How much organic carbon have UK lakes stored in the Holocene? A preliminary estimate

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Abstract:

Temperate lake sediments store a substantial amount of organic carbon (OC) over millennia. Despite the importance of quantifying terrestrial carbon budgets for nature-based solutions for climate change mitigation, the long-term accumulation of OC in European temperate lakes is poorly constrained. In this study, we analyzed 30 lake sediment records to generate a preliminary first-order estimate of Holocene OC accumulation rate (OCAR) and OC storage in UK lakes. We also examined the environmental variables that influence OCAR and produced synthesized Holocene records of %OC and z-scores of log-transformed OCAR and sediment accumulation rate (SAR) at 500-year resolution. Based on our estimation, we report an average Holocene OCAR of

7.4 ± 5.5 g C m^{-2} yr^{-1} and a Holocene total OC storage of 0.24 ± 0.18 Pg C in UK lakes. Apart from latitude, no relationship was found between the average Holocene OCAR and the various environmental variables (i.e. temperature, precipitation, surface area, catchment area, depth, altitude and geology type). During the Holocene, OCAR closely resembles variations in SAR, whereas the increase in %OC is largely explained by the warming climate. Early Holocene variations in OCAR are primarily climate-driven, whereas the anthropogenic impact on the landscape exerted a predominant influence on OC burial during the middle-late Holocene. Our results improve the current understanding of terrestrial carbon budgets in the UK and demonstrate the under-appreciated importance of lakes as long-term OC stores as compared to ponds and woodlands.

Keywords:

Organic carbon burial, Terrestrial carbon budgets, Lake sediments, Temperate lakes, Holocene, UK, Paleolimnology

Introduction

In the context of anthropogenic climate change, there is an unparalleled need to achieve carbon neutrality by this century. Nature-based solutions (NbS) comprise a crucial component of climate change mitigation due to the large amount of carbon stored in natural and managed ecosystems. NbS has the potential to mitigate CO_2 emission at a rate of 10 Gt CO_2 yr^{-1} and, in the long-term, reduce peak warming by 0.1-0.3°C depending on the different warming scenarios (Girardin et al., 2021). Quantifying terrestrial carbon budgets is conducive to implementing NbS and could help guide more targeted and informed land management decisions (Cole et al., 2007; Gregg et al., 2021; Keith et al., 2021).

Despite only constituting 3.7% of the Earth's non-glaciated land surface area (Verpoorter et al., 2014), lakes are highly spatially variable and play a critical role in the global carbon cycle (Einsele et al., 2001; Prairie, 2008; Tranvik et al., 2009; Buffam et al., 2011; Radbourne et al., 2017). Lake ecosystems are sites where active processing of carbon (e.g. carbon production, transformation, burial, and evasion) takes place (Cole et al., 2007; Prairie, 2008; Tranvik et al., 2009). Allochthonous input of organic matter from catchments contributes to the lake dissolved organic carbon (OC) or dissolved organic matter pool, which can be assimilated by heterotrophs as an energy source (Prairie, 2008; Hanson et al., 2015). Dissolved inorganic carbon, mainly in the form of CO_2, is consumed during photosynthetic assimilation by heterotrophs and oxidised into organic carbon in both dissolved and particulate forms (McGowan et al., 2016). OC may be reduced back into CO_2 and CH_4 through respiration. Particulate carbon suspended in the water column may sink to the lake bottom and contribute to OC burial in lake sediments (Alin and Johnson, 2007).

Although lakes mostly behave as net carbon sources and are super-saturated in CO_2 in the surface waters (Cole et al., 1994; Tranvik et al., 2009), lake sediments can store a large amount of OC in the long-term due to their high OC burial efficiency, rapid sediment accumulation rates and high aquatic productivity (Cole et al., 2007; Sobek et al., 2009). Some of the deeper and larger lakes of tectonic origin could persist in the landscape for millions of years, and lake sediments in glaciated terrains could accumulate for more than 10,000 years (Alin and Johnson, 2007; Cole, 2013). In contrast, many smaller lakes are short-lived or artificially constructed (i.e. reservoirs). Globally, inland waters (including lakes, rivers, streams and reservoirs) receive carbon at the magnitude estimated at 2.9 Pg C yr^{-1}, amongst which 1.4 Pg C yr^{-1} are evaded into the atmosphere, 0.9 Pg C yr^{-1} are transported to the sea, and the remaining 0.6 Pg C yr^{-1} are buried to sediments (Tranvik et al., 2009). The total amount of carbon storage in lake sediments during the Holocene is estimated at 400-800 Pg C (Cole et al., 2007), and the long-term OC accumulation rate (OCAR) ranges between 4.5-14 g C m^{-2} yr^{-1} (Dean and Gorham, 1998; Stallard, 1998; Cole et al., 2007). Recently, OCAR in lake sediments has increased due to cultural eutrophication (Anderson et al., 2014; Anderson et al., 2020). Carbon burial is expected to continue to increase, driven by climate change, increased runoff and eutrophication (Tranvik et al., 2009).

Lake sediments document spatially and temporally integrated information. Hence, paleolimnological approaches are well-suited for quantifying OC accumulation and storage in lakes and may offer critical insights for understanding changes in the terrestrial carbon cycle in the future (McGowan et al., 2016). One widely adopted method uses loss-on-ignition 550°C (%LOI_{550}) data to estimate %OC in lake sediments (Pajunen, 2000; Anderson et al., 2014) or directly makes use of downcore total organic carbon (TOC) data measured using an elemental analyzer (McGowan et al., 2016). To date, many studies have adopted a paleolimnological approach for quantifying the amount of OC storage and OCAR in lakes at different spatial and temporal scales (e.g. Dean and Gorham, 1998; Kastowski et al., 2011; Anderson et al., 2020). However, there is a bias towards Holocene scale estimates on boreal and arctic lakes within Europe (e.g. Kortelainen et al., 2004; Anderson et al., 2009; Chmiel et al., 2015), whereas temperate lakes, which are large organic matter stores, receive less attention (Scott, 2014). Temperate lakes cover ~25% of the

European lake surface area but contribute to ~35% of European lakes' total carbon accumulation rate (Scott, 2014).

