comparison with eight other palaeohydrological records from peatlands in Scotland (n = 7) and Northern England (n = 1). It is clear that, although a similar sawtooth pattern of wet and dry shifts is apparent (within chronological imprecision) in three of these sites, five have a contrasting palaeohydrological record at this time (Table S3). This variable coherency may be due to regional climatic differences or factors internal to the peatlands themselves; however, it is likely that it is a combination of both factors.

[8] Experiments with our virtual bog were used to investigate how a peatland similar to MTM might respond to external forcing. We report below on those numerical experiments in which net rainfall U was increased in two steps; i.e., in which it was increased once to a new steady value and then again to a higher steady value. These steps were set to occur at the same time as the dated wet shifts at MTM. Figure 4 shows the water-table response of the virtual bog to (i) two wet shifts each of 20 percent of the pre-shift U, and (ii) two wet shifts, each of 40 percent of the pre-shift U. Both cases produce a distinct sawtooth pattern in which the depth of the water-table below the bog's surface first decreases and then increases in response to the wetter regime. That is, the virtual bog shows apparent drying a few years after a shift to a wetter climate. This apparent drying is caused by an increase in the rate of net peat accumulation, so that the rate of rise of the peatland surface outpaces the rate of rise of the water table, giving greater depths to the water table. The dry shifts are, therefore, caused by processes internal to the virtual bog. This finding suggests that

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL051500.

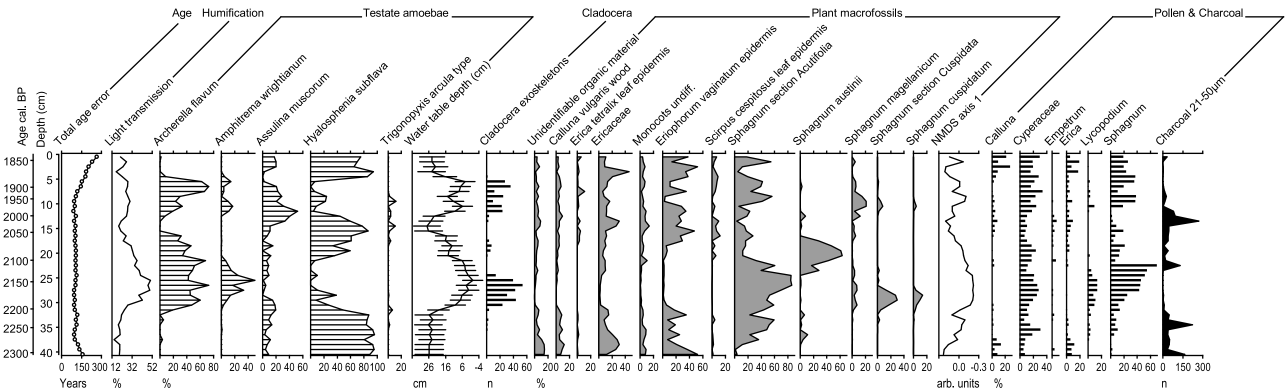

Figure 2. Multiproxy palaeohydrological proxy data (selected variables) from MTM based on peat humification, testate amoebae (with water-table reconstruction), Cladocera remains, plant macrofossils (with NMDS one-dimensional data summary) and peatland pollen taxa. Charcoal abundance is also illustrated. The total age error based on the Bayesian age-depth model is shown. Depths represent those from the sampled peat face and do not correspond to contemporary surface. Full datasets are provided in the auxiliary material.

not all water-table shifts in real peatlands are necessarily climatically-driven.

[9] The simulation also shows that the response of the bog to climatic perturbations is non-linear: the water-table responses to the 40 percent shifts are not twice the size of the responses to the 20 percent shifts. Other features of the responses show non-linearity. For example, the stable water-table position following the second dry shift is similar to that before the first climatic perturbation (Figure 4a), even though the climate after the step increases in U is very different (wetter) from that before (Figure 4b). This return of the water table shows a homeostasis that partially disconnects peatland water tables from external climate drivers. The virtual bog also shows homeostatic response to external dry shifts, by exhibiting autogenic wetting (water-table rise) shortly after externally-imposed dry shifts (reduction in U) (Figure S7). Our numerical experiments suggest that, although peatland water tables do respond to climate, the peatland archive can be contaminated by complex internal responses that are non-linear. The notion of peatlands responding in a homeostatic manner to external perturbations is also supported by observational [e.g., *Loisel and Garneau*, 2010; *van Bellen et al.*, 2011] and experimental [*Bridgham et al.*, 2008] evidence.

