Testing peat humification analysis in an Australian context: identifying wet shifts in regional climate over the past 4000 years

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SUMMARY

Peat humification analysis is presented as a robust palaeoclimatic proxy, suitable for use on mid–late Holocene peat sequences situated in the Southern Hemisphere. The proxy is shown to permit the identification of wet and dry shifts in a peat sequence from the humid tropics of north-eastern Australia. A significant correlation is found between the humification record and other proxies indicative of past climate conditions such as pollen, $\delta^{13}C$, C/N and macrocharcoal. Sixteen wet shifts detected in the humification record for Bromfield Swamp occur at the following dates (with 2σ range): 3830 (3920–3740), 3560 (3640–3480), 3490 (3560–3420), 3380 (3450–3300), 3120 (3250–2970), 2950 (3100–2790), 2560 (2710–2450), 2430 (2600–2260), 2120 (2330–1910), 1750 (1980–1520), 1430 (1660–1200), 1170 (1390–960), 1010 (1220–820), 620 (770–500), 300 (400–200) and 100 (200–10) cal. yr BP. Eleven dry shifts are also identified in the record at 4220 (4330–4110), 3670 (3750–3590), 3330 (3420–3220), 3020 (3170–2870), 2350 (2530–2160), 2020 (2230–1800), 1730 (1980–1510), 1290 (1510–1070), 700 (870–560), 400 (470–300) and 260 (360–150) cal yr BP. *Blechnum* and Poaceae are identified by pollen analysis to be the dominant plants of the swamp surface over the past 4000 years. The ratio of these two plant taxa in the pollen record correlates well with identified wet and dry shifts. It is suggested that a ratio ≤1 possibly indicates dry conditions, a ratio of >1–3 indicates wet or dry conditions, and a ratio >3 implies wet conditions. Large macrocharcoal peaks are recorded during the initiation phase of the peat sequence at approximately 4090 cal. yr BP, and at 3700–3620 cal. yr BP, both of these time periods being coincident with dry phases. Isolated minor macrocharcoal peaks at *ca*. 2860, 2820, 2620, 2560, 2130, 1930, 1740 and 200 cal. yr BP are found to coincide with periods of average effective precipitation (based on the humification proxy) and so may reflect fire on the swamp surface, transport and re-deposition down-slope of old charcoal after a high rainfall event, or burning in the landscape by indigenous people.

KEY WORDS: ENSO; Holocene; humid tropics; pollen; pollen analysis

INTRODUCTION

Humification is a process involving the decay and conversion of organic matter into humic and fulvic acids and humin typically under oxygenated conditions in soils and peatlands. In saturated peatlands humification is limited to the surface aerobic horizon termed the *acrotelm* (Ingram 1978). Further anaerobic decay occurs at depth in the saturated subsurface horizon termed the *catotelm*, but at a much slower rate and releasing methane (CH_4) to the atmosphere (Belyea & Clymo 2001, Chambers *et al.* 2011). Rates of decay displayed by peat sequences are affected by factors including plant taxa composition, water content, available oxygen, temperature and microbial populations (Charman 2002). Clymo (1965) first demonstrated that individual *Sphagnum* species decay at different rates and that all organic materials decay at a greater rate above the water table than below the water table. More recent models of Holocene Peat development (Frolking *et al*. 2010) illustrate the complex links between peatland carbon, water cycles and climate.

Variation in the degree of humification displayed in peat sedimentary sequences has long been used as a proxy for climate change principally reflecting climate related changes in bog/mire surface wetness (Charman 2005), and is one a group of techniques applied to reconstruct surface wetness histories as proxies for Holocene climate change. Most of the development of the technique has been performed on lowland raised and upland blanket bogs in the boreal and temperate zone of northern Europe (Borgmark 2005), the United Kingdom (Blackford & Chambers 1991, 1993, 1995; Blackford 1993, Chambers *et al.* 1997, Mauquoy & Barber 1999) and North America (Booth & Jackson 2003, Payne & Blackford 2008). Almost exclusively these sites are dominated by mosses, sedges, grasses and restricted diversity herb communities and they derive their water as rainfall with limited overland flow.

In this article we report a multi-proxy investigation of a minerotrophic peatland, Bromfield Swamp, in the humid tropics of north-eastern Australia (Figure 1). Bromfield Swamp displays different characteristics from the northern hemisphere sites where humification analysis has been applied, with a different array of plant communities and a more complex hydrological system including overland and groundwater flows.

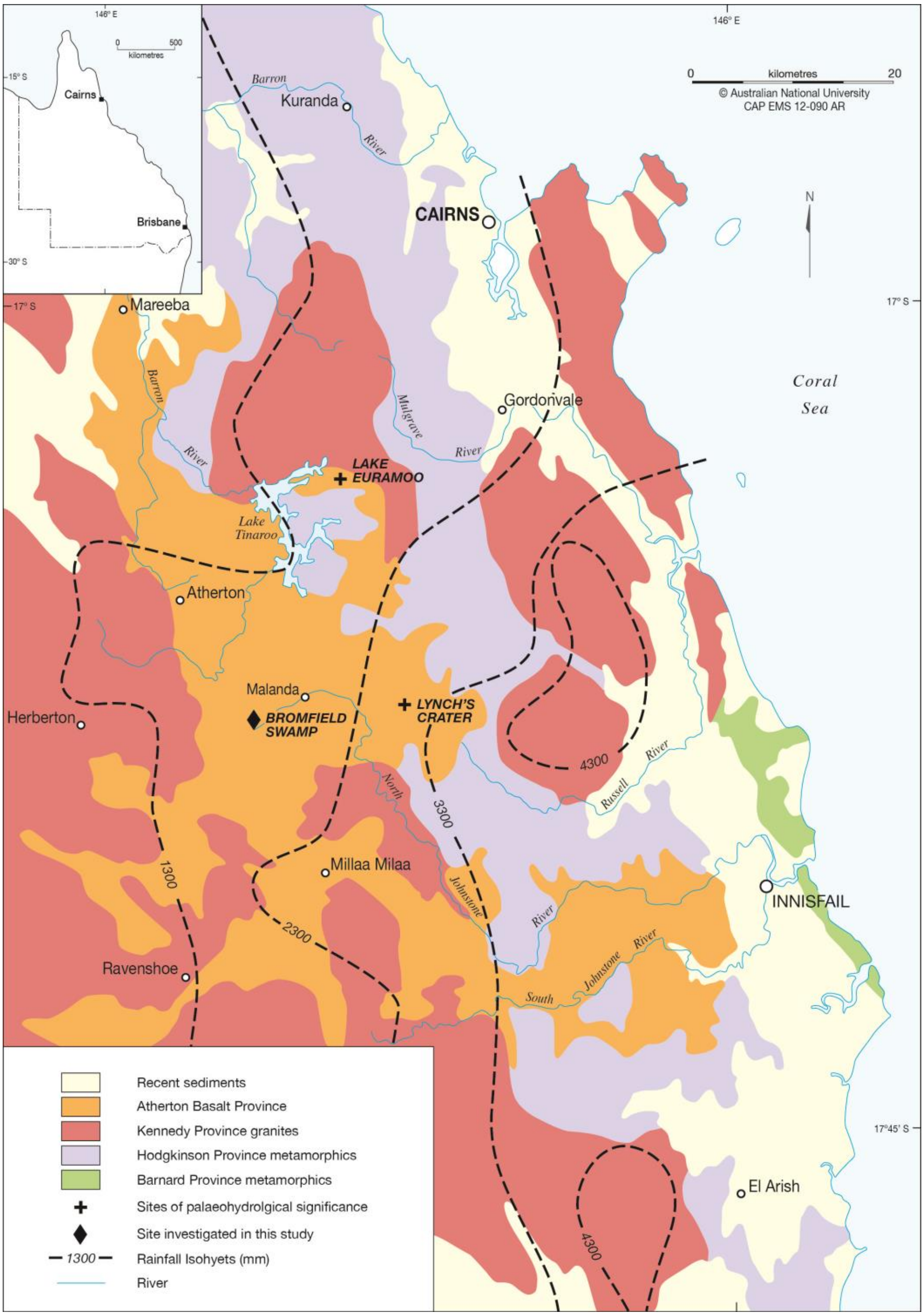

Figure 1. Geological map showing the location of Bromfield Swamp and other sites of palaeohydrological significance on the Atherton Tableland in the wet tropics of north-east Queensland. Quaternary basalts cover a suite of igneous and metamorphic rocks of Palaeozoic age. Rainfall isohyets are shown (1300 mm in the west and 3300 mm to the east). Adapted with permission (P. Kershaw 2013) from Kershaw & Sluiter (1982).

Previous work in Australia, at Goochs Swamp (Blue Mountains of New South Wales) (Black *et al*. 2008) and Lynch's Crater, Atherton Tableland (north-eastern Australia) (Turney *et al*. 2004), has used peat stratigraphical techniques to discern wetness changes from humification and ratios between pollen taxa and to derive charcoal based fire records. These studies revealed sequences of shifts between wetter and drier conditions in the peat stratigraphical records, including a 40k record for Lynch's Crater that showed repeating dry periods related to El Niño events (produced by declines in summer rainfall).

Here we test the robustness of humification as a proxy for relative precipitation and, given the geographical proximity of Bromfield Swamp to Lynch's Crater (Figure 1), attempt to complete the mid- to late-Holocene humification record for the Atherton Tableland. Corroboration of the humification record is achieved through comparison with other proxy records, specifically pollen, $\delta^{13}C$, C/N and macrocharcoal analyses.

STUDY SITE

Location and geology

Bromfield Swamp is located on the Atherton Tableland in north-eastern Queensland (17° 22′ S, 145° 32′ E), at an altitude of 754 m a.s.l. Measuring 1000 m by 800 m, it is set in a topographic low, occupying the base of a large *maar* or hydrovolcanic explosion crater (Gill 2010) (Figure 2) formed in the Late Quaternary (Whitehead *et al*. 2007 give an age >0.011Ma). The crater has walls 50 m high and its diameter exceeds 1700 m. From a viewpoint on the northern side, it appears as a distinctive bowl-shaped feature on an undulating plateau of Late Cainozoic volcanics of the Atherton Basalt Province (Bultitude *et al*. 1999, Whitehead *et al*. 2007).

