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Examining the uncertainties in a ‘tuned and stacked’ peatland water table reconstruction

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ABSTRACT

Tuning and stacking approaches have been used to compile non-annually resolved peatland palaeo-water table records in several studies. This approach has been proposed as a potential way forward to overcome the chronological problems that beset the correlation of records and may help in the upscaling of palaeoclimate records for climate model-data comparisons. This paper investigates the uncertainties in this approach using a published water table compilation from Northern Ireland. Firstly, three plausible combinations of chronological match points are used to assess the variability of the reconstructions. It is apparent that even with markedly different match point combinations, the compilations are highly similar, especially when a 100-year running mean line is used for interpretation. Secondly, sample-specific reconstruction errors are scaled in relation to the standardised water table units and illustrated on the compiled reconstruction. Thirdly, the total chronological errors for each reconstruction are calculated using Bayesian age-modelling software. Although tuning and stacking approaches may be suitable for compiling peat-based palaeoclimate records, it is important that the reconstruction and chronological errors are acknowledged and clearly illustrated in future studies. The tuning of peat-based proxy climate records is based on a potentially flawed assumption that events are synchronous between sites.

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1. Introduction

In the last two decades there has been a proliferation of Holocene palaeoclimate records from many areas of the globe based on palaeoecological, geochemical and sedimentological proxies (cf. Mayewski et al., 2004). This has created a growing need to develop methods for the reconciliation and compilation of individual datasets to a spatial resolution suitable for the testing of climate models (e.g., CAPE project members, 2001). The Intergovernmental Panel on Climate Change (IPCC) has also emphasised that sources of palaeoclimate information should be integrated wherever possible to reduce uncertainty in the assessment (IPCC, 2007).

Surface wetness records from ombrotrophic peatlands are now relatively common in the palaeoenvironmental literature (Woodland et al., 1998; Wilmshurst et al., 2003; Langdon and Barber, 2005; Mauquoy et al., 2008). These reconstructions are usually based on peat humification, plant macrofossils or testate amoebae-inferred water table reconstructions, although multiproxy approaches are commonly adopted (Blundell and Barber, 2005; Hughes et al., 2006; Swindles et al., 2007; Blundell et al., 2008). Although there is debate over what has driven the changes in bog surface wetness in the Holocene (Barber and Langdon, 2007; Charman, 2007), recent evidence suggests that precipitation, reinforced by temperature is the primary driver in mid-latitude Europe (Charman et al., 2004, 2009) and North America (Booth, 2009). Peat records may also prove to be particularly valuable records of past drought variability in the mid-to-high latitudes (Booth, 2009; Swindles et al., 2010).

The approach of tuning and stacking (TAS) peat-derived water table records was first proposed by Charman et al. (2006) and subsequently adopted by Blundell et al. (2008) and Swindles et al. (2010). This method has been proposed as a way of overcoming the chronological problems which inhibit the correlation of such non-annually resolved palaeoclimate records and as a method for producing records that depend less on individual cores/sites. It was suggested that this approach may provide a more reliable basis for comparison with other proxies at a supra-regional scale and a suitable tool for upscaling of records for climate model-data comparisons (Charman et al., 2006). When records are tuned an assumption is made that events in the proxy record were produced by major climatic events in multiple profiles in a simultaneous
manner. In the case of peat-based records, the tuning process is used to align the proxy events between sites and then they are stacked to generate a regional compilation. In other areas of Quaternary palaeoclimatology, undated records are commonly tuned to dated sequences to provide chronological control and constrain specific events (e.g. Shackleton, 2000; Bond et al., 2001; Hughen et al., 2006 – see review in Blaauw et al., in press). Tuning approaches are often based on the chronological correlation of geological archives over significant spatial scales, which has a long history, even in Holocene research (e.g. Dachnowski, 1922).

One apparent problem for compiled peat records is that the sample-specific error estimates (e.g., derived from bootstrapping) are normally removed in the process of tuning and stacking. This is ineffectual as it alludes to a more precise quantitative reconstruction than reality. In addition, the chronological errors are not yet fully acknowledged in the approach, although tuning has only been carried out within the chronological errors of each assay. This paper: i) examines the variability in a TAS peatland water table record by generating several different possible combinations of compiled record based on different logical match point combinations and ii) illustrates the total chronological and reconstruction errors associated with a TAS record.

2. Methodology

2.1. Tuned and stacked water table record

Two high-resolution testate amoebae-derived water table records from Northern Ireland (NI) are investigated here; Dead Island (DI) and Slieveanorra (SA) (Swindles et al., 2010). The reconstructions were carried out using the ACCROTELm pan-European transfer function, which is based on a weighted averaging tolerance-downweighted model with inverse deshrinking (Charman et al., 2007). Sample-specific reconstruction errors were calculated through 1000 bootstrap cycles (Birks et al., 1990; Line et al., 1994). Age control is provided through the combination of AMS radiocarbon dates, spheroidal carbonaceous particles (SCPs) and tephrachronology, leading to significant variation in the chronological precision in the records which makes this a suitable dataset for such an analysis (Chronological data is provided in Supplementary Material A). The highest chronological precision is associated with the occurrence of historically or 14C wiggle-match dated cryptotephras (Swindles et al., 2010). Radiocarbon dates were calibrated using IntCal09 (Reimer et al., 2009), and expressed as 2σ (95.4% ranges). Initial age-depth models were constructed using linear interpolation of mid-point ages as this approach avoids erroneous deviations sometimes apparent in more complex approaches (cf. Bennett and Fuller, 2002; Telford et al., 2004). These records were combined using the TAS approach to provide a regional proxy hydroclimate record spanning the last ~4500 years (Swindles et al., 2010).