The UK is home to 43,738 water bodies covering 213,911 ha in Great Britain (Hughes et al., 2004) and 1,668 water bodies covering 62,600 ha in Northern Ireland (Gibson et al., 1994), altogether constituting around 1% of the total UK surface area. There are few systematic inventories of OCAR in the UK. Scott (2014) examined the OCAR of two lakes in the Shropshire–Cheshire meres region, and Anderson et al. (2014) included a number of UK lakes in their OCAR estimation for European lakes. Both studies focused on the last 100–150 years. Only a few UK lakes were included in the estimation of Holocene OCAR in European lakes (Kastowski et al., 2011). Thus, there is no clear overview of Holocene OCAR and OC storage estimates in the UK. There are extensive lake sediment records in the UK covering part or the complete sequence of the Holocene (e.g. Bennett et al., 1992; Fossitt, 1996; Watkins et al., 2007), offering an excellent opportunity to conduct a Holocene OC inventory.

Here, we present a first-order preliminary estimate for OCAR and OC storage in UK lakes across the Holocene by adopting a paleolimnological approach. In addition, we investigate the temporal variations in OCAR, sediment accumulation rate (SAR) and %OC during the Holocene and examine the variables influencing OCAR in UK lakes (i.e. temperature, precipitation, surface area, catchment area, depth, altitude, latitude and geology type). By comparing the OCAR in UK lakes to estimates from lakes in different regions and various habitat types in the UK, we evaluate the relative importance of lake sediments as an OC store in the UK.

Methods

Study sites and data collection

The selection of lake sediment cores was based on four main criteria: (1) the sediment record covers at least 3 kyr during the Holocene; (2) a $\%LOI_{550}$, TOC, or organic matter (OM) record exists; (3) a minimum of three radiocarbon dates to ensure a relatively reliable age control; and (4) extant lakes.

A wide range of search terms was employed to identify relevant studies. These include "lake", "loch", "llyn", "lough", "Holocene", "Britain", "England", "Scotland", "Wales", "Northern Ireland", "organic matter", "LOI", "TOC", "vegetation", and "pollen". We are aware that this search was not exhaustive, and additional sediment records must exist in earlier publications or remain unpublished. However, in contrast to other Holocene estimates for lakes (e.g. Anderson et al., 2009, n=11; Chmiel et al., 2015, n=7), fjords (e.g. Smeaton et al., 2017, n=5) and peatlands (e.g. Ratcliffe et al., 2018, n=12), the number of lakes included is sufficient for a preliminary first-order estimate.

A total of 30 lake sediment records across the UK were selected (Figure 1). This includes three new lake sediment records (Loweswater, Loch na Claise and Loch an Aigeil) that were analyzed for $\%LOI_{550}$ following Heiri et al. (2001), which entails burning at 550°C for 4 hours and calculating using Equation (1). $\%LOI_{550}$ data for the 27 published records were generated using a temperature range between 450-550°C and furnace times of 1-12 hours (references are in SI). Scottish lakes (n=19) comprise most of the selected records, followed by lakes in England (n=6), Wales (n=3) and Northern Ireland (n=2). The proportional representation of lakes from each country is roughly consistent with the spatial distribution of lakes in the UK, dominated by lakes in Scotland (57%) and England (36%) in terms of absolute numbers (Gibson et al., 1994; Hughes et al., 2004).

$$\%LOI_{550} = 100\left(\frac{(DW_{105} - DW_{550})}{DW_{105}}\right)$$

(Equation 1)

Chronology

To obtain Holocene temporal trends in OCAR, SAR and %OC, radiocarbon dates for all 30 lake records were (re)calibrated with the IntCal20 curve (Reimer et al., 2020) using Bayesian age-depth modelling in the Bacon package (version 2.5.8) (Blaauw and Christen, 2011) in R (see Figures S1-S30 for the new age models and Tables S1-S3 for radiocarbon ages from the three new records). The 95% confidence intervals from the Bacon age-depth models were used as conservative age uncertainties. The maximum age uncertainties across all interpolated depth layers ranged from 289 years (Lochan Uaine) to 1,705 years (Loch na Claise), with 77% of the lake records having maximum age uncertainties below 1,000 years.