Figure 2. Bromfield Swamp, south-east sector. The Swamp measures 1000 m × 800 m and occupies the base of a large maar on the Atherton Tableland. In June 2009, a rod-in-rod piston corer mounted on a floating platform was used to extract core BSAT03 (site marked with cross). The photograph shows the surface of the Swamp on 25 January 2010, immediately after a three-day rain event during which a data logger mounted on solid substrate in the Swamp indicated that the water level had risen by 0.3 m.

Climate

The Atherton Tableland is situated in the wet tropics of north-eastern Queensland, where precipitation is highly dependent on the austral summer monsoon system of the western Pacific Ocean (Muller *et al*. 2008), more lately identified as the Quasi-Monsoon (Kershaw & van der Kaars 2012), and the seasonal migration southward of the Intertropical Convergence Zone or ITCZ (Muller *et al*. 2008). Northward movement of the ITCZ and a north-east movement of the South Pacific Convergence Zone (SPCZ) herald an El Niño event during which summer precipitation typically falls 150–300 mm below the seasonal average (Haberle *et al*. 2010).

Average annual rainfall totals are not uniform across the Atherton Tableland (Figure 1). The highest rainfall values are recorded on its eastern side adjacent to the Bellenden Ker Range and fall rapidly to the north and west. Lynch's Crater, located near the eastern margin of the Tableland, is estimated to receive about 2570 mm of rainfall *per annum* (Bushby 1991) whereas Bromfield Swamp, located 15 km to the west of Lynch's Crater, receives approximately 1700 mm (Kershaw 1975). Monthly rainfall data for Bromfield Swamp, collected in the period 1999–2009, indicates a higher average of 1899 mm rainfall *per annum* (F. Moller-Neilson, pers. comm., August 2010.)

Ecohydrology

Bromfield Swamp is described as a lacustrine wetland (Australian Wetlands Database 2010) with the water table positioned at the swamp surface for extended periods of time throughout the year (Charman 2002). It receives water as precipitation, from intermittent seasonal streams, as runoff from the surrounding crater walls, and as groundwater (two nearby maars known as Lakes Barrine and Eacham intercept the local water table; P. Siemsen, pers. comm., 18 February 2014.). Thus, for the purposes of this study, it is more accurately described as a minerotrophic peatland or *fen*, with water supplied by precipitation, surface runoff and possibly groundwater (Barber & Charman 2005). A stream running through a deep defile in the eastern wall of the crater allows water to flow from the wetland. The Swamp is covered by a mosaic of wetland plants and open water. Several plant communities recognised by Kershaw (1973, 1975) are utilised in this study. *Cyperus*-dominated plant communities ring the eastern, northern and western sectors of the Swamp, their boundaries moving with the rising and falling of water levels over the wet and dry seasons. *Rhynchospora corymbosa* growing on solid substrate is conspicuous at the landward edge, while dense stands of *Cyperus lucidus*, *Cyperus sp*., *Typha domingensis* and *Juncus usitatus* occur farther into the swamp. *Leersia hexandra*, an aquatic or semi-aquatic perennial, forms thin floating mats over extensive areas of shallow water. Also occurring throughout these communities are a range of aquatic and semi-aquatic herbs (*Oenanthe javanica*, *Limnophylla aromatica*, *Nymphoides indica*) and the pteridophyte *Cyclosorus interruptus*. Lakeward of the *Cyperus*-dominated communities of the Swamp boundary is found a species-rich plant community growing on a thick floating root mat. This community is dominated by *Baumea rubiginosa* (soft twigrush) and *Cyclosorus interruptus*. A separate community is recognised in the southern sector of the Swamp. This community grows on solid substrate and is dominated by *Baumea rubiginosa* and the pteridophyte *Blechnum indicum* (also known by the indigenous names *bungwall* in the Moreton Bay area and *dugal* in the Tully River area, see Jones & Clemesha 1980, Bailey 1909). Areas of open water are present in the central parts of Bromfield Swamp. The water is of varying depth (commonly 1–2m) and supports a range of floating leaf aquatic vegetation (*Nymphoides indica*, *Brasenia peltata*), emergents (*Eleocharis dulcis*, *E. equisetina*) and free-floating *Azolla pinnata.* The submerged aquatic *Ceratophyllum demersum* is found in deeper water or that disturbed by a current.

Water levels on Bromfield Swamp are determined by the height of the outlet into the North Johnstone River tributary. Today, water exiting the Swamp runs through a concrete culvert laid over basalt blocks, the whole structure supporting a roadway for farm vehicles and allowing stock movement. Constructed and rebuilt over several decades by the present landowners, the culvert raises the water level in the Swamp (estimate >0.3 m). Water levels were appreciably lower in the early 20th Century, when Chinese market-gardeners are known to have cultivated sites on the present-day swamp surface (Kershaw 1973, 1975). Lines of old fence posts running into the Swamp (Kershaw 1973) confirm cultivation of its margins in the recent past and a lower water level in the crater basin. A lower water level is also indicated by a 1907 survey of Bromfield Swamp and adjoining land: a road is gazetted, running east–west across the northern sector of the Swamp (Malanda Parish Plan No. 335 1907).

Stratigraphy

The peats of Bromfield Swamp are comprised of decaying remains of the fern, sedge, grass and other herb taxa that dominate the wetland vegetation. Kershaw (1973, 1975) produced a simple but effective three-dimensional view of the sediments infilling the basin from two cross transects of 18 piston cores. Kershaw's (1975) long pollen analytical core sampled the centre of the Swamp and recovered the stratigraphy described in Table 1.

METHODS

Three continuous cores of sediment, BSAT01 (6.89 m), BSAT02 (8.48 m) and BSAT03 (9.53 m) were extracted from Bromfield Swamp (dry season, June 2009) using a piston corer mounted on a floating platform. BSAT03 (focus of this study) was taken in 1.1 m of water from a small embayment on the swamp surface, 270 m due west of the outlet into the North Johnstone River tributary (X in Figure 2). Core litho-stratigraphy was determined in the laboratory, followed by sub-sampling at 1 cm intervals.

Geochronology

Ten peat and organic lake mud sediment samples were extracted from core BSAT03 and dated using bulk organic matter. Ages were obtained by accelerated mass spectrometry at NOSAMS Woods Hole Oceanographic Institution, RSES Australian National University and the University of Waikato Radiocarbon Dating Laboratory in New Zealand. The dried, crushed samples were pre-treated with HCl-NaOH-HCl and washed with milli-Q and the insoluble residue freeze-dried for AMS analysis. Radiocarbon ages were calibrated using OxCal v4.2.2 with the SHCal04 calibration data set (Bronk Ramsey 2005). Calibrated ages are displayed in cal. yr BP.

Table 1. General stratigraphy of Bromfield Swamp, constructed from central basin core A7 (after Kershaw 1973, 1975). Sediment description and representation follow a modification of the Troels-Smith system (Kershaw 1997).

Unit	Depth	Description
1	0–100 cm	Floating root mat approximately 40 cm thick over water. Mat composed of living herbaceous plants and slightly decomposed remains, commonly roots and stems (*turfa herbacea*).
2	100–110 cm	Fragments of herbaceous plants >2 mm (*detritus herbosus*) and some clay (*argilla*); dark brown colour, fibrous. Water content 750 % of dry weight.
3	110–120 cm	Fragments of herbaceous plants >2 mm (*detritus herbosus*) and some clay (*argilla*); dark grey-brown, fibrous. Water content 800 % of dry weight.
4	120–360 cm	Coarse fragments of herbaceous plants (*detritus herbosus*); dark brown at 120 cm, altering to red-brown at 360 cm.
5	360–429 cm	Fragments of herbaceous plants >2 mm (*detritus herbosus*) at 360–383 cm; fragments of herbaceous plants (*detritus herbosus*) and some organic lake mud (*limus*) at 383–413 cm; organic lake mud (*limus*) with a herbaceous plant (*detritus herbosus*) component from 413–429 cm. Red-brown colour throughout unit.
6	429–751 cm	Organic lake mud (*limus*) with fine fragments of plants (*detritus*); yellow-brown with reddish tinged bands at 719–724 cm and 743–751 cm; some clay (*argilla*) 721–751 cm.
7	751–753 cm	Compact and fairly dry granular mix of organic lake mud (*limus*) and clay (*argilla*). Dark grey in colour.
8	753+ cm	Slightly granular clay (*argilla*), blue-grey.

Humification analysis

Laboratory measurement of peat humification used BSAT03 following the laboratory protocol developed for the European ACCROTELM palaeoclimate project (Chambers 2006, Chambers *et al*. 2011). Peat humification was measured on samples at either 1 cm or 2 cm contiguous intervals using a filtered (Whatman No 1 filters) NaOH (8 %) extract from 0.2 g of dried peat, with % light transmission (3 repeats) and absorbance (3 repeats) at 540 nm measured on a double-beam Shimadzu UV-1800 spectrophotometer using distilled water as zero standard. There is mixed practice in the literature (Blackford & Chambers 1993, Turney *et al*. 2004, Borgmark 2005) over the use of % light transmission *versus* absorbance; here we plot percentage light transmission values against depth (i.e. high percentage values representing little humification of peats and low percentage values representing increased levels of humification). The humification data were smoothed by using a three-point moving average to remove the impact of aberrant values and plotted; detrending of the data, by applying a 4^{th} order polynomial and plotting the residual values, removed the impact of slow and ongoing decay in the catotelm and emphasised high-frequency shifts in humic acid.

Pollen analysis

Thirteen samples were extracted from core BSAT03 for pollen analysis, targeting samples straddling shifts in peat humification. An additional sample targeted the mud-water interface (core BSAT-MW) to assess the representativeness of contemporary vegetation-pollen relationships. Pollen preparation followed standard procedures (Bennett & Willis 2001), with near-surface samples needing HF treatment for silica content and an additional fine (10µm) sieving and ultrasonic agitation treatment required to remove fine peat particulates (Richardson & Hall 1994). Pollen concentrations were calculated volumetrically, following addition of exotic *Lycopodium clavatum* as a spike to all samples. Pollen spectra were identified and counted using a Zeiss Axiophot Microscope (×630 magnification), with reference to pollen image archives and the reference collection of the Department of Archaeology and Natural History (Australian National University). The total pollen sum (500n) included all aquatic vascular plant pollen, fern spores and low frequencies of terrestrial taxa. Pollen diagrams were constructed using Tilia 1.5.12 (Grimm 1993, 2004). All plant taxa identified in samples were recorded, including spores contributed by bryophytes and pteridophytes (including *Blechnum* and *Cyclosorus*) and pollen from angiosperms and gymnosperms growing on the swamp and surrounding drylands. Pollen and spore counts for wetland plant taxa were displayed as percentages of the total pollen sum, whereas only presence/absence was presented for the pollen of dryland plant species due to very low counts. Three pollen zones were determined by stratigraphically-constrained cluster analysis using CONISS (Grimm 1987, 2004) utilising Square Root Transformation (considered suitable because scarcer taxa contribute to the analysis).

