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A 1000-year reconstruction of summer precipitation from Ireland: calibration of a peat-based palaeoclimate record

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Abstract

Calibration of proxy climate records is well-established for annually resolved proxies such as tree rings, but it has not been attempted for non-annually resolved proxies such as those from peatland surface wetness records. Several previous studies have suggested that peatland surface wetness is primarily driven by warm season moisture balance and implied a potential for producing calibrated records of deficit or precipitation. This paper presents a high-resolution testate amoebae analysis of a peat record from central Ireland covering the last c.1000 years, and provides the first attempt to produce a calibrated record of past precipitation from a peat record. Past water table depth was reconstructed using a transfer function applied to contiguous samples for the top 1m of the profile. The chronology was constrained by a series of radiocarbon ages (including 'bomb-spike' ages) and spheroidal carbonaceous particles. Correlations between reconstructed water tables and meteorological records (1958-1995) of precipitation and deficit were strongly positive and were used to reconstruct precipitation and deficit from the last 1000 years. Validation using earlier meteorological records was hampered by very low peat accumulation rates, but suggested the summer precipitation and deficit reconstructions were more robust than a reconstruction of annual precipitation. The summer precipitation reconstruction suggests that the period AD1400-1850 experienced higher summer rainfall than for much of both the preceding 400 years and the last 150 years. The change in regime from low to high summer rainfall may be attributed to changes in the summer North Atlantic Oscillation. Combined with tree ring and speleothem records of winter NAO, this suggests a major change in seasonality of precipitation in far western Europe between the Medieval Climate Anomaly and the Little Ice Age. The MCA was characterised by dry summers and wet winters, whilst the LIA had wet summers and dry winters. Calibration of peat surface wetness records using meteorological records holds much potential for the future and may lead to improved insights into seasonal precipitation and water balance changes. This study was limited by slow accumulation rates leading to low temporal resolution for the late 19th and early 20th century part of the record. Further development of the technique will require more highly temporally resolved records of change over the whole of the instrumental time period to allow a full calibration and validation approach to be applied.

Key words: *calibration, palaeoclimate, testate amoebae, peat, precipitation, NAO*

1. Introduction

Reconstructions of past climate change provide a context for current and future climate variability, insights into large-scale mechanisms of climate variability and tests of climate response to a range of climate forcings. The last 1000 years is an important period because major climate change has occurred over this time, many of the forcings are important in the context of future climate change, and data density is sufficient to reconstruct large-scale spatial patterns of past changes (Jones *et al.* 2009). Temperature variability over the northern hemisphere is quite well understood (Mann *et al.* 1998, Mann *et al.* 1999, Mann and Jones 2003, Moberg *et al.* 2005, National Research Council, 2006) but precipitation and water balance are generally poorly constrained. It is more difficult to gain an accurate understanding of hydroclimate because: 1) instrumental records are generally not as extensive in time or space and there are significant problems with homogeneity of early measurements; 2) precipitation change displays greater spatial variability over the period of instrumental records and presumably further back in time as well; 3) most proxy-climate records are sensitive to temperature, and few records contain a clear hydroclimate signal. However, precipitation and water balance are vitally important in societal terms, both because of the dependence of food production and water supply, but also because extreme events have the potential to cause major natural disasters through flooding. Furthermore, many changes in large scale atmospheric circulation patterns manifest themselves in precipitation patterns as well or more clearly than in temperature changes, so past changes in these features may be revealed better in precipitation-sensitive proxies than temperature-sensitive proxies. Because of the importance of hydroclimate to human society, the potential for much greater spatial variability of temporal trends and the relationship between large scale circulation patterns and precipitation changes, an important if ambitious goal in palaeoclimate science should be to build enough records of precipitation change from a range of key regions to reconstruct hemispheric or global scale patterns of change over the past 1000 years and potentially beyond. Temperature reconstructions for the last 1000 years have shown that testing, calibration and integration of proxy records with instrumental meteorological data plays a key part in developing high quality reconstructions (Proctor *et al.* 2000, Moberg *et al.* 2005, Jones *et al.* 2009). Relatively few precipitation reconstructions have achieved this but there are good examples from precipitation sensitive tree ring series (Brazdil *et al.* 2002, Wilson *et al.* 2005, Touchan *et al.* 2005, Masson-Delmotte *et al.* 2005, Treydte *et al.* 2006, Davi *et al.* 2006, Cook *et al.* 2007), and annually banded speleothems (Proctor *et al.* 2002).

Peatlands provide records of water balance at approximately decadal resolution for much of the mid-late Holocene, and recent work has demonstrated that reconstructed water table records for the past 1-200 years based on testate amoebae analysis can be produced at sufficiently high resolution for direct comparison with instrumental climate data (Hendon and Charman 2004, Charman 2007). These studies mainly support the idea that peatland water tables are driven by warm season water deficit (Charman 2007, Charman et al., 2009), rather than precipitation or temperature *per se*. Warm season deficit is the total deficit for all months in the year where evapotranspiration exceeds precipitation. However, the relative importance of precipitation and temperature in driving warm season deficit varies geographically with climate regime. In temperate Europe, it is primarily a function of warm season precipitation because evapotranspiration rates are relatively low. However, there is a gradient across Europe, with precipitation more important in oceanic regions and an increasing influence of temperature variability in continental areas (Charman et al. 2004). However, these studies have so far been conducted at only a small number of sites and whilst most of the results support the broad interpretation above, there are too few data to provide a thorough test of this hypothesis. Further data, particularly from the climatic extremes of peatland distribution, are required to build a more complete understanding of response to climate change over decadal timescales.

The aim of this study is to derive a high resolution record of water table variability for a hyperoceanic site in Ireland and correlate it with local meteorological records for the past 100 years, to assess whether it can be interpreted as a record of precipitation variability, and to determine the primary drivers of water table change here. The paper also presents a first attempt at producing calibrated records of precipitation and annual deficit using the relationship with instrumental records. So far no studies have attempted to use the relationships between water table reconstructions and instrumental climate data to calibrate longer-term reconstructions. The validity of the calibrated records derived here is assessed by comparison with both older instrumental records and regional reconstructions from documentary records.

2. Methods

Ballyduff is a raised bog 95 ha in extent, located in county Tipperary, central Ireland, at 53° 05' 10'' N, 7° 59' 35'' W, 60 m a.s.l. The geology in the area is dominated by Carboniferous limestone, overlain by glacial till deposited during the last glacial cold stage (Mitchell and Delaney, 1997). Climatic observations from Birr weather station (6 km east of the site) show mean annual temperatures of 9.3^{o}C , with mean temperature of the warmest month (July) at 15.0^{o}C and the mean temperature of the coldest month (January) at 4.8^{o}C. The average annual rainfall is 831 mm/yr (Met Éireann, unpublished data for the period 1961-1990 (www.met.ie)). The Armagh observatory is 170 km NW of Ballyduff and at the same altitude (60m). Ballyduff belongs to the true midland raised bogs that are typically found in regions with rainfall below 1000 mm/yr (Hammond, 1981). Although Ballyduff is not entirely intact, it is one of the less disturbed raised bogs in Ireland. The edges of the bog have been hand cut for domestic fuel resulting in encroachments of up to 50m. A series of commercial drains were cut into the SE corner of the bog between 1995 and 1999. These drains cover an area of c.10 ha but are at least 1 km from the coring site. The bog was never exploited commercially and the drains have recently been blocked for conservation management. The bog retains a dome-shaped profile with well developed hummock-hollow microtopography. The modern vegetation is typical for an Irish midland raised bog (Kelly and Schouten 2002); the ground layer on the central dome is dominated by *Sphagnum papillosum, S. cuspidatum* and *S. capillifolium*. In the field layer *Calluna vulgaris, Erica tetralix, Eriophorum vaginatum, E. angustifolium* and *Rhynchospora alba* are most common.

Fieldwork in Ballyduff took place in June 2003. The core was taken from a *Sphagnum papillosum* lawn in the centre of the bog to minimise edge effects. A Wardenaar monolith corer was used to extract the top 67 cm of peat with Russian corer sections (50 x 7 cm) below which overlapped by 25 cm. The bog was over 800 cm deep at the coring site.

2.1 Testate amoebae and water table reconstructions

Samples of 2 cm^3 were prepared for testate amoebae analysis using standard techniques (Hendon and Charman 1997), except that deionised water was used as a storage and counting medium and Safranin dye was not used. Samples were analysed contiguously every 1 cm down to 90cm depth, estimated as being c. 1000 AD from previous radiocarbon results (Yeloff *et al.* 2006). Counts in excess of 150 tests were made using the taxonomy of (Charman *et al.* 2000). Test concentration was very low in two samples near the surface (0-1 and 4-5 cm depth) and in one other sample at 24 cm depth. Counts in these samples only reached 50 tests. Reconstructed water table depth was calculated from percentage data, by applying the transfer function from (Charman *et al.* 2007), which includes 18 surface samples from Ballyduff bog. Cosmopolitanism in testate amoebae means that a Europe-wide data set is suitable for application at a smaller spatial scale and is likely to be more robust than a training set based on a smaller number of local sites (Payne et al., in press). A complex weighted average partial least squares (WAPLS) model performed slightly better in cross validation of the modern samples (RMSEP= 5.63 cm), but a weighted average tolerance downweighted (WA-Tol) model was adopted for this site because of its similar performance in cross validation (RMSEP= 5.97 cm) and its relative simplicity (See also (Sillasoo *et al.* 2007). Changes in water table are described in terms of the reconstructed water table (RWT). A fall in RWT indicates drier conditions (deep water tables) and a rise indicates wetter conditions (shallower water table depths).