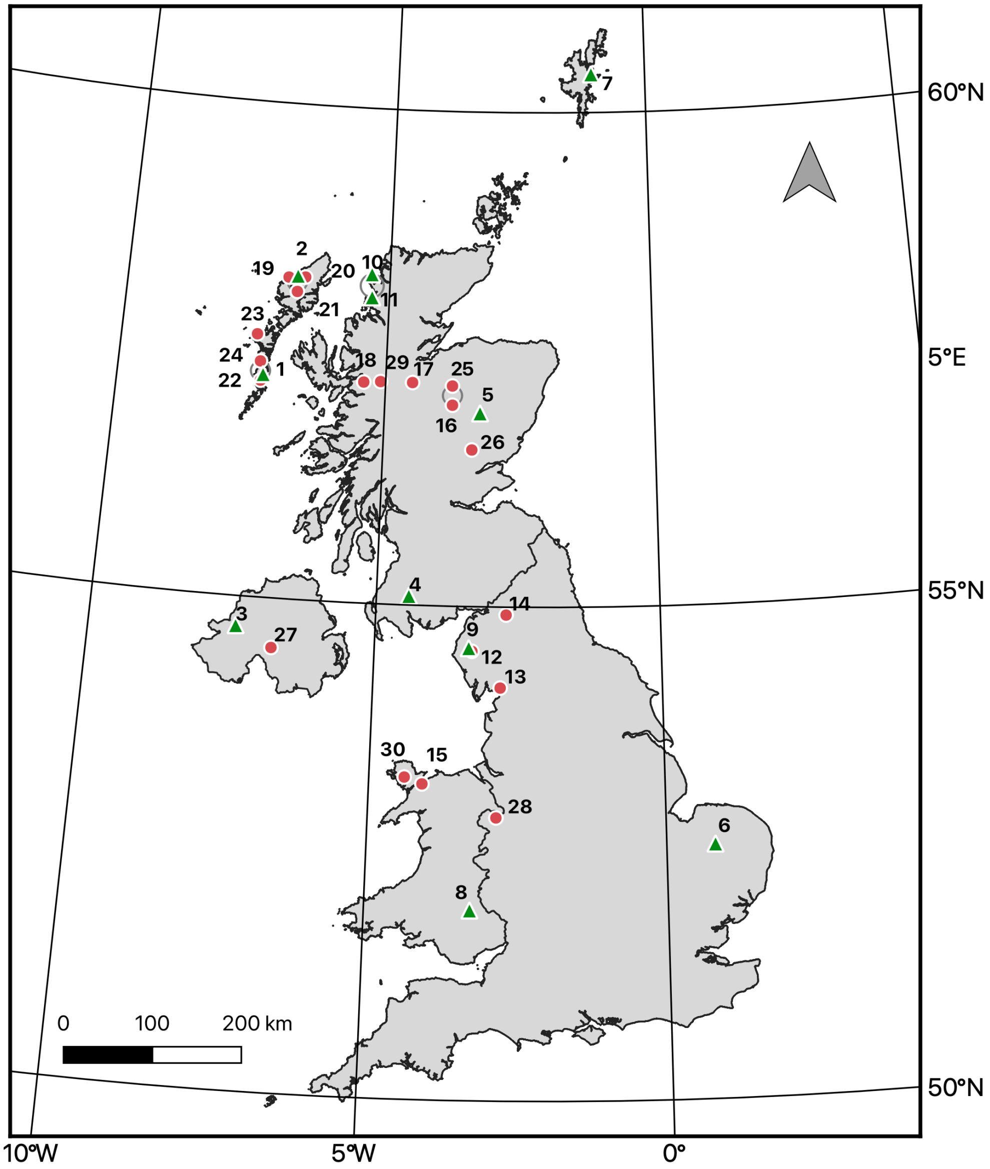

Figure 1. Overview map showing the 30 study sites. Green triangles (n=11) represent lakes with reported dry bulk density data (required to calculate organic carbon accumulation rate); red circles (n=19) represent lakes lacking dry bulk density data. List of lake names, published reference sources and further information associated with each lake are given in the supplementary table.

Calculation of average Holocene OCAR and OC storage

$\%LOI_{550}$ was multiplied by a factor of 0.469 to convert it into %OC based on previous comparisons of $\%LOI_{550}$ and %OC (Dean, 1974). Most of the published literature (n=19) did not report data on dry bulk density (DBD) (Figure 1), but DBD and SAR are required to calculate dry mass accumulation rate (DMAR), which is essential in the calculation of OCAR (see below). Following Dean and Gorham (1998), an empirical relationship between $\%LOI_{550}$ and DBD was established using data from the 11 lakes with DBD reported (Figure 1) (Equation 2), which has r^2=0.6 and $p<2.2*10^{-16}$. This $\%LOI_{550}$-DBD relationship is highly similar to existing empirical relationships (Dean and Gorham 1998; Moyle et al. 2021) (see Figure S31).

$$DBD = 2.4355\ \%LOI_{550}^{-0.827}$$

(Equation 2)

This relationship was applied to the estimation of DBD for the 19 lakes. OCAR (g C m^{-2} yr^{-1}) was determined by multiplying DMAR (g cm^{-2} yr^{-1}) by %OC and a conversion factor of 10000 (Anderson et al., 2014).

To account for the higher-than-average SAR occurring at the deepest part of the lake (Engstrom and Rose, 2013; Anderson et al., 2014), a sediment focusing factor based on the ratio of sediment ^{210}Pb flux to regional atmospheric ^{210}Pb flux was applied. Due to the paucity of sediment ^{210}Pb flux data for most study sites, we employ a regional average focusing factor of 1.78 based on data from 90 UK lakes since 1850 CE (Handong Yang, unpublished data). Sediment focusing varies over time as the pattern of deposition evolves and lake morphometry or size changes (Engstrom and Rose, 2013). However, we assume that the focusing factor remains constant over the Holocene for ease of estimation. The focusing-corrected average Holocene OCAR in each lake sediment record was then averaged to estimate the average focusing-corrected Holocene OCAR in UK lakes. The total Holocene OC storage in UK lakes was calculated by multiplying the average focusing-corrected Holocene OCAR by 11,650 years and a total UK lake area of 276,511 ha (Gibson et al., 1994; Hughes et al., 2004). Standard deviations were calculated for the OCAR in each sediment record and propagated to obtain uncertainty of the average Holocene OCAR in UK lakes. We recognize that there are compounding error sources associated with each step of the estimation, but the reported error values represent a conservative estimate of the uncertainty, which means that the true value lies within the range provided.

Examining controlling factors on OCAR

Pearson's product-moment correlation was performed to determine the relationship between the average Holocene OCAR from each sediment record and various modern environmental variables at each site, assuming that OCAR and these variables have remained constant over time. Data for surface area, catchment area, altitude, mean depth, maximum depth, geology type (categorized into low, moderate and high alkalinity groups) and latitude were obtained from the UK Lakes Portal (UK Centre of Hydrology and Ecology, 2016) and the original publications; the maximum annual temperature and mean annual precipitation between 1961-2020 at the nearest weather station for each site were obtained from the Met Office (2022). Spearman's rank correlation coefficient was performed to analyze the relationship between OCAR and the three geology types.

Average UK Holocene temporal trends

The OCAR, SAR and %OC data for each lake were linearly interpolated between neighbouring data points to the nearest 500-year since the sampling resolution of all sediment cores lies below 500-year. The OCAR and SAR data were log-transformed for normality (hereafter referred to as $\mathrm{OCAR_{log}}$ and $\mathrm{SAR_{log}}$). For each sediment record, z-scores of $\mathrm{OCAR_{log}}$ and $\mathrm{SAR_{log}}$ were calculated by subtracting the mean and dividing by the standard deviation. Synthesized $\mathrm{OCAR_{log}}$ and $\mathrm{SAR_{log}}$ z-scores were produced by taking the average z-scores for all lakes at each resampled age (i.e. one average value every 500 years). Pearson's product-moment correlation was performed to assess the relationship between the synthesized $\mathrm{OCAR_{log}}$ z-score and the synthesized $\mathrm{SAR_{log}}$ z-score and %OC.