[10] Recent work has attempted to compare peat-based water-table reconstructions with instrumental data to infer the climatic controls on the recent (last ~200 years) record [*Charman et al.*, 2009] and, through calibration based on linear-regression, reconstruct quantitative climatic variables over millennial timescales [*Charman et al.*, 2012]. This approach is problematic because changes in the magnitudes of peatland water table may not be linearly related to climatic parameters. While it appears that some shifts in peatland water tables are climatically driven, caution must be applied when interpreting the peat archive because other changes in water-table position may be products of internal peatland dynamics, independent of climate. Peatland water-table records represent complex ecohydrological dynamics as suggested by our modelling approach, and illustrated by the variable correspondence of high-resolution water-table reconstruction data (Figure 1 and Table S3). Records from multiple sites with high-resolution chronologies are fundamental for helping to identify real climatic events [*Swindles et al.*, 2007; *Blaauw*, 2012]. Despite over 100 years of debate concerning the strength of linkage between peat stratigraphy and climate change [*Blytt*, 1876; *Sernander*, 1908;

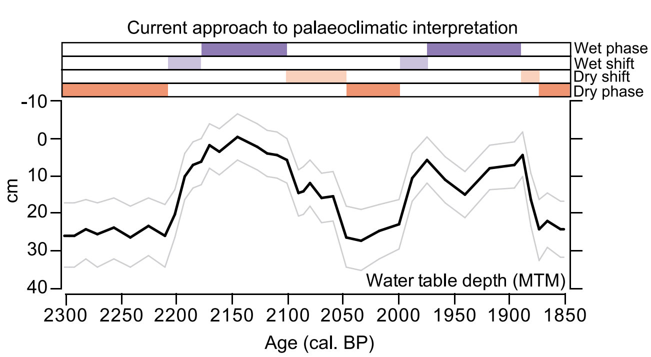

Figure 3. Water-table reconstruction from MTM, with current approach to palaeoclimatic interpretation illustrated.

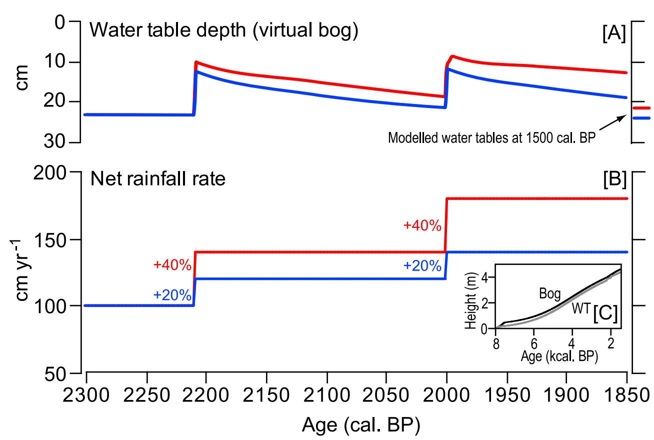

Figure 4. (a) Modelled water-table wet and dry shifts in response to (b) climatic wetting in two steps. (c) Modelled bog surface and water-table position. The positions of the stable water tables after the second dry shift are also shown (~1500 cal. BP).

Osvald, 1923; *Barber*, 1981; *Backeus*, 1990; *Chambers and Charman*, 2004], recent researchers have tended to interpret peat-based proxy records in a predominately climatic way. Researchers now need to consider fully how climatic forcing is filtered by peatland ecohydrological controls and feedbacks. Only after such consideration can the peatland archive be used for testing climate models.

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References

Aaby, B. (1976), Cyclic climatic variations in climate over past 5,500 yr reflected in raised bogs, *Nature*, *263*, 281–284, doi:10.1038/263281a0.