2.2 Chronology

The chronology for the core was based on radiocarbon analyses (pre- and post-bomb samples) and spheroidal carbonaceous particles (SCPs). Lead-210 analyses were attempted but detected activity was too low to permit calculation of an independent chronology (Philip Toms, pers. comm.)

SCP analysis was adapted from Rose (1990, 1994). Small aliquots of peat (100–400 mg) were air dried at 50 ºC. The air-dried samples were weighed and subsequently digested in 25 ml concentrated HNO_3 at 180 ºC for 1 hour. The remaining residues were washed and decanted into pre-weighed vials. A small amount of each residue was mounted onto separate microscope slides and individual particles were counted under x400 magnification. Final weights of the vials and remaining residues were established to permit the calculation of the number of SCPs per gram of dried sediment

For radiocarbon analyses, samples of c. 5 cm^3 were boiled in 5% KOH, sieved with a 100 µm stainless steel sieve and washed with demineralised water until the water ran clear. Selected above-ground plant remains were picked out for radiocarbon analyses, mainly *Sphagnum* stems, branches and leaves, but also leaves of Ericaceae. These were carefully cleaned of rootlets and other contamination and stored at 4ºC prior to analysis at the Groningen Radiocarbon Laboratory. Full details are given in (Yeloff *et al.* 2006).

The SCP and radiocarbon age estimates were used to produce an age-depth model using OxCal4.1 (Bronk Ramsey 2009), using the P_sequence command (k=5, interpolated every 1 cm as an intermediate condition between complete flexibility and rigidity) (Bronk Ramsey 2008). Calibration curves applied were INTCAL04 (Reimer *et al.* 2004) and the NH01 dataset of (Hua and Barbetti 2004) for post-bomb ages.

2.3 Meteorological data

Monthly precipitation and temperature data were sourced from the IPCC data distribution centre (1901-1995, www.ipcc-data.org) and the Armagh observatory (1838-2001, www.arm.ac.uk, Butler *et al.* 1998, Garcia-Suarez et al. 2003). The IPCC data are interpolated from a network of stations with historical meteorological data and represent the 0.5^o x 0.5^o grid square in central Ireland where the site is situated, but the Armagh data go back to AD 1838, so span a longer time period. Monthly deficit was calculated from P-E and the sum of all months with P<E was calculated as total deficit for each year. The relationship between the IPCC and Armagh data sets was explored and compared with the water table reconstruction.

3. Results

3.1 Stratigraphy

The core is composed of well preserved *Sphagnum* peat throughout. Between 90 and 80 cm depth, the peat is poorly humified and composed of *Sphagnum cuspidatum* giving way to *Sphagnum imbricatum* with decreasing depth. Above 80 cm, the peat becomes more humified and is dominated by *S. imbricatum* and *S. capillifolium* with *Calluna* and *Erica* remains. A zone dominated by *Eriophorum vaginatum* occurs around 50 cm. The upper 40 cm are poorly humified and composed of *S. cuspidatum* giving way to *S. capillifolium* and *S. papillosum* towards the surface.

3.2 Testate amoebae and water table variability

The testate amoebae assemblages are dominated by *Amphitrema* species (*A. flavum*, *A. wrightianum*, *A. stenostoma*), *Difflugia pulex* and *Euglypha strigosa* and *Nebela militaris* in the top 30cm (Figure 1). The deepest part of the profile from 90cm suggests falling water tables associated with declines in *A.wrightianum* and *A. flavum*, and rising *D.pulex* and *N.militaris*. A deep water table persists until 57cm when *A.stenostoma* becomes constant and *A. wrightianum* begins a rise. The rise in water tables culminates at around 35cm when these taxa are at their maximum and are accompanied by the strongly hydrophilic *N. carinata* and *D. bacillifera*. The water table then shows a fluctuating but long term decline with reductions in all the hydrophilic taxa, their replacement by some of the taxa that were previously present in the deepest samples, but also the appearance of other taxa with more intermediate hydrological preferences such as *N. griseola*, *Heleopera sylvatica* and *Hyalosphenia elegans*. The combination of *D. pulex* and *Arcella discoides* in the inferred drier zones at the top and bottom of the core may also imply stronger fluctuations in water table (Sullivan and Booth, 2011).

The assemblage data and water table reconstructions were continued right to the surface at 1cm intervals. However, living tests of some taxa were found in the top 8 cm of the peat, and the record in these samples cannot be interpreted as a record of past changes. The depth at which assemblages can be considered fossil is variable between locations, dependent on the host plant species and physical structure of the peat, but it is clear that this zone extends down to at least 8cm here. This is deeper than in a previous study where living tests only occurred to 5cm depth (Charman et al., 2004). The interpretation of the uppermost zones is returned to in the discussion below.

3.3 Chronology

The SCP curve (Figure 2a) displays a clear start point (30.5 cm), rapid increase (24.5 cm) and peak (15.5 cm) in concentration, similar to that found for many other locations in the British Isles (Rose, 1995). Because of the difficulty in precise identification of the rapid take off point, dates were assigned to each 10% increase in the cumulative SCP curve (Figure 2b), where 100% is the peak in SCPs, as recommended by Rose and Appleby (2005). Some of these markers are regarded as being more or less consistent between regions, with the 50% point being particularly consistent between regions (Rose and Appleby, 2005).

The radiocarbon ages (Table 1, Figure 3) are a conformable sequence of ages, with no clear reversals despite the large number of dates. All ages were therefore retained in the age-depth model. The age-depth model shows there have been major changes in accumulation rate. The lowermost part of the sequence (90-50 cm) accumulated over approximately 240 years between c. 1020 and 1260 cal AD. The radiocarbon probability distributions constrain this part of the model very well, and 2σ error estimates are of the order of ± 30-35 years for this part of the profile. Following this, there is a reduction in peat accumulation rate, with only 25cm of peat accumulating over the next c. 700 years. The estimated errors also increase to ±40-95 years because of the broader error ranges in the radiocarbon ages and the lower number of age estimates over this period. The age model in the 19th and early 20th century is poor because the only age estimate in this period comes from the start of the SCP curve dated to AD 1850 ± 25 years (Rose and Appleby, 2005). This date should be regarded with caution because it is difficult to detect the start of the SCP curve precisely. Dating the uppermost part of the profile is potentially problematic, but the post-bomb radiocarbon ages all fall into a clear sequence and show good fits to the bomb-spike curve. Certainly it is clear that peat accumulation was very slow until the mid 1950s when the first post-bomb age is recorded. The SCP ages generally indicate slightly older dates than the radiocarbon ages, although most are within the error ranges. The 10% increments in the SCP cumulative curve are not all equally consistent between regions (Rose and Appleby, 2005), and the increments up to 50%

values (the mid 1950s) are especially likely to be unreliable here because of the coarse resolution of the record due to low peat accumulation rates. The age-depth model in the upper section is therefore primarily constrained by the radiocarbon ages.

The acceleration of peat accumulation over the last 50 years coincides with a switch from relatively wet to drier conditions, with water tables dropping from 1.8 cm to 9.4 cm deep over four samples representing about 5 years of peat growth in total. This is also associated with the stratigraphic change from *Sphagnum cuspidatum* to *S. papillosum* dominated peat. *S. papillosum* is stronger growing and probably less susceptible to decay than *S.cuspidatum*, which would explain the step-change in accumulation rates.

3.4 Water tables and meteorological data

The correlation between the local IPCC data and the Armagh data is strong for both temperature and precipitation, with slightly higher coefficients for temperature than for precipitation, and lowest correlations for the annual deficit, although r^2 values are still 0.78 (Table 2). Correlations with the reconstructed water table were explored with both data sets. In terms of average conditions, Armagh is slightly drier and warmer with higher deficits than is indicated for the local area by the IPCC record.

The age-depth model was used to assign a date to each sample depth and annual water table depths were estimated by interpolation for comparison with the meteorological data. Correlations with meteorological data were based on 5 year averages of precipitation, temperature and annual deficit data. This was done for several reasons; 1) individual samples mostly span > 1 year, 2) there is likely to be a lag in biological response to changes in prevailing weather, 3) the chronological precision is not sufficient to reliably attribute individual samples to individual years. The 2σ age ranges for modelled ages after the mid-1950s is of the order of 1-3 years so a 5 year mean is reasonable. Correlations were limited to the period AD 1958 onwards because of the very slow accumulation rate and large error ranges (± 15-20 years) in the age-depth model prior to this.

The correlation with the local data 1958-1995 shows strongest correlations with precipitation (JJA and annual) and deficit (Table 3). A similar result is derived from the Armagh data. Data from Armagh were available to 2001, equivalent to samples almost at the surface of the core. However, correlations with this longer time period are lower than for 1958-1995, both those based on local data and the Armagh data. This is likely to be because the samples in the surface peats show major fluctuations over short timescales. The nominal accumulation rate here is 0.3 to 1 year cm^{-1} and the derived annual data are difficult to interpret. More importantly, these samples occur within the living zone for testate amoebae so that contemporary and recently deceased populations are mixed. Living tests were detected down to at least 8 cm depth (equivalent to c. AD 1999). Therefore, the post 1995 record is excluded from further analyses. Interestingly, a 5 year mean of WT (not shown in Table 3) shows some increase in r values for the period up to 2001. The averaging of the reconstructed changes in the upper peat simulates the compaction and consequent 'averaging' of assemblages that takes place during fossilisation in deeper peat samples.