Macro-charcoal analysis

Preparation of samples for macro-charcoal analysis (>125µm) followed Stevenson & Haberle (2005), with 1 cm contiguous samples processed from core BSAT03. Macro-charcoal particles of two size fractions (125–250 µm, >250 µm) were counted under a stereomicroscope at ×10 magnification. Macro-charcoal concentrations for each size fraction were calculated (particles cm^{-3}). The two size fractions were used as indicators of the proximity of fire, with the >250 µm fraction reflecting local fires and the 125–250 µm fraction interpreted as farther travelled (Haberle 2005).

Organic carbon isotope and C/N analyses

Changes in the C isotope ratios (Coleman & Fry 1991) preserved in the organic matter of peat bogs and lake sediments can be used for pinpointing possible sources of organic matter, recognising fluctuations in nutrient availability in surficial waters and deducing alterations in past productivity (Hillaire-Marcel *et al*. 1989, Sukumar *et al*. 1993, Aucour *et al*. 1999, Meyers & Teranes 2001). While several processes are believed to direct this variation, it is thought that differences in the source of organic matter (Ariztegui *et al*. 1996, Aucour *et al*. 1999) such as lacustrine algae, aquatic macrophytes and terrestrial plants with differing photosynthetic pathways (C_3, C_4) are particularly important.

Prevailing environmental conditions, coupled with the particular photosynthetic pathway, determine the isotopic range of plants (O'Leary 1988). $\delta^{13}C$ for C_3 plants (dominant in cooler, wetter conditions) commonly range from -32 ‰ to -20 ‰ (Boutton 1991, Tieszen 1991). The relative abundance of C_3 plants falls with an increase in temperature or a decrease in rainfall. $\delta^{13}C$ for C_4 plants (commonly grasses in the tropics) range from -15 ‰ to -9 ‰ (Montanari *et al*. 2013) or -17 ‰ to -9 ‰ (Boutton 1991): these plants are particularly adapted to drier and hotter environments (Wang & Wooller 2006).

C/N ratios are used to separate autochthonous sources of sediment from allochthonous sources (Wang & Wooller 2006). Typically, C/N values have been used to distinguish the algal origins of organic matter in sediments from land-plant origins (Meyers 1994). The C/N values of terrestrial plants is typically >20, while aquatic plants and algae typically record a value between 4 and 10 (Herczeg *et al*. 2001).

Percentage carbon and nitrogen were measured using a Carlo Erba 1500 elemental analyser, calibrated through an internal acedanalid standard, for 11 samples (core BSAT03) targeting peaks in peat humification. Replicate analysis of samples gave a precision of ≤ 0.1 % (1 SD). $^{13}C/^{12}C$ analyses were performed by combustion using a Carlo Erba 1500 on-line to a VG Triple Trap and Optima dual-inlet mass spectrometer. $\delta^{13}C$ values were calculated with respect to the Vienna Pee Dee Belemnite (VPDB) scale using a within-run laboratory standard (cellulose, Sigma Chemical prod. no. C-6413) calibrated against NBS–19 and NBS–22. Replicate analysis of sample material gave a precision of ≤0.1 ‰ (1 SD) (Mackie *et al*. 2007).

RESULTS

Age-depth model

All ten samples contained sufficient carbon for AMS radiocarbon dating and the results are shown in Table 2. Figure 3 shows changes in the rate of accumulation of the sediments of Bromfield Swamp, with an age-depth model tested using OxCal v4.2.2 and the SHCal04 calibration curve. The P-sequence (1, 1) age-depth model uses Bayesian modelling (Bronk Ramsey 2008) to interpolate between the ten radiocarbon-dated horizons generating an age probability function for each depth. The P-sequence model assumes that deposition follows a Poisson distribution, here calculated at one event (k parameter) *per* 0.01 m unit length with a 0.01 m scale for interpolation. Essentially this models the age distribution for each 0.01 m of depth and assumes that changes in sediment accumulation rate occur at the 0.01 m scale. The model shows (Figure 3) that while peats have accumulated at Bromfield for little more than 4000 years, the longer Holocene history shows a slowing of accumulation during the final phase of organic lake muds, more rapid accumulation with peat initiation, and a slight slowing of the rate from 3440 cal. yr BP (with a 2σ range of 3508–3392 cal. yr BP) through to the period of initial European settlement in the late 19th century.

The Bayesian model returns an age probability distribution for each 1 cm level in the stratigraphic record. Throughout the presentation of results and in discussion of specific events in the chronology we use the median modelled age or posterior density estimate (e.g. *ca*. 250 cal years BP), but acknowledge that there is a 2σ uncertainty in the range 150–400 years around that central age within which each event actually lies. The modelled median and 2σ error age ranges are declared fully in Tables 2 and 3 and shown on the age-depth model (Figure 3).

Table 2. Accelerator mass spectrometry or AMS radiocarbon ages (^{14}C yr BP) and calibrated ages (cal. yr BP) for Bromfield Swamp BSAT03 subsamples. OxCal v4.2.2 used to calibrate radiocarbon data. OLM is Organic Lake Mud.

Sample ID	Lab. ID	Sample type	Depth (cm)	Radiocarbon age (yr BP)	Calibrated age – Median (cal. yr BP)	Median +2σ	Median -2σ
Bromfield core							
BSAT03B-C1	OS-89417	Bulk	27–28	385±25	476	510	335
BSAT03B-C2	OS-89418	Bulk	119–120	2480±25	2559	2712	2450
BSAT03B-C8	Wk-35182	Bulk	159–160	3232±29	3416	3471	3377
BSAT03B-C9	Wk-35183	Bulk	182–183	3494±34	3730	3812	3645
BSAT03B-C3	OS-89419	Bulk	219–220	3680±30	4142	4235	4065
BSAT03B-C10	Wk-35184	OLM	235–236	4225±25	4667	4758	4589
BSAT03-C3	S-ANU15333	OLM	315–316	5375±40	6067	6253	5995
BSAT03-C4	S-ANU15334	OLM	450–451	7130±45	8095	8170	7938
BSAT03-540	Wk-35185	OLM	539–540	9417±31	10589	10651	10508
BSAT03-C5	S-ANU16416	OLM	584–585	9710±35	11184	11226	11130

Stratigraphy

The basal 3.5 m of BSAT03 sediments are characterised as clays with a small, although significant, organic component (1.1–3.7 %C). Overlying the clays are 4 m of organic lake muds (19.1–36.4 %C) rich in *Botryococcus* and other algae (determined by microfossil analysis), and thought to have accumulated below a water column 4.5–30 m in depth, depending on the height of the crater outlet in the early to mid-Holocene (Kershaw 1975). Depth range 2.22–2.16 m shows a mix of organic lake muds and peat, with a sample at 2.20 m recording 52.1 %C. Carbon age-depth modelling (see Figure 3) constrains the cessation of organic lake mud deposition at 4120 cal. yr BP with a 2σ range of 4213–4045 cal. yr BP. The sequence is capped by 2.16 m of organic humified peat, deposited in little more than 4000 years. The peat deposits are very dark brown to black (Munsell 10YR 2/2 – 5YR 2.5/1) and contain 54.8–51.2 %C. Physical features are not uniform with depth, eight rather ill-defined layers being identified (Figure 2). A mud-water interface core (BSAT-MW), taken from a location 30 m north-east of BSAT03, recorded deposition of organic lake muds above the peat sequence. The rate of accumulation of these sediments is rapid; a CIC Model of ^{210}Pb dating prepared at the Australian Nuclear Science and Technology Organisation (ANSTO) indicates a mass accumulation rate of 0.148 ±0.01 g cm^{-2} yr^{-1}. These findings support the hypothesis that swamp water levels were appreciably lower prior to and in the early years of European settlement, and then rose incrementally through the second half of the 20th Century following construction of a culvert at the exit from the swamp.

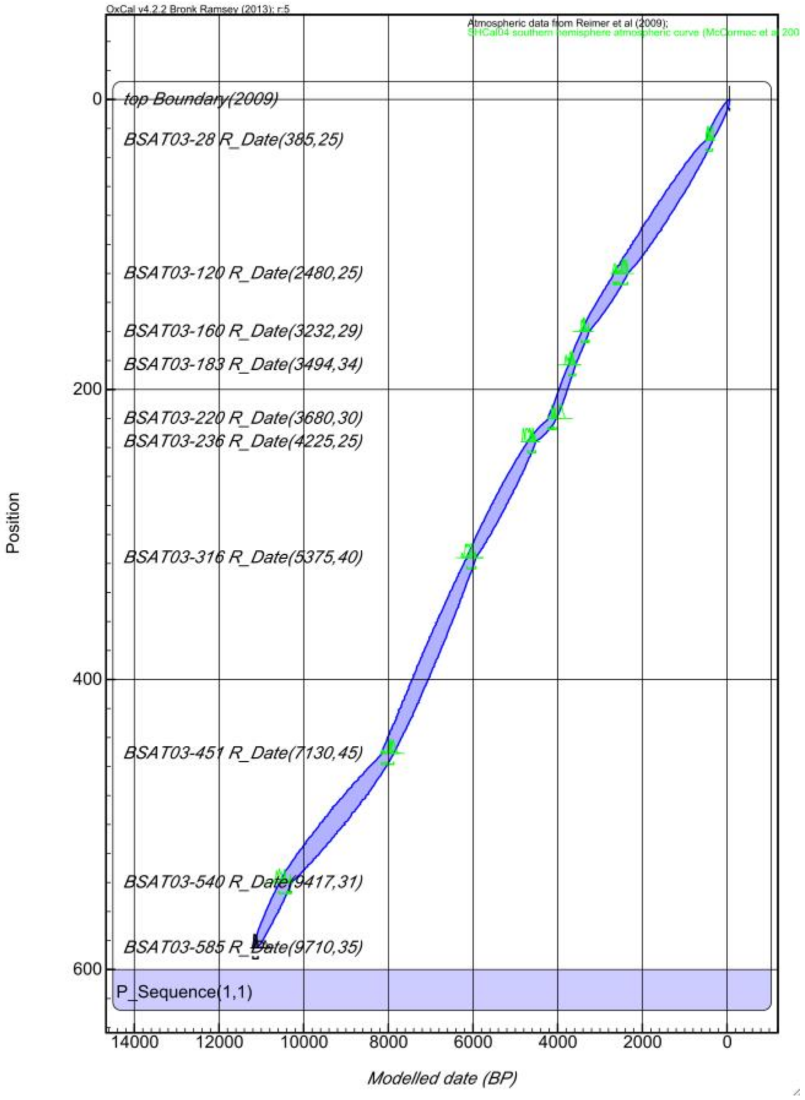

Figure 3: Age-Depth plot for Bromfield Swamp. Constructed using ten radiocarbon dates calibrated using OxCal v4.2.2 (the P_Sequence command with the SHCal04 calibration data set).