Standardisation of the water table records was undertaken using the standard score. Major features in the standardised records were used as chronological matching points. The dates of the matching points were averaged from the original age-depth models and linear interpolation applied between them, producing a modified model. Several versions of these were produced to examine the variability of the outputs from this approach. The adjusted age models lie within the original 2σ of the radiocarbon dates and the tephra layers provided additional tie points between the records. A 100-year running mean was calculated for the compiled records. Full details describing the generation of the records are given in Swindles et al. (2010).

2.2. Examining uncertainties

Probability distributions for the calibrated dates were used for the estimation of the age-depth models along with the tephra and SCP determinations. In addition, the calendar year of AD 2003 was attributed to the top of the sequence as this was the time of core

![Fig. 1. Water table reconstructions from DI and SA and three versions of the compiled water table record. The reconstruction errors (derived from bootstrapping) have been removed solely for the purpose of diagrammatic clarity. The reconstructions with the errors illustrated are provided in supplementary material B. The three versions of the compiled record were generated using different match point combinations as follows: version 1: major peaks in water table; version 2: major and minor peaks in water table; version 3: selected major peaks and troughs in water table. An un-tuned version of the stacked record is also presented for comparison and the thick blue lines represent a 100-year running mean values. Version 2 of the compilation was presented in Swindles et al. (2010). The tephra layers found in both profiles are shown and negative values indicate wet conditions (high bog water tables). The major wet shifts at ca. 750 BC, AD 770 and AD 1650 and the major dry phases at ca 1150–800 BC, 320 BC–AD 470 and AD 1850–2000 are shown as arrows and black rectangles respectively on version 2. The number of match points used is indicated (n values). Enlarged figures showing the different compilation versions are provided in supplementary material C.](image-url)
collection. Initial exploratory age-depth modelling was carried out using the P_Sequence in OxCal 4.1 (Bronk Ramsey, 1994, 2009). These models assume that the dated events occur in a specific order and fluctuations of the deposition rate can occur (Bronk Ramsey, 2008). The 'k' parameter was set to 0.2 (i.e. 0.2 events per cm) and an interpolation value of 0.2 was used.

Following exploratory data analysis, the chronological data points were included in Bacon, a new age-depth model based on a piece-wise linear accumulation model (Blaauw and Christen, in press), where the accumulation rate of sections depends to a degree on that of preceding sections. The age-modelling procedure is akin to that described in Blaauw and Christen (2005), although many more shorter sections are used (of 5 cm thickness), resulting in more flexible and robust chronologies. A priori, accumulation rates were assumed to have been between ca. 5 and 40 yr/cm (mean 20; Fig. 3). The degree of dependence of accumulation rates between neighbouring sections was believed to be low a priori. The prior information was combined with the radiocarbon and tephra dates using thousands of Markov Chain Monte Carlo iterations (Blaauw and Christen, 2005, in press). As the bootstrap-derived sample-specific reconstruction errors cannot be standardised in the same way as the water table records, they were scaled to representative ranges in relation to the standardised water table records. Finally, the TAS record was generated including both the chronological and reconstruction errors of the two standardised water table records, spanning the last 4500 years.

3. Results

Fig. 1 shows the water table records from DI and SA and three versions of the tuned compilation, based on inferred combinations of match points. Three versions of the compiled record are shown: version 1: major peaks in water table; version 2: major and minor peaks in water table; version 3: selected major peaks and troughs in water table. An un-tuned version of the stacked compilation is also presented for comparison. It is very encouraging to note that the compilations are extremely similar, even when based on markedly different combinations of match points. Although some differences are observed in the tuned water table data, no major differences are observed when the interpretation is based on the 100-year running mean. The major dry phases at ca 1150–800 BC, 320 BC–AD 470 and AD 1850–2000 and the wet shifts at ca. 750 BC, AD 770 and AD 1650 (Swindles et al., 2007, 2010; Kerr et al., 2009) are visible in all versions of the compilations. This adds support to the argument that tuning and stacking is a robust way to compile peat-based records.