Different data sets and different time periods produce slight differences in correlations between water table and meteorological variables (Table 3). However the strongest correlations are consistently with JJA precipitation, annual precipitation and annual deficit. Correlations with temperature are consistently low and vary in sign so very likely occur by chance. Although there is often a perception that dry summers are also warm, the correlation between JJA precipitation and JJA temperature is relatively weak (-0.45 and -0.48 for IPCC and Armagh data respectively for 1901-1995), suggesting that this is not necessarily true. It is interesting that annual precipitation shows such a strong correlation with reconstructed water table, only slightly lower than for JJA precipitation and higher than for annual deficit. Annual precipitation could be important for testate amoebae (and hydrology) in this site because the seasonal deficit can extend into mid-winter (January and February in some years) and mid-autumn (October). Furthermore, the annual average temperature is relatively high (8.9^{o}C, 1901-1995, JJA 14.0^{o}C, DJF 4.4^{o}C), so that the active season for the microbial population is likely to be longer than for many other sites in Europe. Moisture levels may therefore be influential for testate amoebae populations over most of the year.

3.5 Water table and climate reconstructions for the last 1000 years

The relationships described above provide the basis for the calibration of the 1000 year record of water table change, and to compare the calibrated results against earlier meteorological data. The 1958-1995 period is used here to establish linear relationships between the magnitude of water table change, precipitation and deficit. The top 10cm of the peat record are excluded because of the large magnitude variability shown (Figure 1), likely to be at least partly a function of the vertical zonation of the contemporary population in the upper peat.

Reconstructed values are plotted together with the 5 year mean Armagh record from 1842 and the local DDC record from 1901 (Figure 4). The temporal resolution and chronological precision of the water table data are not sufficient to provide a robust validation statistic to be calculated for the period prior to 1960 (there are only 6 data points between 1842 and 1958). However, a visual comparison of the data over this period provides some insights into the validity for calibration of the earlier record for the main climate variables. Although the annual precipitation shows a strong correlation over the 1958-1995 calibration period (Table 3), the reconstruction overestimates the magnitude of variability for the late 19th and early 20th century (Figure 4c, d). Furthermore, the rising trend in annual precipitation shown by the Armagh record during the late 19th century is not reproduced by the reconstructed values. The magnitude of change is more accurate for both summer precipitation and deficit (Figure 4 a-f), although it is better for summer precipitation than for deficit. The patterns of change are also similar with the declining trend in both parameters in the late 19th and early 20th century, the rapid rise in the 1920s and continued high values through to the late 1950s reproduced in the reconstructed record. Two severe summer droughts in the late 19th century (AD 1869-70 and 1885 to a lesser extent) are not clearly registered in the reconstructed water table record because the record is very coarsely resolved during this period. However, the major decline in reconstructed summer precipitation and increase in deficit occurs immediately after the sample dated to c. cal AD 1870. Although the 2 years of drought conditions would be averaged over a sample covering approximately 20 years of peat growth, it is possible that the 1869-1870 summer drought triggered the change to drier conditions at this time.

The reconstructed water table changes and summer precipitation reconstructions for the last millennium (Figure 5) suggest that the long-term average summer precipitation during the period c. cal AD 1400 to 1850 was higher than for any time during the last 150 years. The earlier period shows greater variability, with precipitation falling steeply between c. cal AD 1020 and 1055, when the first period of dry conditions commences and lasts until cal AD 1220. It is punctuated by two more extreme dry periods centred on cal. AD 1090 and 1170. The age-depth model suggests the age estimates for these transitions are accurate to within ±15-20 years

(2σ). Following cal AD 1220, precipitation rises gradually to cal AD 1330 and remains high until c. cal AD 1870 (±23 yrs, 2σ).

There are few directly comparable independent reconstructions of longer term precipitation change, but Pauling et al. (2006) provide Europe-wide reconstructions back to AD 1500 based on documentary, instrumental and a few proxy data. To make a direct comparison, the data for the area covering the whole of Ireland (55.5°N 6°W to 51°N 10.5°W) was extracted from the JJA gridded data available on the NOAA Palaeoclimatology web site (http://www.ncdc.noaa.gov/paleo/, Pauling et al., 2007) and calculated 5 year running averages. A comparison with the longer term reconstruction of summer precipitation of (Pauling *et al.* 2006) suggests that the water table reconstruction over-estimates the magnitude of precipitation increases in the 16th to early 19th centuries (Figure 5). This could be because the linear relationship between water table and precipitation assumed for the reconstruction is not valid; the water tables are outside the range of the calibration time period. However, the Pauling *et al.* reconstructions are most reliable for central Europe and Iberia, especially during the winter season (Pauling *et al.* 2006). The JJA records for the extreme west mid-latitudes are likely to be some of the least reliable. The records used for the reconstruction in this region are based only on the same instrumental series discussed above; the closest longer record used is the speleothem record of (Proctor *et al.* 2000), which is sensitive to annual and winter precipitation rather than summer variability, probably also with some influence of temperature. Low frequency precipitation variability may be reduced in the Pauling *et al.* (2006) reconstruction. Even in the historical time period, low frequency variability is less than that of the meteorological records (Figure 4 a, b). Hence it remains plausible that long-term average summer precipitation was consistently higher during the 15th to 19th centuries. The driest periods of the Medieval Climate Anomaly (MCA) were similar to those experienced in the 1970s and early 1980s. Clearly further work is required to substantiate these temporal patterns and to provide improved estimates of uncertainty associated with both reconstruction methods and potential influences of non-climatic factors on the record. The relatively low temporal resolution of the record related to low accumulation rates in the 13th to 20th centuries also limits the extent to which the record can be tested against independent instrumental and documentary reconstructions of summer precipitation.

4. Discussion and conclusions

A key aim of this paper was to provide a further test for previously published hypotheses concerning the drivers of peatland water tables and therefore the interpretation of peat surface wetness reconstructions for palaeoclimatic reconstructions. The hypothesis that warm season precipitation and annual deficit are the main drivers of water table change is supported by the results from correlation with instrumental records of temperature and precipitation, despite the fact that data with adequate temporal resolution were only available for the last 50 years. In particular, previous studies have suggested that the strength of the precipitation signal would be greatest in oceanic regions where summer temperature is low throughout the summer (Charman et al., 2004). This idea is also supported by the data, which show no correlation between water table and temperature but a strong correlation with precipitation and deficit. However, an apparent correlation with annual precipitation after AD 1958 is not supported by longer instrumental time series (Figure 4), demonstrating the need for further studies which not only provide correlations with instrumental data, but are also sufficiently long to attempt validation. In this case, a formal validation test has not been possible because of the low rate of peat accumulation prior to the 1950s, but the multi-decadal trends can be used as a partial check on the calibration. Based on this, the correlation with annual precipitation is clearly non-stationary and because there is no clear process-based rationale for the relationship, the water table record is regarded as representing summer precipitation.

One of the problems with all natural archives for proxy-climate reconstruction is that the records of any individual site are always at least partly driven by factors other than climate. Comparisons both within individual sites and between sites have demonstrated that most major past changes in surface wetness and water tables are plausibly replicated at a range of sites and locations within those sites (Barber et al., 1998; Hendon *et al.* 2001; Charman *et al.* 2006). More subtle and precisely dated changes have not been demonstrably linked across sites, although replication of cores within sites shows that the variability between locations is smaller than the climate signal (Charman, 2007). There are many records covering this period from northwest Europe but often both temporal precision and chronological accuracy of records is too low for a reasonable comparison with the record presented here. However, (Mauquoy *et al.* 2008) used a similar 'wiggle-matched' dating of multiple radiocarbon dates to estimate ages for significant shifts to wetter conditions at c. cal AD 1050 and 1300 in Butterburn Flow, northern England, and parallel shifts at 1020 and 1280 in Lille Vildemosse, Denmark, both followed by relatively high water tables until the last few hundred years (where age depth models and temporal precision are poorer). The same pattern is seen on the Dead Island record of Swindles et al. (2010), from approximately 250km away in Northern Ireland, although the wet phase from another nearby site is punctuated by strongly fluctuating hydrology between AD 1500-1700 rather than consistently wet conditions. The records of Mauquoy et al. (2008) mirror the two stage change to wetter conditions seen in the Ballyduff record, and the timing of the final change to higher water tables in the late 13th century is particularly clear (dated to cal. AD 1307±28 at Ballyduff). All the data that are available for the last few hundred years from these sites confirm the hypothesis that summer precipitation was as low during the MCA as it has been over the latter part of the 20th century (Charman et al., 2006; Mauquoy et al., 2008; Swindles et al., 2010).

The Ballyduff and other peatland records from the region represent warm season precipitation and water balance. Comparison with the speleothem record of winter precipitation from northwest Scotland (Proctor *et al.* 2000) suggests that centennial trends in winter and summer precipitation were in antiphase over the past 1000 years. A similar but less clear long term trend is shown in the record of $CaCO_3$ deposition from western Ireland interpreted as a record of annual precipitation (Schettler et al., 2006), which may also be dominated by a winter signal. The interpretation of the speleothem record as a winter precipitation signal is supported by its anti-correlation with a winter precipitation tree ring series from Morocco which has been used to build a winter NAO (WNAO) series (Trouet *et al.* 2009). These records suggest a persistent positive WNAO mode during the MCA, with a transition to negative and more variable WNAO after the late 13th and early 14th century. The transition between positive and negative WNAO modes, from wet to dry winters in Scotland, coincides with the transition from dry to wet summers shown here (Figure 5). This suggests a major change in seasonality of precipitation over this period. The strong dependency of winter precipitation on the WNAO is well-known but the relationship with summer precipitation is less clear (Hurrell, 1995). The positive phase of the summer NAO (SNAO) is associated with dry, warm summers over northwest Europe (Folland et al., 2009). Thus, it is tentatively suggested that the persistent positive WNAO mode during the MCA was associated with a positive

SNAO phase, leading to much greater seaonality in rainfall variability. This was reversed in the LIA with negative WNAO and SNAO, and wet summers and dry winters.