Backeus, I. (1990), The cyclic regeneration on bogs—A hypothesis that became an established truth, *Striae*, *31*, 33–35.

Barber, K. E. (1981), *Peat stratigraphy and Climatic Change: A Palaeoecological Test of the Theory of Cyclic Peat Bog Regeneration*, 219 pp., Balkema, Rotterdam, Netherlands.

Barber, K. E., D. Maddy, N. Rose, A. C. Stevenson, R. Stoneman, and R. Thompson (2000), Replicated proxy-climate signals over the last 2000 yr from two distant UK peat bogs: New evidence for regional palaeoclimate teleconnections, *Quat. Sci. Rev.*, *19*(6), 481–487, doi:10.1016/S0277-3791(99)00102-X.

Belyea, L. R. (2009), Nonlinear dynamics of peatlands and potential feedbacks on the climate system, in *Carbon Cycling in Northern Peatlands*, *Geophys. Monogr. Ser.*, vol. 184, edited by A. J. Baird et al., pp. 5–18, AGU, Washington, D. C., doi:10.1029/2008GM000829

Belyea, L. R., and A. J. Baird (2006), Beyond "the limits to peat bog growth": Cross-scale feedback in peatland development, *Ecol. Monogr.*, *76*, 299–322, doi:10.1890/0012-9615(2006)076[0299:BTLTPB]2.0.CO;2.

Belyea, L. R., and R. S. Clymo (2001), Feedback control of the rate of peat formation, *Proc. R. Soc. B*, *268*, 1315–1321, doi:10.1098/rspb.2001.1665.

Belyea, L. R., and N. Malmer (2004), Carbon sequestration in peatland: Patterns and mechanisms of response to climate change, *Global Change Biol.*, *10*, 1043–1052, doi:10.1111/j.1529-8817.2003.00783.x.

Blaauw, M. (2012), Out of tune: the dangers of aligning proxy archives, *Quat. Sci. Rev.*, *36*, 38–49, doi:10.1016/j.quascirev.2010.11.012.

Blaauw, M., and J. A. Christen (2011), Flexible paleoclimate age-depth models using an autoregressive gamma process, *Bayesian Anal.*, *6*, 457–474, doi:10.1214/11-BA618.

Blackford, J. (2000), Palaeoclimatic records from peat bogs, *Trends Ecol. Evol.*, *15*, 193–198, doi:10.1016/S0169-5347(00)01826-7.

Blytt, A. G. (1876), *Essay on the Immigration of the Norwegian Flora During Alternating Rainy and Dry Periods*, A. Cammermeyer, Oslo.

Bridgham, S. D., J. Pastor, B. Dewey, J. F. Weltzein, and K. Updegraff (2008), Rapid carbon response of peatland to climate change, *Ecology*, *89*, 3041–3048, doi:10.1890/08-0279.1.

Chambers, F. A., and D. J. Charman (2004), Holocene environmental change: Contributions from the peatland archive, *Holocene*, *14*, 1–6, doi:10.1191/0959683604hl684ed.

Charman, D. J. (2007), Summer water deficit variability controls on peatland water-table changes: Implications for Holocene palaeoclimate reconstructions, *Holocene*, *17*, 217–227, doi:10.1177/0959683607075836.

Charman, D. J., A. Blundell, R. C. Chiverrell, D. Hendon, and P. G. Langdon (2006), Compilation of non-annually resolved Holocene proxy climate records: Stacked Holocene peatland palaeo-water table reconstructions from northern Britain, *Quat. Sci. Rev.*, *25*, 336–350, doi:10.1016/j.quascirev.2005.05.005.

Charman, D. J., A. Blundell, and ACCROTELM Members (2007), A new European testate amoebae transfer function for palaeohydrological reconstruction on ombrotrophic peatlands, *J. Quat. Sci.*, *22*, 209–221, doi:10.1002/jqs.1026.

Charman, D. J., K. E. Barber, M. Blaauw, P. G. Langdon, D. Mauquoy, T. J. Daley, P. D. M. Hughes, and E. Karofeld (2009), Climate drivers for peatland palaeoclimate records, *Quat. Sci. Rev.*, *28*(19–20), 1811–1819, doi:10.1016/j.quascirev.2009.05.013.