Table 3. Bromfield Swamp wet and dry shifts in cal. yr BP (median age and ±2σ). The estimated duration of wetter and drier phases (in years) is shown in the right-hand column.

Wet shifts (median)	+2σ	-2σ	Duration of wetter phases in years
100	200	10	100
300	400	200	50
620	770	500	180
1010	1220	820	300
1170	1390	960	130
1430	1660	1200	140
1750	1980	1520	<50
2120	2330	1910	<50
2430	2600	2260	80
2560	2710	2450	90
2950	3100	2790	390
3120	3250	2970	90
3380	3450	3300	50
3490	3560	3420	110
3560	3640	3480	<50
3830	3920	3740	110
Dry shifts (median)	**+2σ**	**-2σ**	**Duration of drier phases in years**
260	360	150	160
400	470	300	100
700	870	560	80
1290	1510	1070	120
1730	1980	1510	300
2020	2230	1800	270
2350	2530	2160	230
3020	3170	2870	70
3330	3420	3220	210
3670	3750	3590	110
4220	4330	4110	380

Humification record

The humification record for Bromfield Swamp displays a high degree of variability over the last 4000 years (Figure 4). With higher light transmission interpreted as indicating wetter episodes and lower light transmission drier episodes (Sillasoo *et al*. 2007), the smoothed humification record shows two major shifts, both of which must be recognised prior to interpretation of the data. The dramatic fall at 4130–4050 cal. yr BP reflects both a swift change in lithology from organic lake mud to peat (the result of terrestrialisation) and an intense dry phase (also identified in the Mount Quincan crater swamp humification record and reported in Burrows *et al*. in press). A general rise in all percentage transmission values from approximately 1500 cal. yr BP to the present day relates to the incomplete and ongoing decay of the upper horizons of the peat in the acrotelm (Sillasoo *et al*. 2007, Chambers *et al*. 2011). The detrended and smoothed data highlight the higher-frequency oscillation in peat humification, which is potentially related to changes in surface wetness of Bromfield Swamp. Sixteen shifts to wetter conditions are recognised in

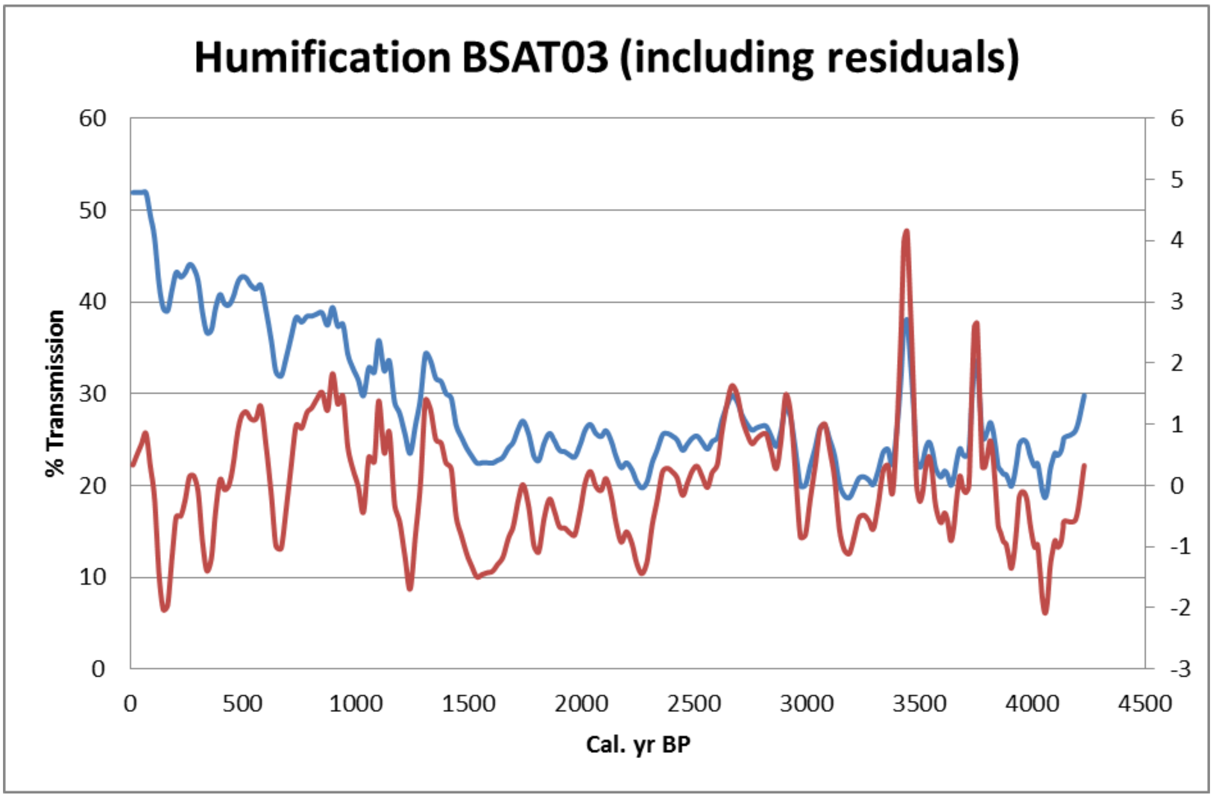

Figure 4. Peat humification record for Bromfield Swamp. Raw data (with a 3-point moving average applied) is shown in blue; detrended and smoothed data (residuals) are shown in red.

the peat humification record (Table 2). An additional eleven dry shifts are tentatively identified, although caution must be exercised in attributing all changes to climate forcing as autogenic succession processes (e.g. slow sediment infilling) can also cause drying by elevating the mire surface (Ruppel *et al.* 2013, Tuittila *et al.* 2007) leading to drying of the peat. The age-depth model indicates that 0.01 m of peat accumulates every 18 years and the humification data are smoothed to three samples (~54 year resolution), so the record is not of sufficiently fine resolution to allow detection of decadal or sub-decadal hydrological change.

Testing the assumption that humification is indicative of wet–dry shifts

The pollen diagram (Figure 5) shows that wetland aquatic and herbaceous plant taxa dominate the mid–late Holocene pollen record of Bromfield Swamp. As in the results of Kershaw (1973, 1975), dryland plant taxa are present at all levels through the sediment profile but account for only a very small fraction of the pollen sum. Pollen zones guided by the cluster analysis dendrogram (Figure 6) are numbered from the surface of the peat sequence and compared with the diagrams of Kershaw (1973, 1975) below.

- Zone BSAT-3 is defined by the presence of *Cyclosorus*, a ground fern. *Cyclosorus* was the dominant swamp plant during initiation of the peatland sequence. Several terrestrial plant taxa are present, with the highest recorded frequency of *Casuarina* pollen found in this zone. This zone is equivalent to Kershaw's Zone BB (Kershaw 1973, Figure 5.8).

- Zone BSAT-2 is defined by the presence of the *Lygodium*, a terrestrial fern with a climbing habit. Six terrestrial dryland plant taxa are recorded including *Casuarina*, *Eucalyptus*, *Grevillea*, *Syzygium*, *Mallotus* and *Balanops*. *Blechnum* is the dominant wetland plant taxon. This zone is equivalent to the lower half of Kershaw's Zone BA (Kershaw 1973, Figure 5.8).

- Zone BSAT-1 is distinguished by the presence of eight dryland tree taxa (*Casuarina*, *Mallotus*, *Leptospermum*, *Eucalyptus*, *Podocarpus*, *Sundacarpus amara*, *Araucaria* and *Cardwellia*), three herbaceous species and the general absence of the pteridophyte *Lygodium*. *Blechnum* remains the dominant wetland plant taxon. This zone is equivalent to the upper half of Kershaw's Zone BA (Kershaw 1973, Figure 5.8).