There is likely to be much more detail in precipitation variability over the last millennium than a simple shift from relatively wet to relatively dry conditions around the MCA/LIA transition. There are certainly significant changes between AD1000 and 1300. However, the lower resolution of the record for the LIA precludes the identification of obvious multi-decadal change. Further well-dated records from higher resolution deposits are required to be able to identify the nature and magnitude of such changes.

4.1 Calibration of water table reconstructions

Calibration of palaeoclimate records is routine for tree-ring studies and is self-evidently much easier for annually resolved proxies than it is for non-annual proxies, which are also usually of variable temporal resolution over time with dating precision of several years to a decade or more. Despite these problems, comparison with instrumental records provides a rigorous test of proxy-climate relationships (e.g. Larocque et al., 2009). Extending this comparison and correlation to calibration of the record is the next logical step in improving the usefulness of palaeoclimate records, allowing quantification of the record in climatic terms and more direct comparison and integration with other proxies. There has been partial success in achieving this for the peat record from Ballyduff, but the temporal precision of the record limited the potential for working with the late 19th and early 20th century record. Nonetheless, this is a worthwhile objective to explore for peatland records, alongside alternative approaches such as forward modelling of the full range of processes affecting peatland water table records. Interest in forward modelling is now a growing area of interest for palaeoclimate proxies (Jones et al., 2005) and is ultimately provide a more satisfactory quantitative interpretation of proxy records.

Acknowledgements

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References

Brazdil, R., Stepankova, P., Kyncl, T., Kyncl, J. 2002. Fir tree-ring reconstruction of March-July precipitation in southern Moravia (Czech Republic), 1376-1996. Climate Research 20, 223-239.

Bronk Ramsey, C., 2008. Deposition models for chronological records. Quaternary Science Reviews 27, 42-60.

Bronk Ramsey, C., 2009. Bayesian Analysis of Radiocarbon Dates. Radiocarbon 51, 337-360.

Butler, C.J., Coughlin, A.D.S. Fee, D.T., 1998. Precipitation at Armagh Observatory 1838-1997. Biology and Environment-Proceedings of The Royal Irish Academy 98B, 123-140.

Charman, D.J., Hendon, D., Woodland. W.A., 2000. The identification of peatland testate amoebae. Quaternary Research Association Technical Guide, London.

Charman, D. J., 2007. Summer water deficit variability controls on peatland water-table changes: implications for Holocene palaeoclimate reconstructions. Holocene 17, 217-227.

Charman, D.J., Barber, K.E., Blaauw, M., Langdon, P.G., Mauquy, D., Daley, T.J., Hughes, P.D.M., Karofeld, E., 2009. Climate drivers for peatland palaeoclimate records. Quaternary Science Reviews 28, 1811-1819.

Charman, D.J., Blundell, A., Accrotelm Members, 2007. A new European testate amoebae transfer function for palaeohydrological reconstruction on ombrotrophic peatlands. Journal of Quaternary Science 22, 209-221.

Charman, D.J., Blundell, A., Chiverrell, R.C., Hendon, D., Langdon, P.G., 2006. Compilation of non-annually resolved Holocene proxy climate records: stacked Holocene peatland palaeo-water table reconstructions from northern Britain. Quaternary Science Reviews 25, 336-350.

Charman, D.J., Brown, A.D., Hendon, D., Karofeld, E., 2004. Testing the relationship between Holocene peatland palaeoclimate reconstructions and instrumental data at two European sites. Quaternary Science Reviews 23, 137-143.

Cook, E.R., Seager, R., Cane, M.A., Stahle, D.W., 2007. North American drought: Reconstructions, causes, and consequences. Earth-Science Reviews 81, 93-134.

Davi, N.K., Jacoby, G.C., Curtis, A.E., Baatarbileg, N., 2006. Extension of drought records for central Asia using tree rings: West-central Mongolia. Journal of Climate 19, 288-299.

Folland, C.K., Knight, J., Linderholm, H.W., Fereday, D., Ineson, S., Hurrell, J., 2009. The Summer North Atlantic Oscillation: past, present and future. Journal of Climate 22, 1082–1103.

Garcia-Suarez, A,M., Butler, C.D., Cardwell, A.D.S., Coughlin, A., Donnelly, D., Fee, T., Hickey, K.R., Morrow, B., Taylor, T., 2003. Meteorological data recorded at Armagh Observatory: Volume I – daily, monthly and annual rainfall 1838-2001. Armagh Observatory. http://climate.arm.ac.uk/calibrated/rain/index.html.

Hammond, R.F., 1981. The Peatlands of Ireland 2nd edition. An Foras Taluntais, Dublin.

Hendon, D., Charman, D. J., 1997. The preparation of testate amoebae (Protozoa: Rhizopoda) samples from peat. Holocene 7, 199-205.

Hendon, D., Charman, D. J., 2004. High-resolution peatland water-table changes for the past 200 years: the influence of climate and implications for management. Holocene 14, 125-134.

Hendon, D., Charman, D.J., Kent, M., 2001. Palaeohydrological records derived from testate amoebae analysis from peatlands in northern England: within-site variability, between-site comparability and palaeoclimatic implications. Holocene 11, 127-148.

Hua, Q.,, Barbetti, M., 2004. Review of tropospheric bomb C-14 data for carbon cycle modeling and age calibration purposes. Radiocarbon 46, 1273-1298.

Hurrell, J.W. 1995., Decadal trends in the North Atlantic oscillation: Regional temperatures and precipitation, Science, 269, 676–679.

Jones, P.D., K. R. Briffa, T. J. Osborn, J. M. Lough, T. D. van Ommen, B. M. Vinther, J. Lutherbacher, E. R. Wahl, F. W. Zwiers, M. E. Mann, G. A. Schmidt, C. M. Ammann, B. M. Buckley, K. M. Cobb, J. Esper, H. Goosse, N. Graham, E. Jansen, T. Kiefer, C. Kull, M. Kuttel, E. Mosley-Thompson, J. T. Overpeck, N. Riedwyl, M. Schulz, A. W. Tudhope, R. Villalba, H. Wanner, E. Wolff,, E. Xoplaki., 2009. High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects. Holocene 19, 3-49.

Jones, M.D., Leng, M.J., Roberts, C.N., Turkes, M., Moyeed, R., 2005. A coupled calibration and modelling approach to the understanding of dry-land lake oxygen isotope records. Journal of Paleolimnology 34, 391–411.

Larocque, I., Grosjean, M., Heiri, O., Bigler, C., Blass, A., 2009. Comparison between chironomid-inferred July temperatures and meteorological data AD 1850–2001 from varved Lake Silvaplana, Switzerland. Journal of Paleolimnology 41:329–342.

Kelly, L., Schouten, M.G.C., 2002. Vegetation. In: Schouten, M.G.C. (ed.) Conservation and restoration of raised bogs. pp110-169. Dúchas, Dublin.

Mann, M. E.,, Jones, P.D., 2003. Global surface temperatures over the past two millennia. Geophysical Research Letters 30, Art-1820.

Mann, M.E., Bradley, R.S., Hughes, M.K., 1998. Global-scale temperature patterns and climate forcing over the past six centuries. Nature 392, 779-787.

Mann, M.E., Bradley, R.S., Hughes, M.K., 1999. Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. Geophysical Research Letters 26, 759-762.

Masson-Delmotte, V., Raffalli-Delerce, G., Danis, P.A., Yiou, P., Stievenard, M., Guibal, F., Mestre, O., Bernard, V., Goosse, H., Hoffmann, G., Jouzel, J., 2005. Changes in European precipitation seasonality and in drought frequencies revealed by a four-century-long tree-ring isotopic record from Brittany, western France. Climate Dynamics 24, 57-69.

Mauquoy, D., Yeloff, D., van Geel, B., Charman, D.J., Blundell, A., 2008. Two decadally resolved records from north-west European peat bogs show rapid climate changes associated with solar variability during the mid-late Holocene. Journal Of Quaternary Science 23, 745-763.

Mitchell, F.J.G., Delaney, C., (eds.) 1997. The Quaternary of the Irish Midlands. Field Guide No. 21, 84 pp. Irish Association for Quaternary Studies, Dublin.

Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., Karlen, W., 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. Nature 433, 613-617.

Pauling, A., et al., 2007. European Gridded Seasonal Precipitation Reconstructions. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # 2007-054. NOAA/NCDC Paleoclimatology Program, Boulder CO, USA.

Pauling, A., Luterbacher, J., Casty, C.and Wanner, H., 2006. Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. Climate Dynamics 26, 387-405.

Payne, R.J., Telford, R.J., Blackford, J.J., Blundell, A., Booth, R.K., Charman, D.J., Lamentowicz, L., Lamentowicz, M., Mitchell, E.A.D., Potts, G., Swindles, G.T., Warner, B.G., Woodland, W., in press. Testing peatland testate amoeba transfer functions: appropriate methods for clustered training-sets. The Holocene.

Proctor, C.J., Baker, A., Barnes, W.L., 2002. A three thousand year record of North Atlantic climate. Climate Dynamics 19, 449-454.