Charman, D. J., V. Hohl, A. Blundell, F. Mitchell, J. Newberry, and P. Oksanen (2012), A 1000-year reconstruction of summer precipitation from Ireland: Calibration of a peat-based palaeoclimate record, *Quat. Int.*, doi:10.1016/j.quaint.2011.12.011, in press.

Frolking, S., N. T. Roulet, E. Tuittila, J. L. Bubier, A. Quillet, J. Talbot, and P. J. H. Richard (2010), A new model of Holocene peatland net primary production, decomposition, water balance, and peat accumulation, *Earth Syst. Dyn.*, *1*, 1–21, doi:10.5194/esd-1-1-2010.

Langdon, P. G., A. G. Brown, C. J. Caseldine, S. P. E. Blockley, and I. Stuijts (2012), Regional climate change from peat stratigraphy for the mid- to late Holocene in central Ireland, *Quat. Int.*, doi:10.1016/j.quaint.2011.11.018, in press.

Loisel, J., and M. Garneau (2010), Late Holocene paleoecohydrology and carbon accumulation estimates from two boreal peat bogs in eastern Canada: Potential and limits of multi-proxy archives, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *291*, 493–533, doi:10.1016/j.palaeo.2010.03.020.

Mauquoy, D., D. Yeloff, B. Van Geel, D. J. Charman, and A. Blundell (2008), Two decadally resolved records from north-west European peat bogs show rapid climate changes associated with solar variability during the mid-late Holocene, *J. Quat. Sci.*, *23*(8), 745–763, doi:10.1002/jqs.1158.

Morris, P. J., L. R. Belyea, and A. J. Baird (2011), Ecohydrological feedbacks in peatland development: A theoretical modelling study, *J. Ecol.*, *99*, 1190–1201, doi:10.1111/j.1365-2745.2011.01842.x.

Osvald, H. (1923), Die vegetation des Hochmoores Komosse, *Sven. Växttsociologiska Sallskäpets Handl.*, *1*, 1–436.

Sernander, S. (1908), On the evidences of postglacial changes of climate furnished by the peat mosses of northern Europe, *Geol. Foeren. Stockholm Foerh.*, *30*, 465–473, doi:10.1080/11035890809445601.

Swindles, G. T., G. Plunkett, and H. M. Roe (2007), A delayed climatic response to solar forcing at 2800 cal. BP: Multi-proxy evidence from three Irish peatlands, *Holocene*, *17*, 177–182, doi:10.1177/0959683607075830.

Swindles, G. T., A. Blundell, H. M. Roe, and V. A. Hall (2010), A 4500-year proxy climate record from peatlands in the north of Ireland: The identification of widespread summer 'drought phases'?, *Quat. Sci. Rev.*, *29*, 1577–1589, doi:10.1016/j.quascirev.2009.01.003.

Swindles, G. T., M. Blaauw, A. Blundell, and T. E. Turner (2012), Examining the uncertainties in a 'tuned and stacked' peatland water table reconstruction, *Quat. Int.*, doi:10.1016/j.quaint.2011.04.029, in press.

Väliranta, M., A. Korhola, H. Seppa, E. S. Tuittila, K. Sarmaja-Korjonen, J. Laine, and J. Alm (2007), High-resolution reconstruction of wetness dynamics in a southern boreal raised bog, Finland, during the late Holocene: A quantitative approach, *Holocene*, *17*(8), 1093–1107, doi:10.1177/0959683607082550.

van Bellen, S., M. Garneau, and R. Booth (2011), Holocene carbon accumulation rates from three ombrotrophic peatlands in boreal Quebec, Canada: Impact of climate-driven ecohydrological change, *Holocene*, *21*, 1217–1231, doi:10.1177/0959683611405243.

Woodland, W. A., D. J. Charman, and P. C. Sims (1998), Quantitative estimates of water tables and soil moisture in Holocene peatlands from testate amoebae, *Holocene*, *8*, 261–273, doi:10.1191/095968398667004497.