Results

Average Holocene OCAR and OC storage estimates

The average focussing-corrected Holocene OCAR in UK lakes is 7.4 ± 5.5 g C m^{-2} yr^{-1} (uncorrected OCAR: 13.2 ± 9.9 g C m^{-2} yr^{-1}), with values ranging from 2.5 ± 0.9 g C m^{-2} yr^{-1} for Loch Buailaval Beag to 20.3 ± 8.9 g C m^{-2} yr^{-1} for Lough Catherine (Figure 2). The area-weighted OCAR is 21 ± 15 Gg C yr^{-1} (rounded to 2 significant figures). During the Holocene, the total OC storage in UK lakes is approximately 0.24 ± 0.18 Pg C with areal OC storage of 86.5 ± 64.6 Kg C m^{-2}.

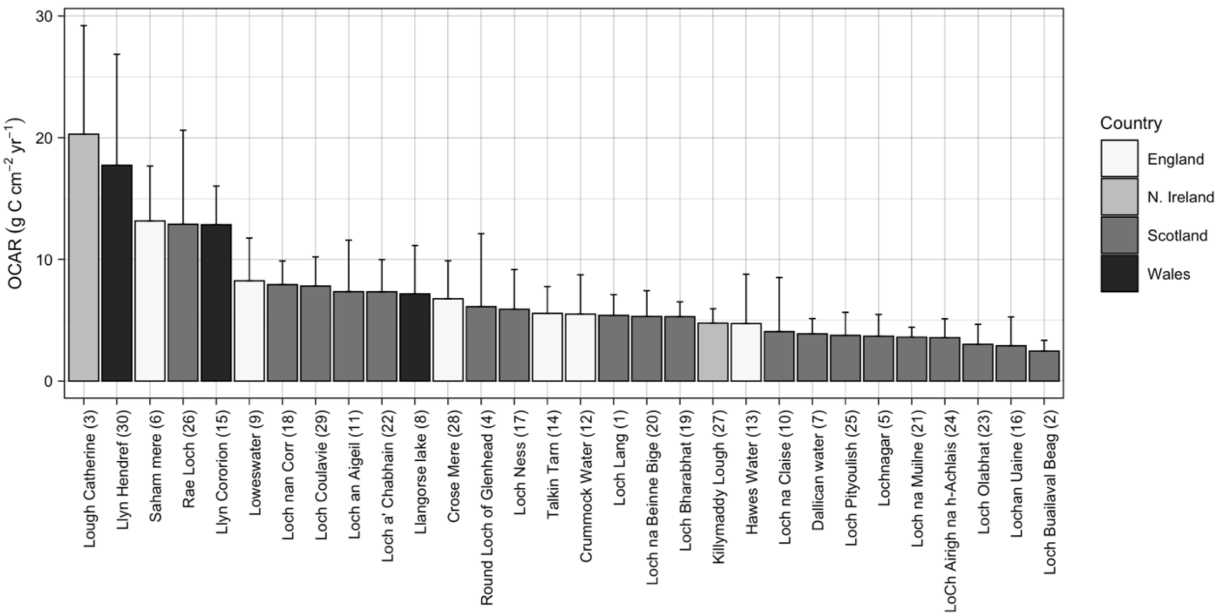

Figure 2. Focusing-corrected average Holocene organic carbon accumulation rate (OCAR) (g C m^{-2} yr^{-1}) in each lake sediment record.

Relationship between OCAR and environmental variables

The only variable that significantly correlates with the average Holocene OCAR from each sediment record is latitude ($r=-0.5$, $p=3.2*10^{-3}$). No significant correlations were found between OCAR and any other of the variables tested (see Supplementary Information).

Average UK Holocene temporal trends

Since 12 cal kyr BP, %OC has increased rapidly from ca. 6.8 to 17.3%, stabilizing after 8 cal kyr BP around 16-17% with a gradual increase (Figure 3a) to present-day values of 18.1%. The OCAR$_{\log}$ z-score remains stable between 12-10 cal kyr BP and subsequently declines between 10-8 cal kyr BP (Figure 3b,d). In contrast, the SAR$_{\log}$ z-score displays a more extended decline between 12-8 cal kyr BP (Figure 3c). Both records display a long-term increase from 8 cal kyr BP to the present, interrupted by a temporary decline between 6-5 cal kyr BP. After 3 cal kyr BP,

$OCAR_{log}$ z-score lies predominantly above the average (i.e. when z-score=0), which is greater than the early and middle Holocene.