Proctor, C.J., Baker, A., Barnes, W.L., Gilmour, R.A., 2000. A thousand year speleothem proxy record of North Atlantic climate from Scotland. Climate Dynamics 16, 815-820.

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C. E., 2004. IntCal04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP. Radiocarbon 46, 1029-1058.

Rose, N. L., 1990. A method for the extraction of carbonaceous particles from lake sediments. Journal of Palaeolimnology 3, 45-53

Rose, N. L., 1994. A note on further refinements to a procedure for the extraction of carbonaceous fly-ash particles from lake sediments. Journal of Palaeolimnology 11, 201-204.

Rose, NL., 1995. Carbonaceous particle record in lake sediments from the Arctic and other remote areas of the Northern Hemisphere. Science of the Total Environment 160-161, 487-496

Rose NL, Appleby PG, 2005. Regional applications of lake sediment dating by spheroidal carbonaceous particle analysis. I: United Kingdom. Journal of Paleolimnology 34, 349–361

Schettler, G., Romer, R.L., O'Connell, M., Molloy, K., 2006. Holocene climatic variations and postglacial sea-level rise geochemically recorded in the sediments of the brackish karst lake An Loch Mór, western Ireland. Boreas, 35, 4, 674-693.

Sillasoo, U., 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 Mannikjarve bog as indicators of late Holocene climate changes in Estonia. Boreas 36, 20-37.

Sullivan, M.E., Booth, R.K., 2011. The potential influence of short-term environmental variability on the composition of testate amoeba communities in *Sphagnum* peatlands. Microbial Ecology 62, 80–93.

Swindles, G.T., Blundell, A., Roe, H.M., Hall, V.A., 2010. A 4500-year proxy climate record from peatlands in the North of Ireland: the identification of widespread summer 'drought phases'? Quaternary Science Reviews 29, 1577-1589.

Touchan, R., Xoplaki, E., Funkhouser, G., Luterbacher, J., Hughes, M.K., Erkan, N., Akkemik, U., Stephan, J., 2005. Reconstructions of spring/summer precipitation for the Eastern Mediterranean from tree-ring widths and its connection to large-scale atmospheric circulation. Climate Dynamics 25, 75-98.

Treydte, K. S., Schleser, G. H., Helle, G., Frank, D.C., Winiger, M., Haug, G.H., Esper, J., 2006. The twentieth century was the wettest period in northern Pakistan over the past millennium. Nature 440, 1179-1182.

Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J. D., Frank, D.C., 2009. Persistent Positive North Atlantic Oscillation Mode Dominated the Medieval Climate Anomaly. Science 324, 78-80.

Wilson, R.J.S., Luckman, B.H., Esper, J., 2005. A 500 year dendroclimatic reconstruction of spring-summer precipitation from the lower Bavarian Forest region, Germany. International Journal of Climatology 25, 611-630.

Yeloff, D., Bennett, K.D., Blaauw, M., Mauquoy, D., Sillasoo, U., van der Plicht, J., van Geel, B., 2006. High precision C-14 dating of Holocene peat deposits: A comparison of Bayesian calibration and wiggle-matching approaches. Quaternary Geochronology 1, 222-235.

Table 1: Radiocarbon samples from Ballyduff bog.

Lab. code	Depth cm	Sample composition notes	Activity % modern	Age ^{14}C BP	$\delta^{13}C$ o/oo
GrA-30140	5.5	*Sphagnum papillosum*, *S. capillifolium* stems	108.97±0.46		-29.23
GrA-30142	10.5	*Sphagnum papillosum*, *S. capillifolium* leaved stems	109.81±0.44		-28.29
GrA-30143	15.5	*Sphagnum papillosum*, *S. cuspidatum*, *Calluna* leaves	116.19±0.49		-30.74
GrA-30144	20.5	*Sphagnum papillosum*, *S. capillifolium* leaved stems	153.28±0.58		-26.23
GrA-28725	25.5	*Sphagnum cuspidatum* stems	115.95±0.46		-30.81
GrA-26850	36.5	*Erica* leaves and wood, *S.cuspidatum*		175±35	n/a
GrA-28726	40.5	*S. cuspidatum* stems, *Erica* leaves, flowers		295±35	-26.62
GrA30488	45.5	*Sphagnum stems, Erica leaves, Rhynchosporaalba seed*		595±35	-25.25
GrA-28727	50.5	*S. imbricatum, S. capillifolium, Erica, Rhynchopora alba* seeds		795±35	-24.81
GrA-28729	63.5	*S. imbricatum, S. s. acutifolia stems, Erica* wood		970±35	-25.79
GrA-28713	69.5	*S. imbricatum, S. capillifolium*		1030±35	-26.86
GrA-30490	79.5	*S. imbricatum leaved branches, Ericaceae twigs*		890±35	-26.39
GrA-28715	84.5	*S. imbricatum*		965±35	-26.69
GrA-28716	89.5	*S. imbricatum, Erica* leaves, flowers, wood		1615±35	-26.1
GrA-30463	90.5	*S. imbricatum leaved branches, S. cuspidatum, Acutifolia branches, Erica leaves, twigs*		920±35	n/a
GrA-26772	97.5	*S.cuspidatum*, *Erica* leaves, bark, wood		1150±40	n/a

Table 2: Pearson's correlations between the IPCC DDC data for the 0.5x0.5^{o} grid square and the longer Armagh record for selected variables for the period 1901-1995 with means for the same period. All correlations p<0.01.

	Precipitation mm		Temperature ^{o}C		Deficit mm
	JJA	Annual	JJA	Annual	
Correlation	0.91	0.90	0.92	0.94	0.88
IPCC	236	1052	14.0	8.9	-92
Armagh	214	830	14.3	9.2	-145

Table 3: Pearson's correlations between annualised reconstructed water table values and instrumental meteorological data (5 year averages). ** $p<0.01$, * $p<0.05$.

	1958-2001 Armagh	1958-1995 Armagh	1958-1995 DDC
JJA Precipitation	0.56*	0.74**	0.62**
Annual Precipitation	0.59**	0.71**	0.54*
JJA Temperature	0.13	0.18	0.15
Ann Temperature	-0.09	-0.30	0.03
Annual Deficit	0.46*	0.61**	0.50*

Figure captions

Figure 1: Location map for the study site and core location at Ballyduff. Also indicated are the IPCC 0.5^{o} grid square (53.0-53.5^{o} N, 7.5-8.0^{o} W) and Armagh meteorological station used for instrumental climate data. The limit of the map showing all of Ireland coincides with the region extracted from Pauling et al. (2006).

Figure 2: Percentage testate amoebae diagram for Ballyduff bog with reconstructed water table and bootstrapped error estimates. The stratigraphic column indicates the dominant plant macrofossil taxa only.

Figure 3: Spheroidal carbonaceous particle abundance (SCPs) expressed as a) concentration and b) cumulative % of peak SCP values.

Figure 4: Age depth model from OxCal for a) full profile and b) Upper 50cm only. Age distributions shown as full 2σ ranges (pale grey shading) and modelled 2σ age ranges. SCP ages shown as Gaussian curves with mean and 2σ ranges based on Rose and Appleby (2005). Post-bomb radiocarbon ages shown in green. Modelled 2σ age-depth model shown as shaded envelope. See text for details.

Figure 5: Reconstructions of JJA precipitation (a, b), annual precipitation (c, d) and annual deficit (e, f) (black lines) compared with 5 year means from instrumental records (grey lines). LHS shows Armagh Observatory record and RHS shows the local record based on IPCC data. The relevant part of the Pauling et al (2006) reconstruction for Ireland is shown in a and b (dashed grey line). The calibration section (1958-1995) is shown by the vertical dashed line and r^2 values of the regression equations are shown. See text for details.

Figure 6. Reconstructed summer precipitation for a) Armagh and b) central Ireland over the past 1000 years, compared with c) reconstructed winter NAO variations (Trouet et al., 2009). Grey error bars show 2σ error estimates for precipitation and age of sample points for reconstruction. Red curve shows the 5 year average for the whole of Ireland extracted from the Pauling et al. (2006) reconstruction. For a) and b), blue and green curves show the instrumental meteorological data. See text for details.