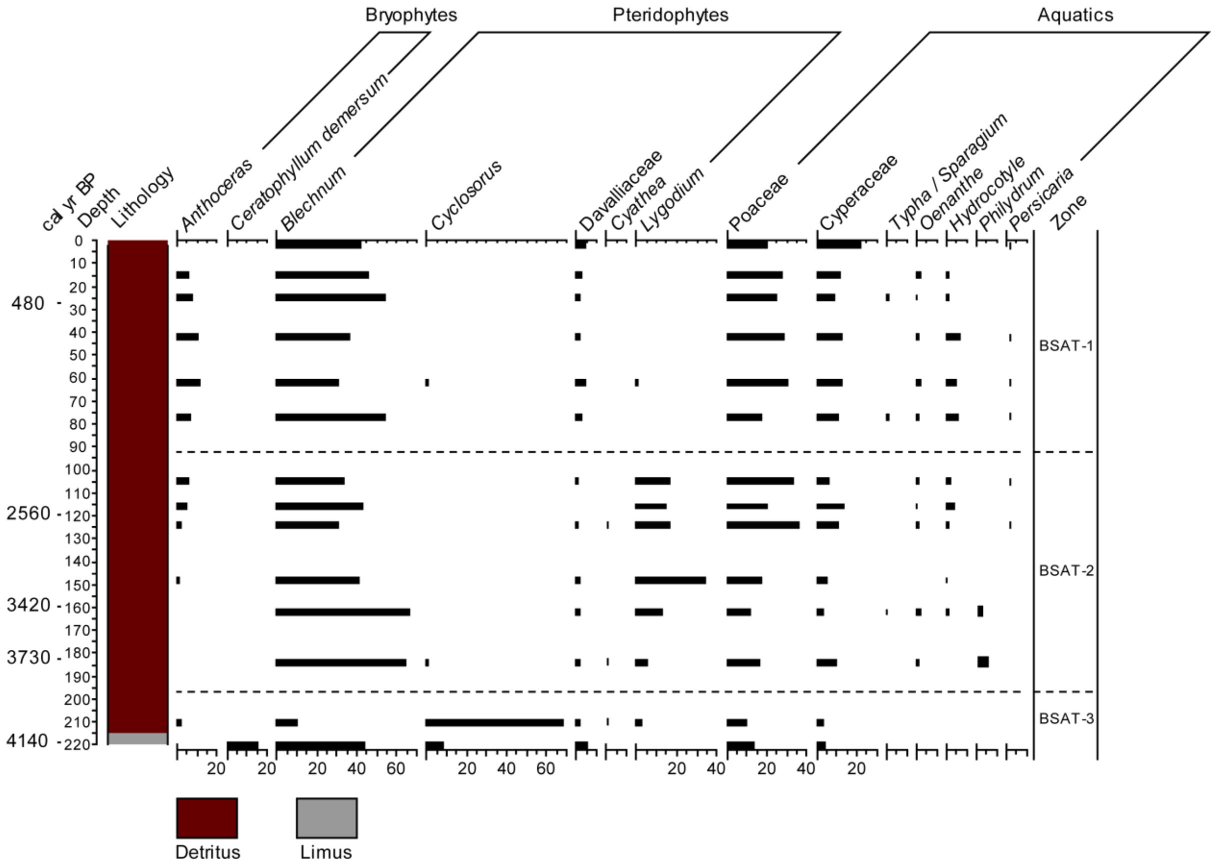

Figure 5. Pollen diagram for Bromfield Swamp. Bryophytes, pteridophytes and aquatic monocot and dicot species are illustrated; terrestrial plants species comprise a very small percentage of the total pollen count at every sample level and so are not shown.

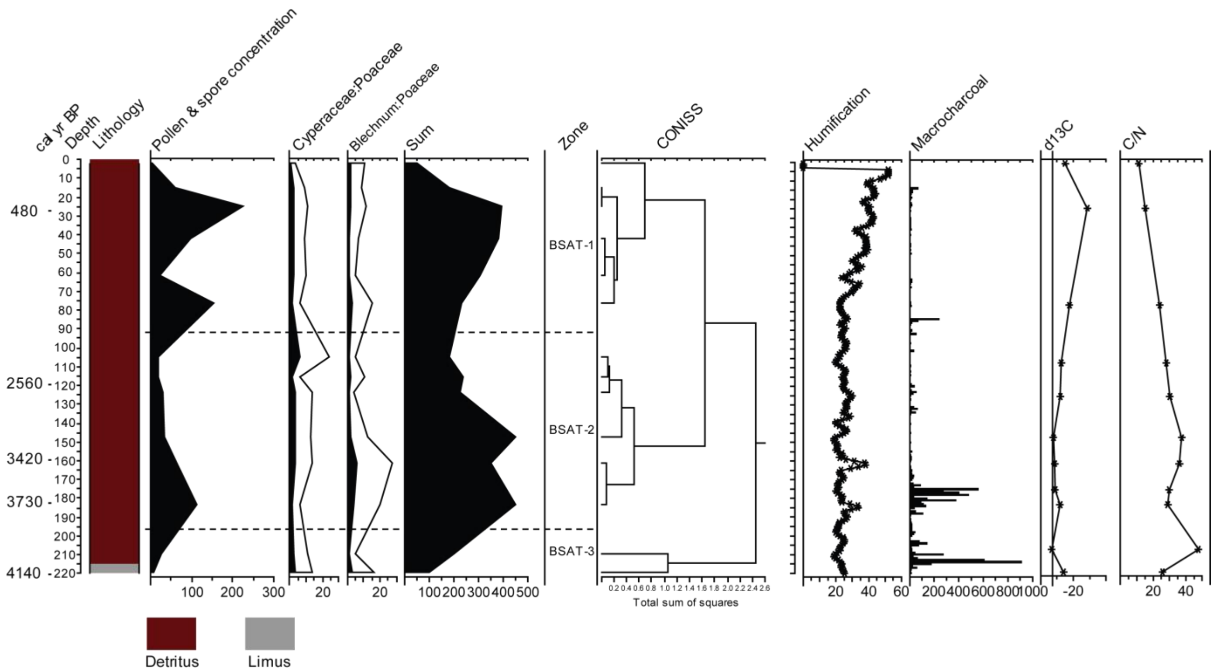

Figure 6. Composite records for Bromfield Swamp (lithology, Cyperaceae-Poaceae ratio, *Blechnum*-Poaceae ratio, pollen zonation, humification, macrocharcoal, d13C (=$\delta^{13}C$) and C/N ratio). CONISS: square root transformation used to identify the three zones designated BSAT-1, BSAT-2, BSAT-3 (see text).

Pollen ratios

Pollen ratios between abundant local wetland taxa are commonly used as indicators of change in wetland ecosystems; for example, Turney *et al*. (2004) and Muller *et al*. (2008) used a Cyperaceae:Poaceae pollen ratio to discern wetting and drying phases at Lynch's Crater. However the success of these ecological indicators depends on equivalent constraints at each site, and at Bromfield Swamp show a less clear relationship to humification and surface wetness. The *Blechnum*:Poaceae ratio (Figure 6) shows a much stronger correlation with wet and dry shifts detected in the humification record. The selection of *Blechnum* and Poaceae as representative of local palaeoenvironmental conditions on the surface of Bromfield Swamp appears valid given differing ecologies: *B. indicum* grows on swampy ground that periodically floods (Chambers & Farrant 1998) to a depth of up to 0.1–0.15 m (Wösten *et al*. 2006); grasses contributing to the pollen record (*L. hexandra* and *Sacciolepis indica*) grow in moist places including muds and peats, particularly on swamp margins (Jacobs & Hastings 1993, Jacobs & James 1993, Kodela & Weiller 2009).

Blechnum:Poaceae ratios vary considerably over the 4000 year period, with the highest ratios recorded for two identified wet shifts between 3500 and 4000 cal. yr BP and low values recorded for two dry phases (4040 cal. yr BP, 2220 cal. yr BP). Here ratios ≤ 1 are interpreted as indicating dry conditions, a ratio of >1–3 wet or dry conditions, and a ratio >3 wet conditions. Not all calculated ratios conform to this scaling; for example, at 77 cm wet surface conditions are indicated while the humification record indicates a drying of the swamp surface, but this may reflect a low pollen sum (≤ 250 grains).

Delta ^{13}C

$\delta^{13}C$ values remain low (-26.6 ‰ to -21.2 ‰) from 2.20–0.75 m, indicating the contribution of C_3 land plants and aquatic macrophytes, before increasing up-sequence towards the swamp surface (Figure 6). Values fall during peat initiation to a low of 26.6 ‰ that corresponds with high humic acid concentrations (indicative of drier conditions) at 4060 cal. yr BP, subsequently rising through an identified wet shift (that commenced at 3830 cal. yr BP) to 24.1 ‰ at 3750 cal. yr BP. Thereafter, $\delta^{13}C$ values slowly fall to -26.1 ‰ at 3160 cal. yr BP. In the upper part of the cored peat sequence $\delta^{13}C$ values rise, with -15.7 ‰ at 0.25 m indicating a mix of C_4 terrestrial plants and aquatic macrophytes. Organic lake mud or gyttja from present swamp surfaces returned values of -22.5 ‰ and -20.2 ‰, pointing to the contribution of pasture grasses and aquatic macrophytes that presently grow about the swamp margin.

Ratio of Carbon to Nitrogen

C/N ratios rise swiftly from 25.5 in the uppermost organic lake muds to 47.7 in the basal peats following the dry shift at 4220 cal. yr BP (Figure 6). This change would seem to indicate a decrease in the contribution of algae and a greater contribution by dryland plants. A lower ratio of 29 following the wet shift of 3830 cal. yr BP may indicate a slightly smaller contribution by plants of dryland origin. C/N ratios then climb again, possibly reflecting a dry shift observed in the humification record at 3380 cal. yr BP. C/N ratios then steadily fall to the present day with ratios of 9.7 and 11.2 in surface sediments reflecting the contemporary contribution of aquatic plants and lacustrine algae.

Macrocharcoal

Large macrocharcoal peaks are recorded during the initiation phase of the peat sequence at approximately 4090 cal. yr BP and 3700–3620 cal. yr BP. Both of these time periods are coincident with dry phases. Smaller charcoal peaks at *ca*. 2860, 2820, 2620, 2560, 2130, 1930, 1740 and 200 cal. yr BP are found to coincide with periods of average effective precipitation and so may signal wildfire on the swamp surface, transport and re-deposition down-slope of old charcoal after a high rainfall event, or burning of swamp vegetation by indigenous people.

DISCUSSION

Mid-Late Holocene evolution of Bromfield Swamp

The high-resolution humification record for Bromfield Swamp provides evidence of possible centennial and millennial-scale changes in peatland surface wetness that reflects mid–late Holocene climates. To assess the strength and validity of the humification proxy, the data are examined alongside high resolution macrocharcoal data and lower resolution records of aquatic plant taxa pollen and spores, and values of $\delta^{13}C$ and C/N documenting the evolution of Bromfield Swamp from lake to terrestrial wetland (Figure 6).

The lowering of water levels on the lake within Bromfield crater and the subsequent development of the swamp (with associated initiation of the peats) has been attributed to active downcutting of the outlet approximately 4600–3900 cal. yr BP. (Kershaw 1973, 1975). This proposition was based on the observed decrease in the inorganic content of sediments over the time segment and an increase in the ratio of aquatic/dryland pollen (Kershaw 1975). Our pollen analysis does support the contention of vegetation change over the time segment; however, magnetic susceptibility records for cores BSAT01, BSAT02 and BSAT03 show no evidence of inorganic sediment deposition for the period 4600–3900 cal. yr BP. We propose, instead, that the lowering of water levels and subsequent swamp development are the result of a slow partial infilling of the basin with sediments (terrestrialisation) coupled with a long period of drying in the landscape or increased seasonality of rainfall (Haberle 2005, Kershaw & Nix 1988). Support for the occurrence of a long dry phase is found in the peat humification record for Mount Quincan crater swamp, a dry shift being recorded at 4580 cal. yr BP., with humification values falling progressively to a very low value (<10 % transmission) at 4040 cal. yr BP (Burrows *et al*. in press).