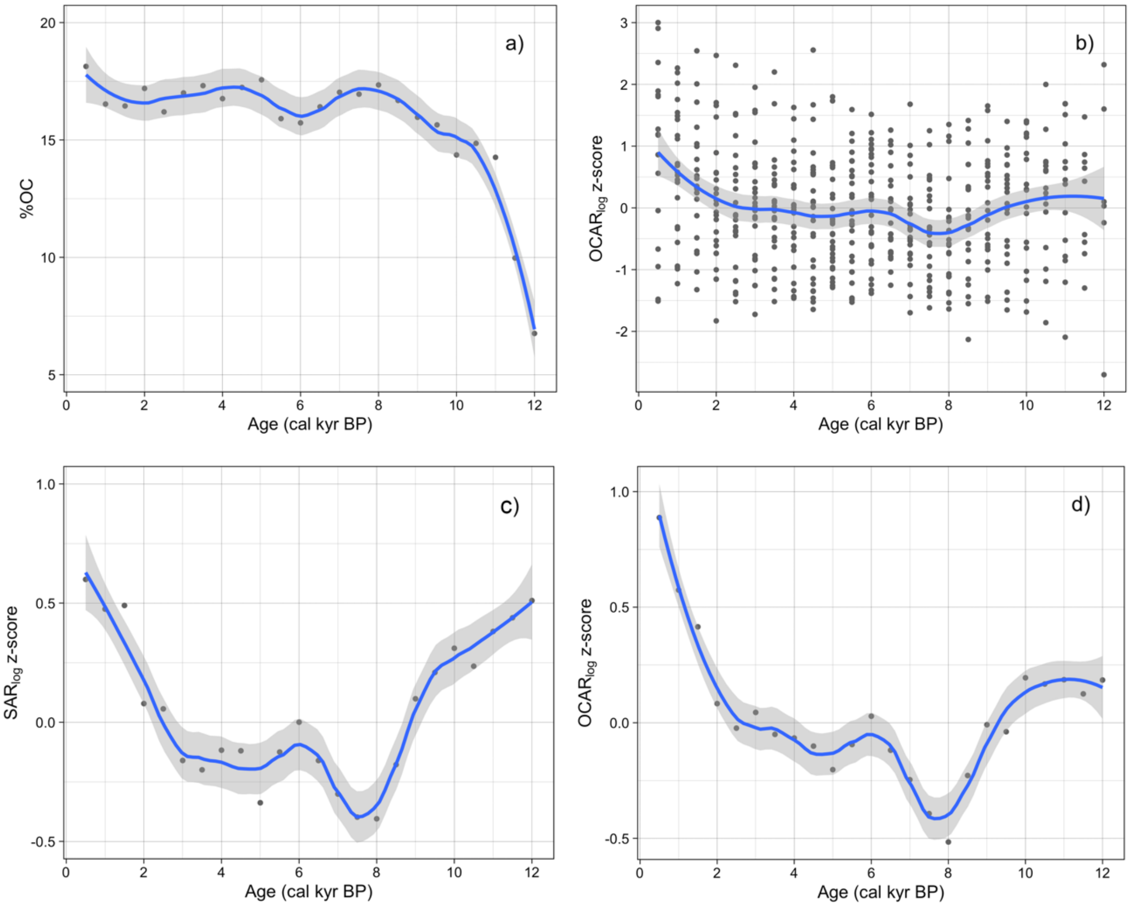

Figure 3. Average Holocene temporal trends for 30 UK lakes with LOESS smoothing (95% confidence interval, span=0.4) at 500-year resolution: (a) percentage organic carbon (%OC); (b) raw log-transformed organic carbon accumulation rate ($OCAR_{log}$) z-score showing data points from all sediment records; (c) synthesized log-transformed sediment accumulation rate (SAR_{log}) z-score; (d) synthesized $OCAR_{log}$ z-score.

A very strong correlation exists between the $OCAR_{log}$ and SAR_{log} z-scores ($r=0.9$, $p=1.8*10^{-8}$). An r^2 of 0.8 suggests that SAR_{log} can explain up to 80% of the variation in $OCAR_{log}$. On the contrary, %OC displays no relationship with the $OCAR_{log}$ z-score ($r=-0.2$, $p=0.5$).

Discussion

Average Holocene OCAR and OC storage estimates

The total Holocene OC storage for UK lakes is estimated to be 0.24 ± 0.18 Pg C (areal OC storage: 86.5 ± 64.6 Kg C m^{-2}), equivalent to 0.88 ± 0.66 Pg CO_2. The magnitude of the average Holocene OCAR of UK lakes at 7.4 ± 5.5 g C m^{-2} yr^{-1} is in good agreement with the global range for lakes between 4.5-14 g C m^{-2} yr^{-1} (Dean and Gorham, 1998; Stallard, 1998; Cole et al., 2007), and is higher than the average Holocene OCAR estimates for lakes in Europe (5.2 g C m^{-2} $yr^{-}1$) (Kastowski et al., 2011), southwest Greenland (6 g C m^{-2} yr^{-1}) (Anderson et al., 2009), Finland (1.6 g C m^{-2} yr^{-1}) (Kortelainen et al., 2004), and Sweden (3.2 g C m^{-2} yr^{-1}) (Chmiel et al., 2015). Variations in OCAR in Europe are likely due to region-specific lake characteristics. For example, lower temperatures in Finland may suppress primary production, thus leading to lower OCAR in boreal lakes (Kortelainen et al., 2004). In contrast, the higher OCAR in southwest Greenland may be explained by the selection of very small lakes in the study (range: 0.05-0.73 km^2) (Anderson et al., 2009) compared to the selection of larger Finnish lakes (average area: 122 km^2) (Kortelainen et al., 2004) because OCAR is often found to be inversely related with lake area (Mulholland and Elwood, 1982; Pajunen, 2000).

Within habitats of the UK, the Holocene OCAR of lakes (7.4 ± 5.5 g C m^{-2} yr^{-1}) is higher than the modern estimates for broadleaf and mixed woodlands (4.2 g C m^{-2} yr^{-1}, range: 0.7-12 g C m^{-2} yr^{-1}), coniferous woodlands (4.9 g C m^{-2} yr^{-1}, range: 0.8-11.7 g C m^{-2} yr^{-1}) and grasslands (2.2 g C m^{-2} yr^{-1}) (Downing et al., 2008), but lower than the Holocene estimates for fjords (8.3 ± 2.0 g C m^{-2} yr^{-1}) (Smeaton et al., 2017), peatlands (17.8 ± 4.9 g C m^{-2} yr^{-1}) (Ratcliffe et al., 2018), the modern estimate for ponds aged between 18-20 years (142 ± 19 g C m^{-2} yr^{-1}) (Taylor et al., 2019) and millennial-scale estimates for seagrasses (138 ± 38 g C m^{-2} yr^{-1}) and salt marshes (218 ± 24 g C m^{-2} yr^{-1}) (Mcleod et al., 2011) (Figure 4a). The area-weighted OCAR for UK lakes (21 ± 15 Gg C yr^{-1}) is lower than all UK habitats apart from seagrasses (Figure 4b) due to the small total surface area of lakes in the UK compared with other habitats.