Figure 1

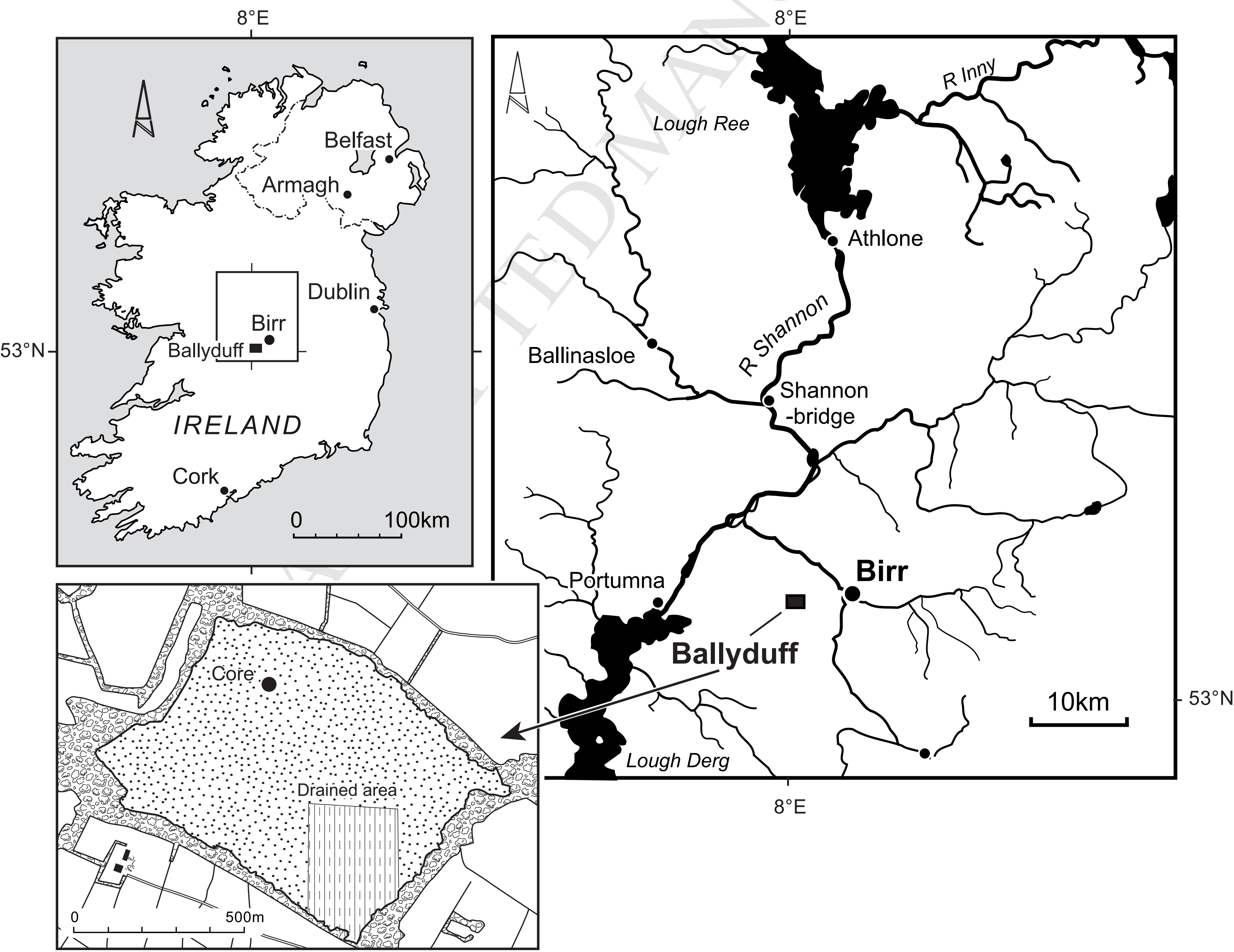
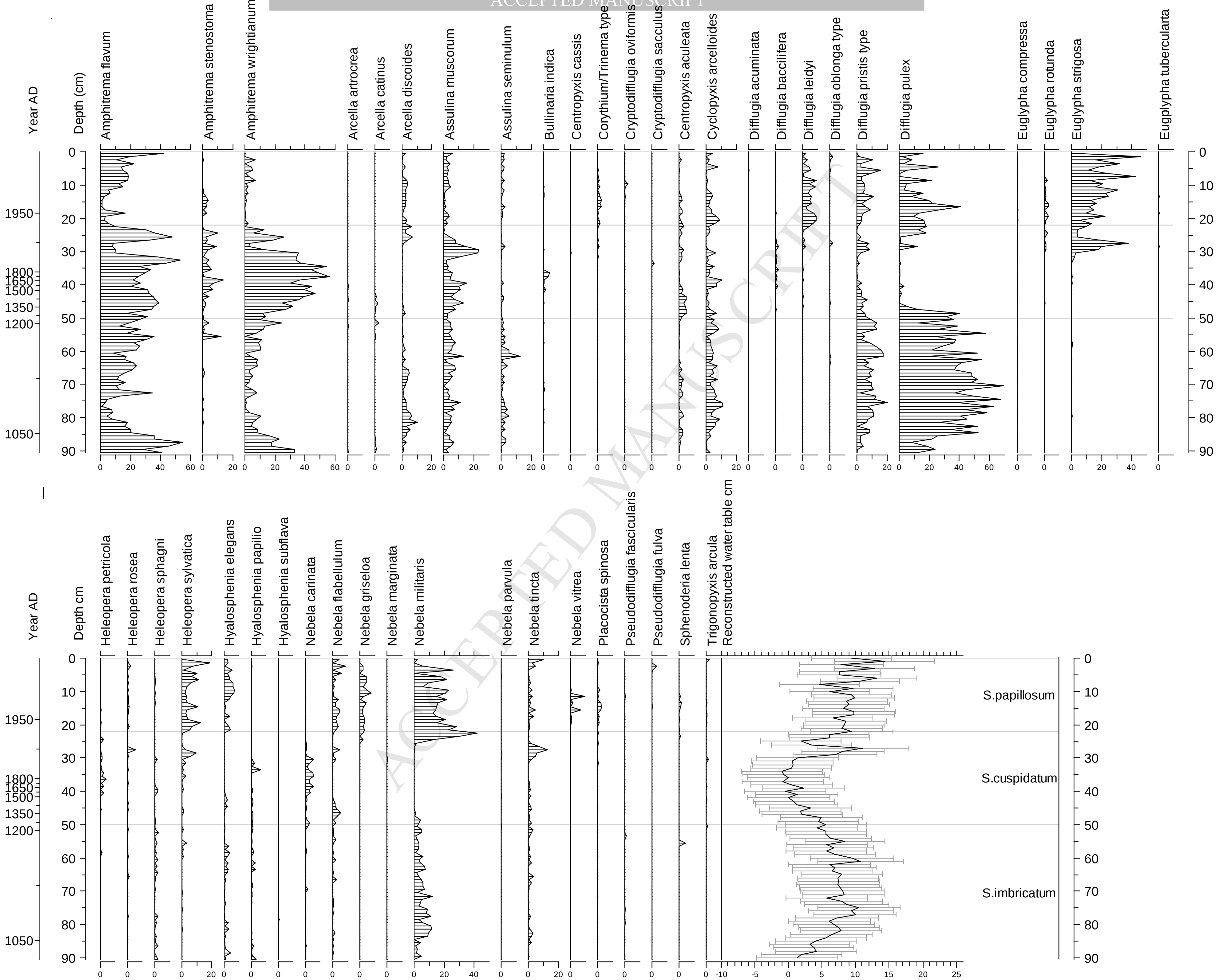
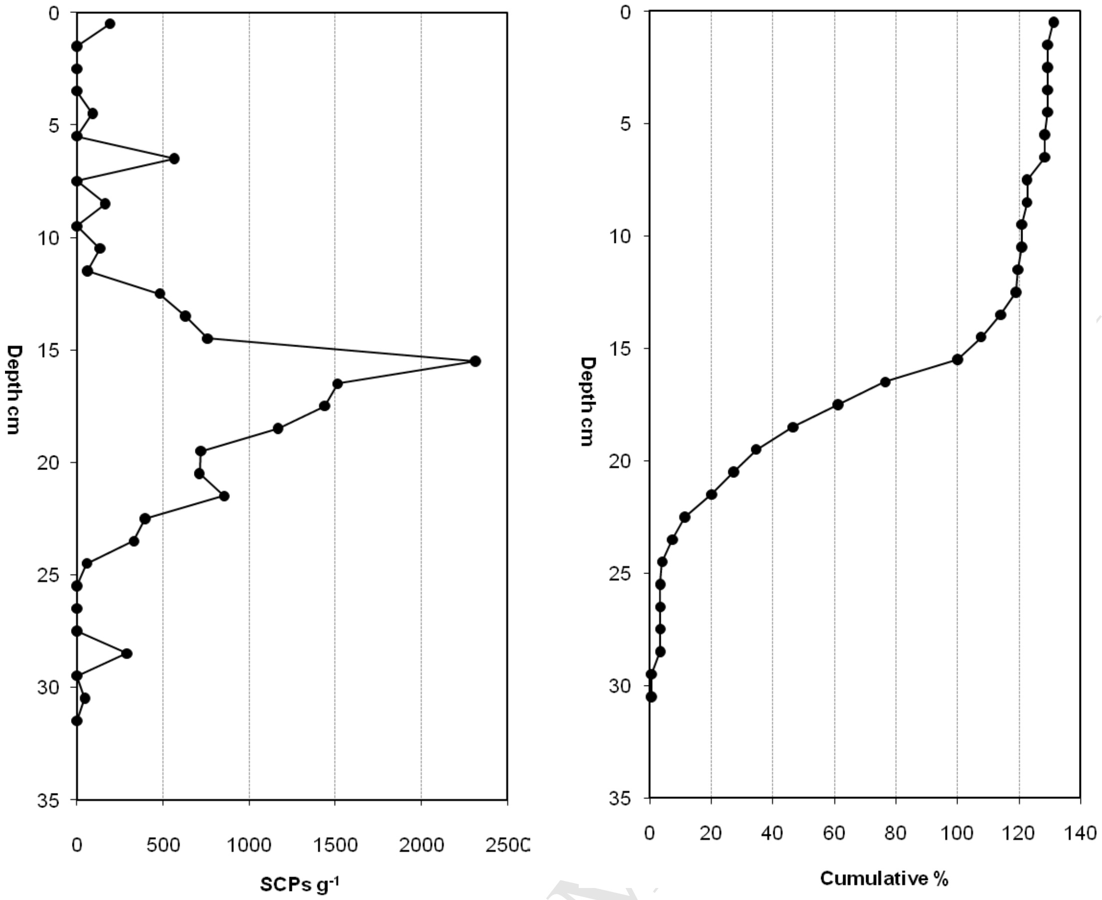