The aquatic plant pollen record shows changes in the environment of deposition over a 4000 year period. The contiguous record of the pteridophyte *Blechnum* over nearly the entire period of peat formation implies the early establishment of wetland plant communities growing on a root mat attached to a solid substrate (Kershaw 1975, 1979). While individual plant taxa recorded in the peat record did change over time, the continued dominance of *Blechnum* spores in the record suggests the likely continuation of plant communities growing on a solid substrate at least until the commencement of European agricultural practices in the catchment, possibly in the first decade of the 20th Century. Spores of *Lygodium* and *Anthoceras* are important constituents of the microfossil record, *Lygodium* at 1.62–1.05 m and *Anthoceras* at 0.62–0.25 m, evidence that Kershaw (1978) used to indicate infrequent flooding of the wetland surface.

Hydrological conditions on the surface of Bromfield Swamp altered with the clearing of rainforest on the crater slopes for agriculture in the first four decades of the 20th century and the construction of a culvert (post 1950s) at the exit from the swamp into the tributary of the North Johnstone River. Organic lake muds with a clay component replaced peat deposition in areas of the swamp and it is possible that parts of the stable vegetation mat rose with the heightened water levels in the swamp, forming a floating mat. Rates of sediment accumulation are presently calculated to be 0.148 ± 0.01 g/cm^2/yr (CIC Model of ^{210}Pb dating), and thus substantially higher than during accumulation of the peats (calculated at 0.1 m every 18 years).

Humification stratigraphy as a proxy for climate wetness

Detrended humification data (Figure 7) show a series of low frequency shifts that in the upper stratigraphy probably relate to changes in surface wetness of the swamp with 16 shifts to wetter conditions (Table 3).

The ratio of *Blechnum* to Poaceae varies considerably over the 4000 year period of peat formation (Figure 6), with the highest ratios recorded for two identified wet phases between 3800 and 3400 cal. yr BP and low values recorded for two dry phases at 4040 and 2220 cal. yr BP. Support for existence of the two wet shifts may be provided by the mid-late Holocene palaeoclimatic reconstructions of Kershaw & Nix (1988). Using the bioclimatic profiles of extant rainforest plant taxa, these authors calculated mean annual precipitation on the Atherton Tableland to be slightly elevated for the period 5000–3600 cal. yr BP and subsequently lower for the period 3600–2600 cal. yr BP. The possible lack of fine resolution in the palaeoclimatic estimates does not, however, allow identification of centennial-length (or shorter) changes in annual precipitation; consequently, wet and dry shifts identified in the humification record are too ephemeral to appear in the palaeoclimatic reconstructions.

δ^{13}C analysis of sediments in core BSAT03 is used as a proxy of the relative abundance of C_3 and C_4 plants in the peats and underlying organic lake muds. δ^{13}C values, while remaining low throughout the lower three-quarters of the sedimentary sequence, fluctuate near the base, falling though the period of peat initiation to a low of -26.6 ‰ at 4060 cal yr BP (during a proposed dry phase) before rising through an identified wet shift to -24.1 ‰ at 3750 cal. yr BP. δ^{13}C values then fall away to -26.1 ‰ at 0.148 m (3160 cal. yr BP) before rising steadily to -21.2 at 0.077 m (1580 cal. yr BP). The input of plants using the C_3 pathway, specifically the local wetland flora, together with an input from trees, shrubs and grasses is thought to be important throughout this period. In the upper part of the sequence δ^{13}C values rise, -15.7 ‰ being recorded for a sample at 0.025 m (420 cal. yr BP), implying that the input of plants using the C_4 pathway, such as subtropical grasses, may have been an important contributor to the swamp flora (Norstrom *et al*. 2009). Significantly, a sample collected from the swamp surface in 2010 and a second taken from the surface of a mud-water interface core (^{210}Pb model suggesting date of deposition around 1990) returned values of -22.5 ‰ and -20.2 ‰ respectively. These values indicate the return of a C_4 assemblage on the present-day

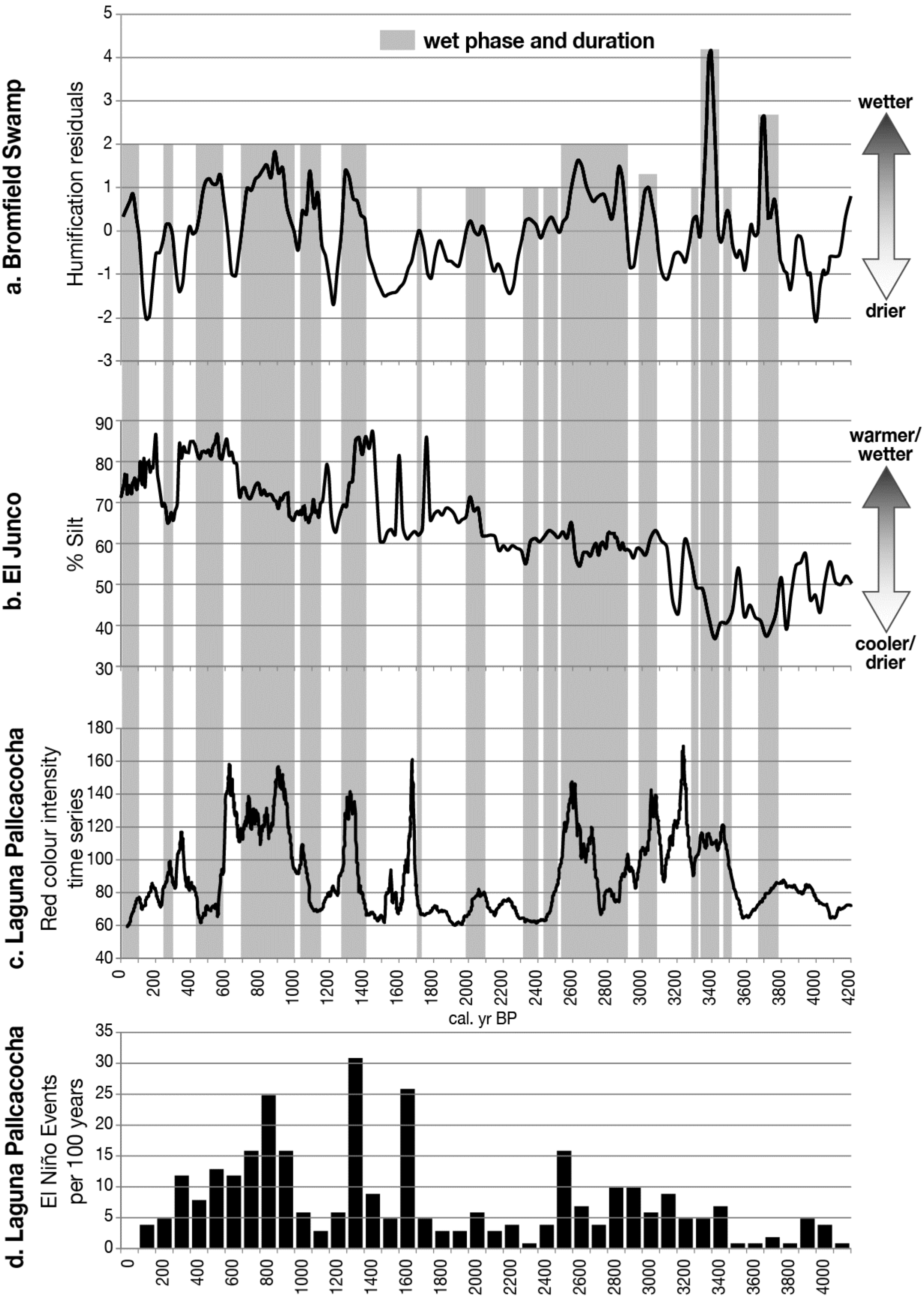

Figure 7. Proxy records of wet phases (Bromfield Swamp humification; El Junco grain size distribution) and El Niño events per hundred years (Laguna Pallcacocha).

wetland, pointing possibly to the contribution of aquatic macrophytes and exotic pasture grasses growing about the swamp margin.

C/N ratios are thought to indicate the probable origin of organics in sediments (Meyers & Teranes 2001). A C/N ratio of 25.5 recorded in the uppermost organic lake muds is indicative of a contribution by algae to the sediments; pollen analysis supported this assertion with the finding of abundant algae including *Botryococcus* sp. A ratio of 47.7 in the basal peats following the dry shift at 4220 cal. yr BP. would seem to indicate a greater contribution by dryland plants and a decrease in the contribution of algae. A subsequent lower ratio of 29 following the wet shift of 3830 cal. yr BP may indicate a slightly smaller contribution by plants of dryland origin. Ratios then climb again, possibly reflecting a dry shift observed in the humification record (3380 cal. yr BP.), to a high of 37.5 at 3160 cal. yr BP. C/N ratios then steadily fall to the present-day with ratios of 9.7 and 11.2 in surface sediments reflecting the contemporary contribution of aquatic plants and lacustrine algae.

The abundance of the two size fractions of macrocharcoal from the core are used as an indicator of the proximity of fire to the central swamp surface. The largest macrocharcoal peaks are recorded during the initiation phase of the peat sequence at around 4090 cal. yr BP and 3700–3620 cal. yr BP: both time periods coincident with identified dry phases in the humification record. The onset of drier conditions may have resulted in a considerable reduction in the spatial area of the swamp, so allowing local fires to burn farther into the crater base. Isolated smaller macrocharcoal peaks at *ca*. 2860, 2820, 2620, 2560, 2130, 1930, 1740 and 200 cal. yr BP coincide with periods of average effective precipitation (deduced from the humification record) and so may indicate the spread of wildfire onto the swamp surface or burning initiated by aboriginal people (Cosgrove *et al*. 2007), possibly to promote the growth of particular plant species (eg. *Blechnum indicum*). Alternatively, high rainfall events may transport and re-deposit old charcoal downslope.