In comparison to most terrestrial habitats, vegetated coastal habitats exhibit very high OCARs owing to their high efficiency in trapping sediments from both riverine and oceanic sources, facilitated by their complex ecosystem structure (Mcleod et al., 2011). Peatlands and ponds also exhibit higher OCARs than lakes. Peatlands are highly efficient OC sinks due to active plant growth (Loisel et al., 2014). Ponds are generally very productive and are effective in trapping and preserving carbon in sediments (Downing et al., 2006; Cole et al., 2007). The higher OCAR in lakes compared to woodlands and grasslands is due to lakes' higher OC preservation rate (Cole et al., 2007).

The OC turnover rates in ponds or forest biomass last for decades to centuries (Cole, 2013). The long-term storage of OC can only occur in soils once forests reach maturity, and yet, the long-term OC burial in soil is much limited compared to its instantaneous carbon assimilation rate due to periodic burning and/or high decay rates (Prairie, 2008). Moreover, despite having very high OCAR, ponds are ephemeral features of the landscape that is more susceptible to in-filling and desiccation compared to lakes. In contrast, lake sediments, peatlands and coastal habitats can store OC for millennia (Cole et al., 2007; Prairie, 2008; Mcleod et al., 2011; Ratcliffe et al., 2018; Taylor et al., 2019). In particular, large and deep lakes in active tectonic regions can store OC for up to millions of years (e.g. Lake Malawi storing 5,500 Pg C) (Alin and Johnson, 2007). Consequently, although the average Holocene OCAR of lakes is modest in contrast to various habitat types in the UK, the capacity of lakes to act as a long-term carbon store cannot be overlooked.

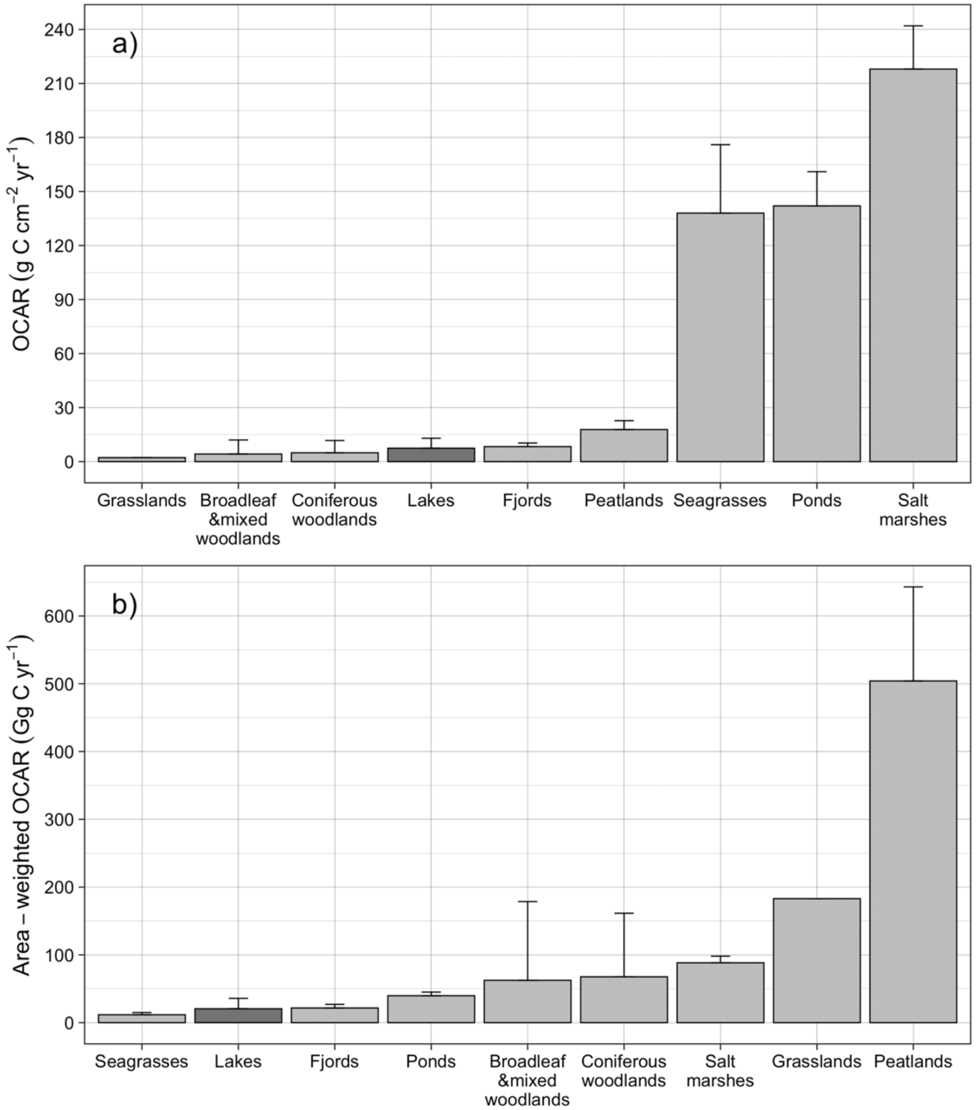

Figure 3. Comparison of (a) average Holocene organic carbon accumulation rate (OCAR) and (b) area-weighted Holocene OCAR in a range of habitats in the UK. Sources of OCAR data include Mcleod et al. (2011) for seagrasses and salt marshes; Smeaton et al. (2017) for fjords; Taylor et al. (2019) for ponds; Downing et al. (2008) for woodlands and grasslands and Ratcliffe et al. (2018) for peatlands. Data for habitat area used for calculating area-weighted Holocene OCAR was

obtained from Gibson et al. (1994) and Hughes et al. (2004) for lakes; Taylor et al. (2019) for ponds; Carey et al. (2008) for woodlands, grasslands and peatlands; Smeaton et al. (2017) for fjords; Phelan et al. (2011) for salt marshes and Green et al. (2021) for seagrasses.