8°E
53°N
Belfast
Armagh
Dublin
Birr
Ballyduff
IRELAND
Cork
0
100km
8°E
R Inny
Lough Ree
Athlone
R Shannon
Ballinasloe
Shannon
-bridge
Portumna
Birr
Ballyduff
10km
53°N
Lough Derg
8°E
Core
Drained area
0
500m

Figure 2



Year AD
Depth (cm)
Amphitrema flavum
Amphitrema stenostoma
Amphitrema wrightianum
Arcella artocrea
Arcella catinus
Arcella discoides
Assulina muscorum
Assulina seminulum
Bullinaria indica
Centropyxis cassis
Corythium/Trinema type
Cryptodifflugia oviformis
Cryptodifflugia sacculus
Centropyxis aculeata
Cyclopyxis arcelloides
Difflugia acuminata
Difflugia bacciliferа
Difflugia leidyi
Difflugia oblonga type
Difflugia pristis type
Difflugia pulex
Euglypha compressa
Euglypha rotunda
Euglypha strigosa
Euglypha tuberculata
1950
1800
1650
1500
1350
1200
1050
Depth cm
Heleopera petricola
Heleopera rosea
Heleopera sphagni
Heleopera sylvatica
Hyalosphenia elegans
Hyalosphenia papilio
Hyalosphenia subflava
Nebela carinata
Nebela flabellulum
Nebela griseloa
Nebela marginata
Nebela militaris
Nebela parvula
Nebela tincta
Nebela vitrea
Placocista spinosa
Pseudodifflugia fascicularis
Pseudodifflugia fulva
Sphenoderia lenta
Trigonopyxis arcula
Reconstructed water table cm
S.papillosum
S.cuspidatum
S.imbricatum

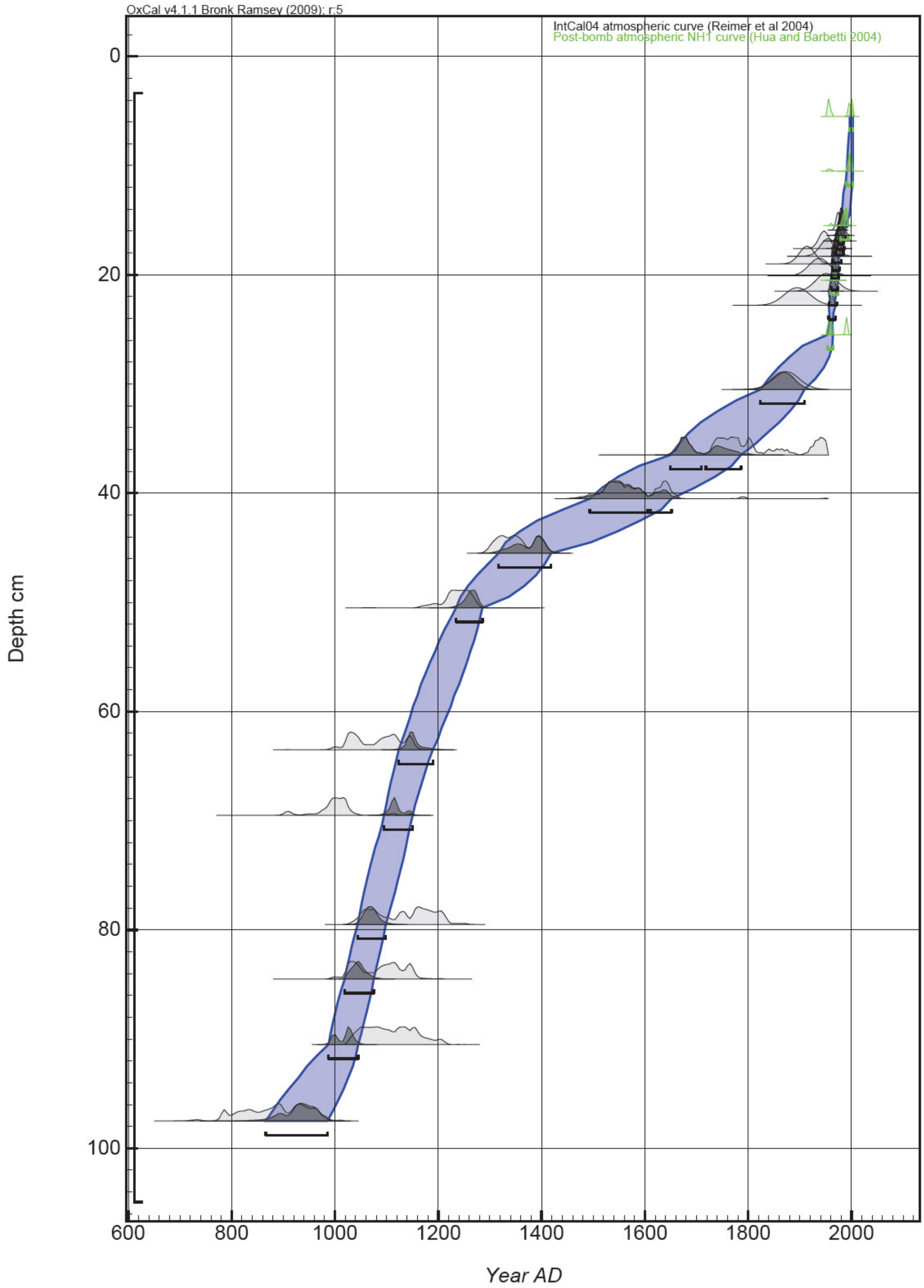
Figure 3



0
5
10
15
20
25
30
35
Depth cm
0
500
1000
1500
2000
2500
SCPs g-1
0
5
10
15
20
25
30
35
Depth cm
0
20
40
60
80
100
120
140
Cumulative %

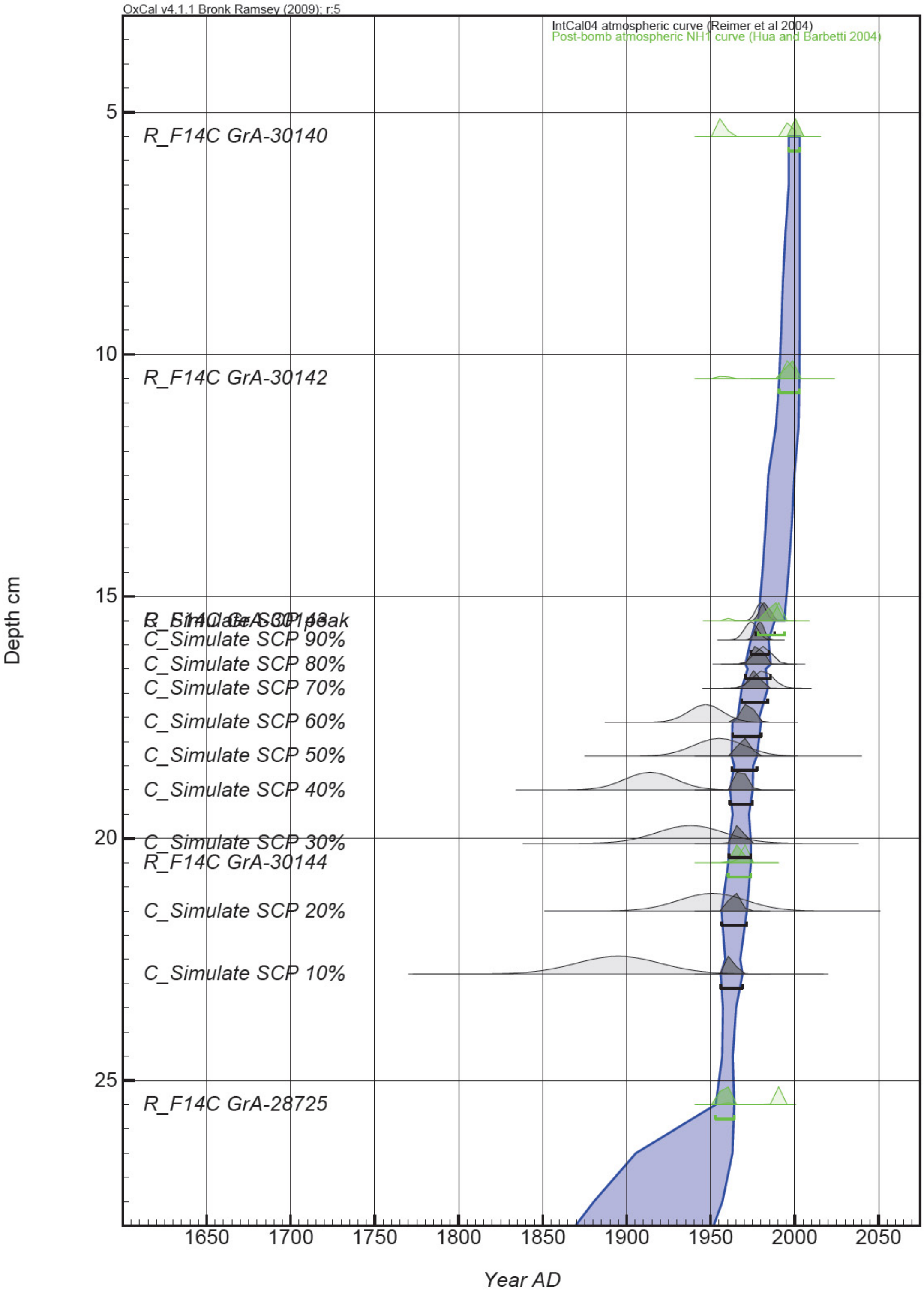
Figure 4

a)