Regional comparisons

The timing and duration of wet and dry shifts identified in this study are consistent with the results of other regional studies indicating increased climatic variability in northern Australia during the mid–late Holocene. Schulmeister & Lees (1995), in a re-examination of a pollen record for Groote Eylandt, identified an effective precipitation maximum in the mid-Holocene, a subsequent sudden fall in effective precipitation during the period 4000–3500 cal. yr BP, and a return to higher effective precipitation in the last 2000 years. Lees (1992) identified phases of increased rainfall at 3500–2800 and 2100–1600 cal. yr BP and at least two more in the last 1000 years, during a period of increased aridity in northern Australia. A wetter phase or event *ca*. 2600 cal. yr BP is recognised by Rowe (2007), based on observed changes in lithology and pollen preservation in freshwater swamp sediments from Mua and Badu Islands in the Torres Strait. Large and irregular charcoal peaks recorded in the sedimentary record for Lake Euramoo after 4000 cal. yr BP, together with indications of rainforest disturbance, lead Haberle (2005) to suggest that fires were not constrained to sclerophyll forest pockets but were also burning through the rainforest canopy on the Atherton Tableland. These peaks of charcoal were found to have occurred with a frequency of 250–1000 years (Haberle 2005, Haberle *et al*. 2010); a frequency similar to that recorded for Bromfield Swamp over the same time period. It should be stated that the increased rainforest disturbance observed by Haberle (2005) is thought to be indicative of onset of drier conditions or increased rainfall seasonality (Kershaw & Nix 1988).

An 800 year archive of tropical cyclone activity, obtained through $\delta^{18}O$ analysis of a stalagmite from the Chillagoe karst, 125 km WNW of Bromfield Swamp, provides further validation for wet shifts identified by humification. Two clusters of higher intensity cyclonic events are identified in the annual resolution $\delta^{18}O$ record, at 550–450 cal. yr BP and 350–150 cal. yr BP (Nott *et al*. 2007). The humification record, while chronicling change at a coarser (multi-decadal) resolution, indicates the occurrence of a wet phase over the period of each cluster of cyclonic events. The oxygen isotope record indicates a high magnitude cyclonic event every 200–300 years (Nott *et al*. 2007): the humification record possibly indicates a similar rate of recurrence of wet phases.

To further evaluate the strength of the Bromfield Swamp humification record, it is set against a proxy record for increased precipitation from the tropical eastern Pacific El Junco grain size distribution (Conroy *et al*. 2008) and a plot of El Niño events per hundred years recorded for Laguna Pallcacocha (Moy *et al*. 2002) (Figure 7). It can be seen that there exists a strong anti-correlation between the humification record for Bromfield Swamp and the two eastern Pacific records: wet phases in the western Pacific match well with increased periods of dryness in the eastern Pacific record. This implies that the Bromfield Swamp humification record may serve as an ENSO proxy for north-east Queensland.

CONCLUSIONS

Our high-resolution humification record for a peat sequence from Bromfield Swamp provides evidence of possible centennial and millennial-scale climate change for the humid tropics of north-eastern Australia in the mid–late Holocene.

Analyses of aquatic and dryland pollen, $\delta^{13}C$, C/N and macrocharcoal data collected from targeted depths in the Bromfield Swamp peat sequence provides validation for millennial-scale changes in effective precipitation on the Atherton Tableland over the past 4000 years. The ratio of *Blechnum* to Poaceae grains appears to validate centennial-scale wet and dry shifts as identified in the humification record.

The degree of agreement between different palaeoclimatic proxies used in this study give us confidence that peat humification analysis, applied here to peat extracted from a Southern Hemisphere fen, is robust. Higher-resolution radiocarbon dating, together with higher-resolution pollen, $\delta^{13}C$ and C/N sampling and analysis may enhance our understanding of climatic variability, particularly for the last 1500 years. Determination of the specific hydrological tolerances of the many pteridophyte species on the present surface of Bromfield Swamp may also prove beneficial in identifying wet and dry shifts in the peatland record.

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REFERENCES

Ariztegui, D., Farrimond, P. & Mckenzie, J.A. (1996) Compositional variations in sedimentary lacustrine organic matter and their implications for high Alpine Holocene environmental changes: Lake St. Moritz, Switzerland. *Organic Geochemistry*, 24(4), 453–461.

Aucour, A-M., Bonnefille, R. & Hillaire-Marcel, C. (1999) Sources and accumulation rates of organic carbon in an equatorial peat bog (Burundi, East Africa) during the Holocene: carbon isotope constraints. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 150, 179–189.

Australian Wetlands Database (2010) *Bromfield Swamp - QLD141. Directory of Important Wetlands in Australia – Information Sheet*. Online at: http://www.environment.gov.au/cgi-bin/wetlands/report.pl (accessed 12 Aug 2013).

Bailey, F.M. (1909) *Comprehensive Catalogue of Queensland Plants Both Indigenous and Naturalised. To Which Are Added, Where Known, the Aboriginal and Other Vernacular Names; With Numerous Illustrations, and Copious Notes on the Properties, Features etc., of the Plants.* Government Printer, Brisbane, 879 pp.

Barber, K. & Charman, D. (2005) Holocene palaeoclimate records from peatlands. In: Mackay, A., Battarbee, R., Birks, J. & Oldfield, F. (eds.) *Global Change in the Holocene.* Hodder Education, London, 210–216.

Belyea, L.R. & Clymo, R.S. (2001) Feedback control on the rate of peat formation. *Proceedings of the Royal Society of London: Biological Sciences,* 268, 1315–1321.

Bennett, K.D. & Willis, K.J. (2001) Pollen. In: Smol, J.P., Birks, H.J.B. & Last, W.M. (eds.) *Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal, and Siliceous Indicators*. Kluwer Academic Publishers, Dordrecht, 5–32.

Black, M.P., Mooney, S.D. & Attenbrow, V. (2008) Implications of a 14200 year contiguous fire record for understanding human–climate relationships at Goochs Swamp, New South Wales, Australia. *The Holocene*, 18(3), 437–447.

Blackford, J.J. (1993) Peat bogs as sources of proxy climatic data: past approaches and future research. In: Chambers, F. (ed.) *Climate Change and Human Impact on the Landscape*. Chapman and Hall, London, 7–24.

Blackford, J.J. & Chambers, F.M. **(**1991) Proxy records of climate from blanket mires: evidence for a Dark Age (1400 BP) climatic deterioration in the British Isles. *The Holocene,* 1, 63–67.

Blackford, J.J. & Chambers, F.M. **(**1993) Determining the degree of peat decomposition in peat-based palaeoclimatic studies. *International Peat Journal*, 5, 7–24.

Blackford, J.J. & Chambers, F.M. **(**1995) Proxy climate record for the last 1000 years from an Irish blanket peat and a possible link to solar variability. *Earth and Planetary Science Letters*, 133, 145–150.

Booth, R.K. & Jackson, S.T. (2003) A high-resolution record of late-Holocene moisture variability from a Michigan raised bog, USA. *The Holocene*, 13(6), 863–876.

Borgmark, A. (2005) Holocene climate variability and periodicities in south-central Sweden, as interpreted from peat humification analysis. *The Holocene*, 15, 387–395.

Boutton, T.W. (1991) Stable isotope ratios of natural materials: II. Atmospheric, terrestrial, marine, and freshwater environments. In: Coleman, D.C. & Fry, B. (eds.) *Carbon Isotope Techniques*. Academic Press Inc., San Diego, 173–186.

Bronk Ramsey, C. (2008) Deposition models for chronological records. *Quaternary Science Reviews*, 27(1–2), 42–60.

Bultitude, R.J., Garrad, P.D., Wegner, S., Donshak, P.J.T. & Fanning, C.M. (1999) *Innisfail, Second Edition. Queensland 1:250 000 Geological Series Explanatory Notes.* Geological Survey of Queensland, Brisbane.

Burrows, M.A., Fenner, J. & Haberle, S.G. (in press) Humification in northeast Australia: dating millennial and centennial scale climate variability in the Late Holocene. *The Holocene*.

Bushby, J.R. (1991) BIOCLIM - a bioclimatic analysis and prediction system. In: Margules, C.R. & Austin, M.P. (eds.) *Nature Conservation Cost Effective Biological Surveys and Data Analysis*. CSIRO, Melbourne, 64–68.

Chambers, F.M. (2006) *ACCROTELM: Abrupt Climate Changes Recorded Over The European Land Mass.* Final Report, Contract No. EVK2-CT-2002-00166, European Commission, Brussels, 117 pp.

Chambers, F.M., Beilman, D.W. and Yu, Z. (2011) Methods for determining peat humification and quantifying peat bulk density, organic matter and carbon content for palaeostudies of climate and peatland carbon dynamics. *Mires and Peat,* 7(11), 1–10.

Chambers, F.M., Barber, K.E., Maddy, D. & Brew, J.S. (1997) A 5500-year proxy-climate and vegetational record from a blanket mire at Talla Moss, Borders, Scotland. *The Holocene*, 7, 391–399.

Chambers, T.C. & Farrant, P.A. (1998) Blechnaceae. In: McCarthy, P.M. (ed.) *Flora of Australia. Volume 48, Ferns, Gymnosperms and Allied Groups*. ABRS Canberra / CSIRO, 359–393.

Charman, D. (2002) *Peatlands and Environmental Change*. John Wiley & Sons Inc., USA, 312 pp.

Charman, D. (2005) Summer water deficit variability controls on peatland water-table changes: implications for Holocene palaeoclimate reconstructions. *The Holocene*, 17(2), 217–227.

Clymo, R.S. (1965) Experiments on breakdown of *Sphagnum* in two bogs. *Journal of Ecology*, 53, 747–758.

Coleman, D.C. & Fry, B. (1991) *Carbon Isotope Techniques*, Academic Press, San Diego, 273 pp.

Conroy, J.L., Overpeck, J.T., Cole, J.E., Shanahan, T.M. & Steinitz-Kannan, M. (2008) Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake sediment record. *Quaternary Science Reviews*, 27, 1166–1180.

Cosgrove, R., Field, J. & Ferrier, A. (2007) The archaeology of Australia’s tropical rainforests. *Palaeogeography, Palaeoclimatology, Palaeo-ecology*, 251, 150–173.

Frolking, S., Roulet, N.T., Tuittila, E., Bubier, J.L., Quillet, A., Talbot, J. & Richard P.J.H. (2010) A new model of Holocene peatland net primary production, decomposition, water balance, and peat accumulation. *Earth System Dynamics*, 1, 1–21.