The estimation of Holocene OC storage and accumulation rate in UK lakes provides an important constraint on the regional terrestrial carbon budget. Using the past as an analogue, our results are highly relevant for understanding how carbon budgets in lakes will change in the future (Hanson et al., 2015; McGowan et al., 2016). Moreover, despite the promising potential of NbS for climate change mitigation, there is currently a bias towards carbon flows (e.g. sequestration) and an underappreciation of carbon storage in carbon accounting (Keith et al., 2021). While both processes are essential for the ecosystem service of climate regulation, the overlooking of carbon storage hampers current NbS efforts by providing incomprehensive information about the mitigation benefits, which may result in perverse outcomes in NbS implementation (Keith et al., 2021). Hence, by quantifying the long-term carbon storage in lake sediments in the UK, we provide critical information that may contribute to a more comprehensive carbon accounting of terrestrial aquatic systems beneficial for facilitating better informed NbS practices and associated land management decisions. Despite the long-term mitigation benefits NbS may offer, we stress that these benefits are limited compared to decarbonisation efforts (Girardin et al. 2021), therefore, NbS should not act as a distraction from emission reduction activities in the near term.

Controlling factors on OCAR

Previous studies have identified a wide range of environmental variables controlling variations in the average Holocene OCAR from each lake record. The main factors include depth (Anderson et al., 2014), surface area (Mulholland and Elwood, 1982; Pajunen, 2000; Downing et al., 2008), lake morphometry (Ferland et al., 2014), precipitation (Tranvik et al., 2009), temperature (Gudasz et al., 2015; Rantala et al., 2016), nutrients (Anderson et al., 2020), oxygen exposure time and mineralization (Sobek et al., 2009). Here, we found a moderate relationship between OCAR and latitude, which may suggest an indirect influence of cooling as latitude increases (Kastowski et al., 2011). The absence of a relationship between OCAR and the environmental variables we tested may suggest the relationships found in previous studies may not apply universally. Moreover, none of the variables alone shape variations in OCAR between lakes, but rather, a combination of many site-specific factors. However, it is beyond the scope of this study to explain variations between lakes. Besides, with over 67% of the studied lakes $\leqslant$ 10 ha, the absence of a relationship between OCAR and the surface area might be due to the bias towards very small lakes with variable OCAR yet narrow environmental gradients (Kastowski et al., 2014).

Average UK Holocene temporal trends

The strong positive correlation between the synthesized $\mathrm{OCAR_{log}}$ and $\mathrm{SAR_{log}}$ z-scores indicates that variations in $\mathrm{OCAR_{log}}$ are largely driven by $\mathrm{SAR_{log}}$, and %OC of the sediment has not changed markedly during the Holocene. The increase in %OC during the early Holocene (12-8 cal kyr BP) likely resulted from the increasing annual temperature in Europe (Figure 5a,b) (Davis et al., 2003; Lang et al., 2010), which facilitated the switch from late glacial minerogenic sediment to organic gyttja as catchment soil developed (Bennett et al., 1990; Snowball and Thompson, 1990; Edwards and Whittington, 1998). The decrease in the synthesized $\mathrm{OCAR_{log}}$ and $\mathrm{SAR_{log}}$ z-scores prior to 8 cal kyr BP can be explained by the progressive establishment of woodlands fostered by the increasingly warm climate, which stabilizes the soils and reduces runoff and erosion (Figure 5a,f,g) (Bennett et al., 1992; Fossitt, 1996; Watkins et al., 2007).