OxCal v4.1.1 Bronk Ramsey (2009); r:5
IntCal04 atmospheric curve (Reimer et al 2004)
Post-bomb atmospheric NH1 curve (Hua and Barbetti 2004)
Depth cm
0
20
40
60
80
100
600
800
1000
1200
1400
1600
1800
2000
Year AD

b)



OxCal v4.1.1 Bronk Ramsey (2009); r:5
IntCal04 atmospheric curve (Reimer et al 2004)
Post-bomb atmospheric NH1 curve (Hua and Barbetti 2004)
R_F14C GrA-30140
R_F14C GrA-30142
R_F14C GrA-30143
C_Simulate SCP peak
C_Simulate SCP 90%
C_Simulate SCP 80%
C_Simulate SCP 70%
C_Simulate SCP 60%
C_Simulate SCP 50%
C_Simulate SCP 40%
C_Simulate SCP 30%
R_F14C GrA-30144
C_Simulate SCP 20%
C_Simulate SCP 10%
R_F14C GrA-28725
Depth cm
5
10
15
20
25
1650
1700
1750
1800
1850
1900
1950
2000
2050
Year AD

Figure 5

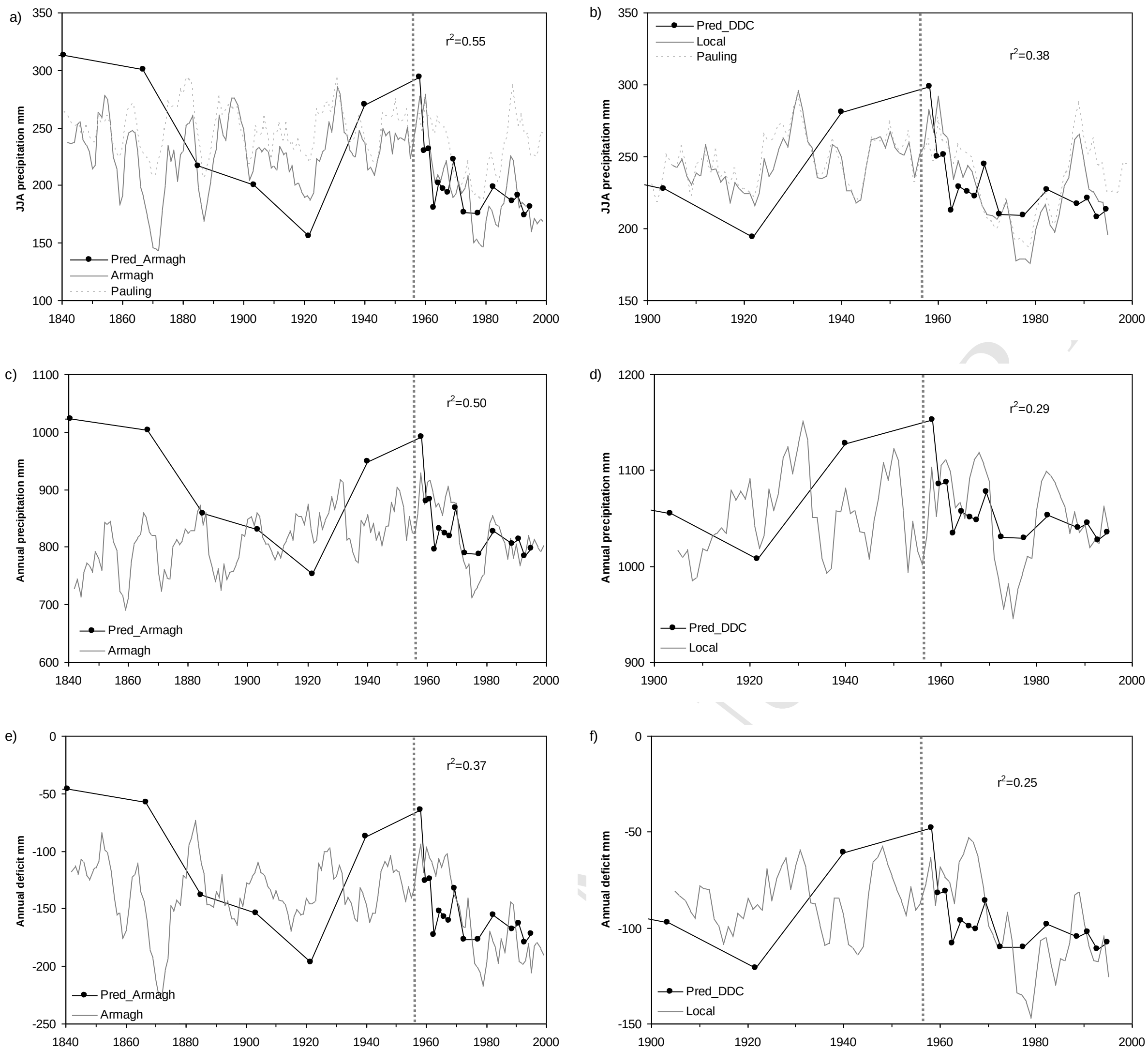
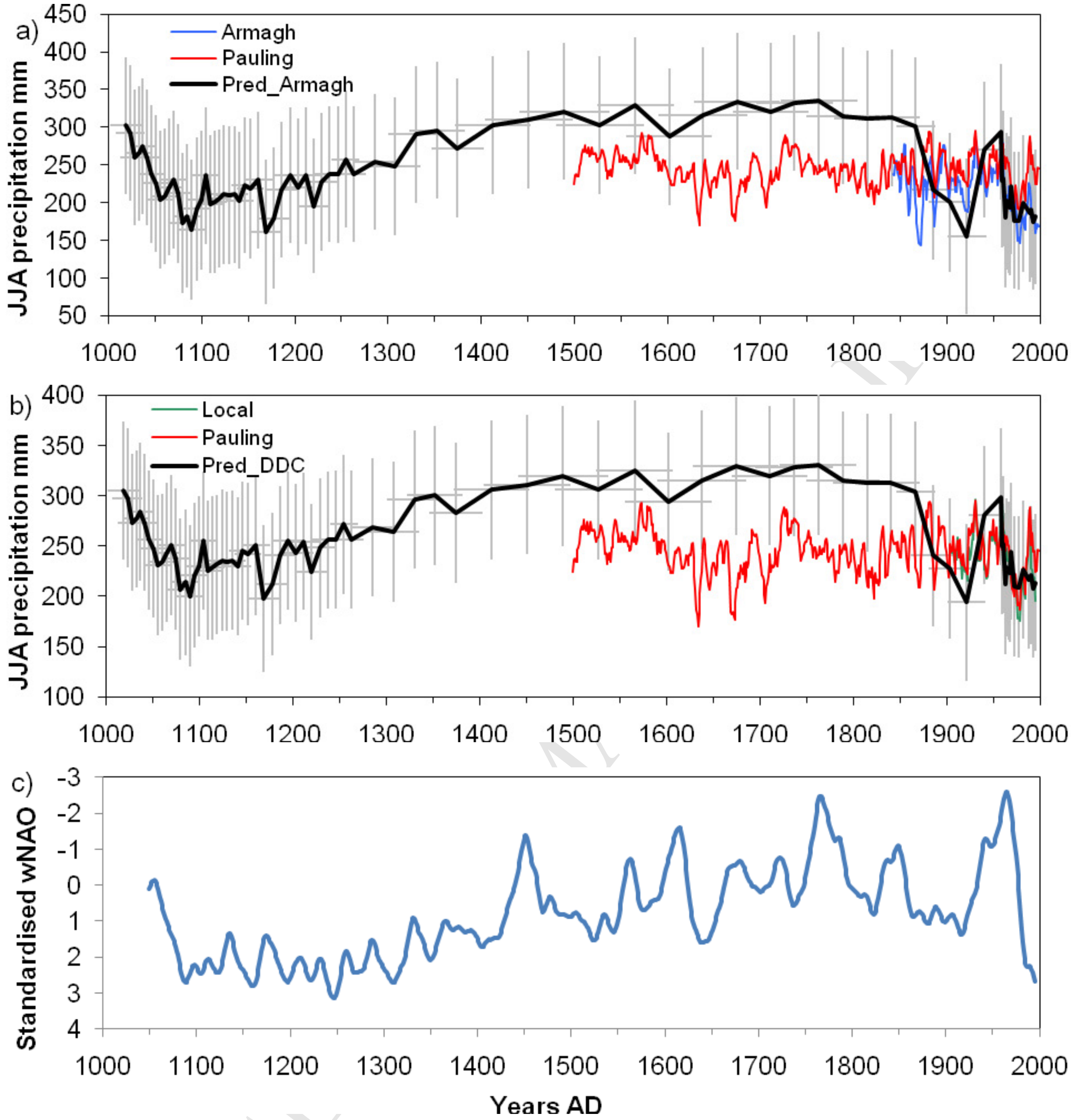

a)
JJA precipitation mm
r²=0.55
Pred_Armagh
Armagh
Pauling
b)
Pred_DDC
Local
Pauling
r²=0.38
JJA precipitation mm
c)
Annual precipitation mm
r²=0.50
Pred_Armagh
Armagh
d)
Annual precipitation mm
r²=0.29
Pred_DDC
Local
e)
Annual deficit mm
r²=0.37
Pred_Armagh
Armagh
f)
Annual deficit mm
r²=0.25
Pred_DDC
Local

Figure 6


a)
450
400
350
300
250
200
150
100
50
JJA precipitation mm
Armagh
Pauling
Pred_Armagh
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
b)
400
350
300
250
200
150
100
JJA precipitation mm
Local
Pauling
Pred_DDC
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
c)
-3
-2
-1
0
1
2
3
4
Standardised wNAO
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Years AD