The age-depth model is illustrated for version 2 (the version presented in Swindles et al., 2010) and shows that tuning was carried out within the chronological errors (Fig. 2). Fig. 3 shows the Bayesian age-depth model (developed using Bacon) which illustrates the significant error associated with the age-depth model. These error ranges have similar pattern to those shown in the initial P-Sequence age-depth modelling which was carried out in OxCal (Supplementary Material D). It is clear that chronological uncertainties become large especially at sections with lower dating density. In the grey-scale plots, darker grey indicates better age control while lighter grey indicates sections with less chronological precision (Fig. 4). Fig. 5 shows the TAS record with the deviation from the original age-depth model, the reconstruction envelope, based on the minimum and maximum scaled bootstrap errors and the total chronological error associated with the record, as derived from the Bacon model. This shows that a significant envelope of reconstruction and chronological error is associated with TAS palaeoclimate records from peatlands and such records should be interpreted with caution.

4. Discussion

Although the errors associated with TAS water table records have been examined, there are further difficulties which are more difficult to quantify. The suitability of tuning peat-based archives can be debated as it implies that events are synchronous within a region, which may not be the case. For example, it has been shown that the Grenzhorizont (a major stratigraphic change from humified to non-humified peat in European peatlands) was asynchronous in peatlands in Northern Germany (van den Bogaard et al., 2002). Asynchronous events would be lost by using tuning approaches and the inferences made would be incorrect. There is thus the potential to create the 'suck-in' effects or 'reinforcement syndrome' coined by Baillie (1991) and Oldfield (2001) respectively.
Real regional variation in peat-based climate records may be removed in the TAS methodology. For example, marked regional differences in climate phases between northern and southern Scotland have been identified (Langdon and Barber, 2005). In the case of the NI record, the individual water table reconstructions are generally similar, which is not surprising as the two peatlands are only 50 km apart. There may be an argument for only applying the TAS methodology to records from proximal sites, where no regional variation is apparent. Therefore, tuning and stacking should only be carried out when i) a general record of climate is required, over a relatively limited geographical area; ii) the chronological control of the record does not permit analysis of (a)synchronicity and iii) the tuning of the records is only within the chronological errors.

Future work needs to address the (a)synchronicity, leads and lags in peat-based records to assess if these are due to autogenic/site specific factors or reflecting the spatio-temporal variations in past climate change. This can only be achieved using well-dated non-tuned proxy climate data. Several recent peat-based palaeoclimate studies have achieved excellent chronological precision based on large arrays of radiocarbon dates (e.g., Yeloff et al., 2006; Mauquoy et al., 2008); a combined approach using many radiocarbon assays and tephrochronology could be used to build age-depth models with ultimate precision in certain regions. Tephra isochrons also provide a useful way of precisely correlating the records at specific points in time, and examining if changes are spatially and/or temporally synchronous (Langdon and Barber, 2004; Swindles et al., 2007).

Further work is possible, for example the chronological uncertainties in the records could be visualised as ‘time-window’ probabilities (cf. Blaauw et al., 2007, 2010). The existing testate amoebae transfer functions (e.g., Booth, 2002; Payne et al., 2006; Charman et al., 2007; Swindles et al., 2009) should be reviewed to examine the persistent sources of error in the models. There may also be ways of significantly reducing model prediction error such as downweighting problematic taxa or by using other statistical models, including Bayesian approaches (Vasko et al., 2000; Holden et al., 2008). As good practice, the significant uncertainties

Fig. 4. Grey-scale graphs of the water table reconstructions for DI (top) and SA (bottom). As in Fig. 3, dark grey areas indicate proxy values within precisely dated sections of the chronology, while lighter grey areas indicate less chronologically secure sections. The grey-scales only indicate chronological uncertainties; uncertainties of the proxy reconstruction are not included.

Fig. 5. (a) Tuned and stacked water table record for Northern Ireland (‘version 2’) spanning the last 4500 years (black line) and a 100-year running mean (thick blue line); (b) total chronological difference between the tuned and original age models; (c) total reconstruction error envelope of the compiled water table record, based on a scaled bootstrap-derived sample-specific reconstruction error; (d) total chronological error range for the compiled water table record, derived from the new Bacon age models. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
associated with TAS records should be illustrated in future studies. Readers should be made aware about the specific limitations of such compiled records, such as the potentially flawed assumption that the events are synchronous between sites. Although this paper focuses on TAS records from peatlands, the implications are highly relevant for other Quaternary palaeoclimate studies that have adopted similar approaches.

5. Conclusions

Peatland water table records from Northern Ireland are used to examine the uncertainties in the tuning and stacking approach proposed by Charman et al. (2006). Several versions of match points are used to compile the palaeoclimate record, and it is promising to note that there is only minimal variation between the different outputs, especially when a 100-year running mean is mainly used for interpretation. Although tuning and stacking may be a useful approach for combining such records, significant error ranges are associated with the resultant compilations due to chronological and reconstruction uncertainties. If the tuning and stacking approach is to be used in future studies, researchers should consider:

1. Presenting several possible versions of a tuned and stacked compilation, based on plausible combinations of match points;
2. Presenting an un-tuned version of the stacked compilation for comparison;
3. Using Bayesian age-depth modelling approaches to determine and illustrate the chronological errors associated with the individual and compiled records;
4. Providing the representative reconstruction errors;
5. Fully acknowledging that tuned peat-based proxy climate records cannot be used to assess the (a)synchrony of events between sites.

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Appendix. Supplementary material


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