Gill, R. (2010) *Igneous Rocks and Processes: A Practical Guide*. Wiley-Blackwell, Chichester, x+428 pp.

Grimm, E.C. (1987) CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers & Geosciences*, 13(1), 13–35.

Grimm, E.C. (1993) *Tilia* (software). Illinois State Museum, Springfield, Illinois.

Grimm, E.C. (2004) *TGView* (software). Illinois State Museum, Research and Collections Center, Springfield, Illinois.

Haberle, S. (2005) A 23,000-yr pollen record from Lake Euramoo, Wet Tropics of NE Queensland, Australia. *Quaternary Research*, 64(3), 343–356.

Haberle, S.G., Rule, S., Roberts, P., Heijnis, H., Jacobsen, G., Turney, C., Cosgrove, R., Ferrier, A., Moss, P., Mooney, S. & Kershaw, P. (2010) Paleofire in the wet tropics of northeast Queensland, Australia. *PAGES News*, 18(2) August, 78–80.

Herczeg, A.L., Smith, A.K. & Dighton, J.C. (2001) A 120 year record of changes in nitrogen and carbon cycling in Lake Alexandrina, South Australia: C:N, δ^{15}N and δ^{13}C in sediments. *Applied Geochemistry*, 16, 73–84.

Hillaire-Marcel, C., Aucour, A-M., Bonnefille, R., Riollet, G., Vincens, A. & Williamson, D. (1989) ^{13}C / palynological evidence of differential residence times of organic carbon prior to its sedimentation in East African lakes and peatbogs. *Quaternary Science Reviews*, 8, 207–212.

Ingram, H.A.P. (1978) Soil layers in mires: function and terminology. *Journal of Soil Science*, 29, 224–227.

Jacobs, S.W.L. & Hastings, S.M. (1993) Leersia. In: Harden, G.J. (ed.) *Flora of New South Wales, Volume 4*, UNSW Press, Australia, 650–651.

Jacobs, S.W.L. & James, T.A. (1993) Sacciolepis. In: Harden, G.J. (ed.) *Flora of New South Wales, Volume 4*. UNSW Press, Australia, 489.

Jones, D.L. & Clemesha, S.C. (1980) *Australian Ferns and Fern Allies*. Reed Books, Frenchs Forest, 232 pp.

Kershaw, A.P. (1973) *Late Quaternary Vegetation of the Atherton Tableland, North-east Queensland, Australia.* PhD thesis, ANU, Canberra.

Kershaw, A.P. (1975) Stratigraphy and pollen analysis of Bromfield Swamp, north eastern Queensland, Australia. *New Phytologist*, 75, 173–191.

Kershaw, A.P. (1978) The analysis of aquatic vegetation on the Atherton Tableland, north-east Queensland, Australia. *Australian Journal of Ecology*, 3, 23–42.

Kershaw, A.P. (1979) Local pollen deposition in aquatic sediments on the Atherton Tableland, North-Eastern Australia. *Australian Journal of Ecology*, 4, 253–263.

Kershaw, A.P. (1997) A modification of the Troels-Smith system of sediment description and portrayal. *Quaternary Australasia*, 15(2), 63–68.

Kershaw, A.P. & Nix, H.A. (1988) Quantitative palaeoclimatic estimates from pollen using bioclimatic profiles of extant taxa. *Journal of Biogeography*, 15, 589–602.

Kershaw, A.P. & Sluiter, I.R. (1982) Late Cenozoic pollen spectra from the Atherton Tableland, north-eastern Australia. *Australian Journal of Botany*, 30, 279–295.

Kershaw, P. & van der Kaars, S. (2012) Australia and the Southwest Pacific. In: Metcalfe, S.E. & Nash, D.J. (eds.) *Quaternary Environmental Change in the Tropics*. Wiley-Blackwell, Chichester, 236–262.

Kodela, P.K. & Weiller, C.M. (2009) Leersia. In: Wilson, A. (ed.) *Flora of Australia, Volume 44A, Poaceae 2*. ABRS Canberra / CSIRO, 360–361.

Lees, B.G. (1992) Geomorphological evidence for late Holocene climatic change in northern Australia. *Australian Geographer*, 23, 1–10.

Mackie, E.A.V., Lloyd, J.M., Leng, M.J., Bentley, M.J. & Arrowsmith, C. (2007) Assessment of δ^{13}C and C/N ratios in bulk organic matter as palaeosalinity indicators in Holocene and Lateglacial isolation basin sediments, northwest Scotland. *Journal of Quaternary Science*, 22(6), 579–591.

Malanda Parish Plan No. 335 (1907) *Plan of Portion No. 165 to 168, 176 to 182*. Landcentre, Department of Environment and Resource Management, Brisbane, Queensland. Electronic version accessed 27 October 2010.

Mauquoy, D. & Barber, K.E. (1999) A replicated 3000 yr proxy-climate record from Coom Rigg Moss and Felecia Moss, the Border Mires, northern England. *Journal of Quaternary Science*, 14, 263–275.

Meyers, P.A. (1994) Preservation of elemental and isotopic source identification of sedimentary organic matter. *Chemical Geology*, 114, 289–302.

Meyers, P.A. & Teranes, J.L. (2001) Sediment organic matter. In: Last, W.M. & Smol, J.P. (eds.) *Tracking Environmental Change Using Lake Sediments, Volume 2, Physical and Geochemical Methods.* Kluwer Academic Publishers, Dordrecht, The Netherlands, 239–269.

Montanari, S., Louys, J. & Price, G.J. (2013) Pliocene paleoenvironments of southeastern Queensland, Australia inferred from stable isotopes of marsupial tooth enamel. *PLoS ONE*, 8(6): e66221. doi:10.1371/journal.pone.0066221.

Moy, C.M., Seltzer, G.O., Rodbell, D.T., & Anderson, D.M. (2002) Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature*, 420(6912), 162–165.

Muller, J., Kylander, M., Wüst, R.A.J., Weiss, D., Martinez-Cortizas, A., LeGrande, A.N., Jennerjahn, T., Behling, H., Anderson, W.T. & Jacobson, G. (2008) Possible evidence for wet Heinrich phases in tropical NE Australia: the Lynch’s Crater deposit. *Quaternary Science Reviews*, 27, 468–475.

Norström, E., Scott, L., Partridge, T.C., Risberg, J. & Holmgren, K. (2009) *Palaeogeography, Palaeoclimatology, Palaeoecology*, 271, 240–258.

Nott, J., Haig, J., Neil, H. & Gillieson, D. (2007) Greater frequency variability of landfalling tropical cyclones at centennial compared to seasonal and decadal scales. *Earth and Planetary Science Letters*, 225, 367–372.

O'Leary, M.H. (1988) Carbon isotopes in photosynthesis. *Bioscience*, 38, 328–336.

Payne, R.J. & Blackford, J.J. (2008) Peat humification and climate change: a multi-site comparison from mires in south-east Alaska. *Mires and Peat*, 3(09), 1–11.

Richardson, F. & Hall, V. (1994) Pollen concentrate preparation from highly organic Holocene peat and lake deposits for AMS dating. *Radiocarbon*, 36(3), 407–412.

Rowe, C. (2007) A palynological investigation of Holocene vegetation change in Torres Strait, seasonal tropics of northern Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 251, 83–103.

Ruppel, M., Väliranta, M., Virtanen, T. & Korhola, A. (2013) Postglacial spatiotemporal peatland initiation and lateral expansion dynamics in North America and northern Europe. *The Holocene*, 23(11), 1596–1606.

Schulmeister, J. & Lees, B.G. (1995) Pollen evidence from tropical Australia for the onset of an ENSO dominated climate at 4000 Yr BP. *The Holocene*, 5, 10–18.

Sillasoo, Ü., Mauquoy, D., Blundell, A., Charman, D., Blaauw, M., Daniell, J.R.G., Toms, P., Newberry, J., Chambers, F.M. & Karofeld, E. (2007) Peat multi-proxy data from Männikjärve bog as indicators of late Holocene climate changes in Estonia. *Boreas*, 36, 20–37.

Stevenson, J. & Haberle, S. (2005) *Palaeoworks Technical Papers 5. Macro Charcoal Analysis: A Modified Technique Used by the Department of Archaeology and Natural History*. ANH, RSPAS, ANU, Australia, 7 pp. Online at: http://palaeoworks.anu.edu.au/paltr05.pdf (accessed 12 Jly 2014).

Sukumar, R., Ramesh, R., Pant, R.K. & Rajagopalan, G. (1993) A $\delta^{13}C$ record of late Quaternary climate change from tropical peats in southern India. *Nature*, 364, 703–706.

Tieszen, L.L. (1991) Natural variations in the carbon isotope values of plants: implications for archaeology, ecology, and paleoecology. *Journal of Archaeological Science*, 18, 227–248.

Tuittila, E.-S.,Väliranta, M., Laine, J. & Korhola, A. (2007) Quantifying patterns and controls of mire vegetation succession in a southern boreal bog in Finland using partial ordinations. *Journal of Vegetation Science*, 18, 891–902.

Turney, C.S.M., Kershaw, A.P., Clemens, S.C., Branch, N., Moss, P.T. & Fifield, L.K. (2004) Millennial and orbital variations of El Nino/ Southern Oscillation and high latitude climate in the last glacial period. *Nature*, 428, 306–310.

Wang, Y. & Wooller, M.J. (2006) The stable isotopic (C and N) composition of modern plants and lichens from northern Iceland: with ecological and palaeoenvironmental implications. *Jökull*, 56, 27–37.

Whitehead, P.W., Stephenson, P.J., McDougall, I., Hopkins, M.S., Graham, A.W., Collerson, K.D. & Johnson, D.P. (2007) Temporal development of the Atherton Basalt Province, north Queensland. *Australian Journal of Earth Sciences: An International Geoscience Journal of the Geological Society of Australia*, 54(5), 691–709, DOI: 10.1080/08120090701305236.

Wösten, J.H.M., Van Den Berg, J., Van Eijk, P., Gevers, G.J.M., Giesen, W.B.J.T., Hooijer, A., Idris, A., Leenman, P.H., Rais, D.S., Siderius, C., Silvius, M.J., Suryadiputra, N. & Wibisono, I.T. (2006) Interrelationships between hydrology and ecology in fire degraded tropical peat swamp forests. *International Journal of Water Resources Development*, 22(1), 157–174.

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