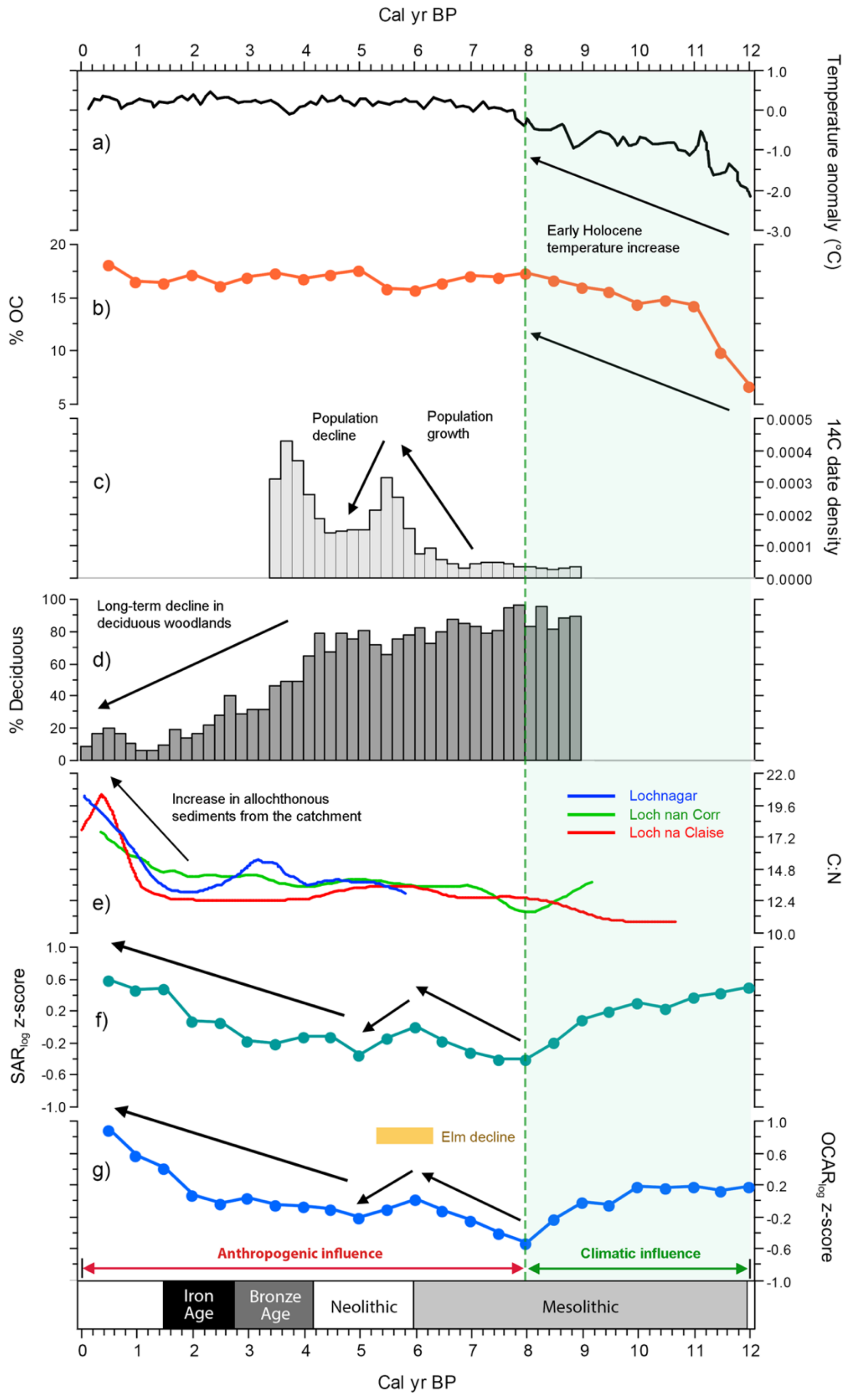

Figure 5. Dominant drivers of Holocene organic carbon accumulation rate (OCAR) and sediment accumulation rate (SAR) variations in 30 UK lakes (see Figure 1). (a) pollen-reconstructed annual temperature record for Europe (Davis et al., 2003); (b) percentage organic carbon (%OC) at 500-year resolution; (c) radiocarbon (^{14}C) date probability density functions from archaeological sites

between 9-3.4 cal kyr BP (Woodbridge et al., 2014); (d) pollen-inferred deciduous woodland change since 9 cal kyr BP (Woodbridge et al., 2014); (e) C:N ratios from three study sites (blue: Lochnagar; green: Loch nan Corr; red: Loch na Claise) with LOESS-smoothing (span=0.2) (Dalton et al., 2005; Mackie et al., 2007; Matthews, 2022); (f-g) synthesized log-transformed SAR (SAR_{log}) and OCAR ($OCAR_{log}$) z-scores at 500-year resolution. The yellow bar above (g) represents the time range for the elm decline between 6,347-5,281 cal kyr BP based on statistical analyses of radiocarbon dates (Parker et al., 2002). The period-based chronology for pre-historic Britain was obtained from Pollard (2008). The green shading separates out intervals where climate exerts more influence on OCAR and SAR variations from periods where anthropogenic impact on the landscape dominates (see text for details).

Since 8 cal kyr BP, the long-term increase in the synthesized $OCAR_{log}$ and SAR_{log} z-scores suggests increasing anthropogenic disturbance on the landscape (Figure 5f,g). The initial population increase in Britain started from ca. 7.6 cal kyr BP during the Late Mesolithic, followed by a long-term population growth trend, indicated by the increase in ^{14}C date densities from archaeological evidence and the sustained decline in deciduous woodlands (Figure 5c,d) (Woodbridge et al., 2014). On the contrary, %OC has remained relatively stable since 8 cal kyr BP, resembling the stabilized trend in temperature (Figure 5b).

The local maxima in the synthesized $OCAR_{log}$ and SAR_{log} z-scores between 6.5-5.5 cal kyr BP coincides with the widely documented elm decline on the British Isles (6,347–5,281 cal yr BP) (Figure 5f,g) for which human activity is one of the hypothesized causes (Parker et al., 2002). The elevated sedimentation and OC burial may have been driven by the transition from Mesolithic hunter-gatherers to Neolithic agriculture in the British Isles between 6.4-6 cal kyr BP (Woodbridge et al., 2014) and the substantial population growth in Britain between 6.1-5.4 cal kyr BP (Collard et al., 2010) (Figure 5c), both increasing anthropogenic pressure on the landscape. The increase in the synthesized z-scores is interrupted by a decline towards lower values in both records between 5.5-4.5 cal kyr BP. This interval coincides with reduced ^{14}C date density between 5.3-4.4 cal kyr, indicating reduced Neolithic impact on the landscape, which leads to the re-establishment of woodlands (Figure 5c,d,f,g) (Woodbridge et al., 2014).

Since 5-4 cal kyr BP, the continued increase in the synthesized $OCAR_{log}$ and SAR_{log} z-scores suggests enhanced soil erosion, which might be attributed to anthropogenic activities (Van Vliet-Lanoë et al., 1992; Edwards and Whittington, 2001). The gradual increase in both z-scores between 4-3 cal kyr BP coincides with the British Bronze Age (2,200-800 BC or 4,150-2,750 BP), whilst the accelerated increase since ca. 3-2.5 cal kyr BP coincides with the British Iron Age (800 BC-43 CE/500 CE or 2,750-1,907/1,450 BP) (Pollard, 2008). Changes in OCAR and SAR are consistent with the long-term increase in C:N at Loch na Claise, Loch nan Corr and Lochnagar, with an accelerated increase over the last 2 kyr (Figure 5e) (Dalton et al., 2005; Mackie et al., 2007; Matthews, 2022). These suggest an increase in allochthonous sediment input linked to human activities. However, there are limited records of C:N from the studied lakes to help further discriminate between allochthonous and autochthonous sources of OC. Compared to natural conditions, anthropogenic sediment delivery can be 5-10 times higher (Dearing and Jones, 2003). Increased land-use pressure, including deforestation, agriculture, and grazing, have all exacerbated soil erosion and increased allochthonous carbon input to lakes (Jones et al., 1985; Beales, 1980; Bennett et al., 1992; Edwards and Whittington, 1998; Mulder, 1999). Soil erosion would also elevate nutrient supply into lakes, increasing autochthonous OC accumulation due to increased aquatic productivity.

Conclusion

This study represents a preliminary first-order estimate of Holocene OCAR and OC storage in UK lakes, and we acknowledge a number of limitations, namely, the assumption of a non-varying %LOI$_{550}$-DBD relationship, spatial and temporal extrapolations of OCAR, uncertainties of radiocarbon chronologies and issues of linear interpolation, which could be improved with analyses of new dated sediment cores. Although the OCAR of lakes is modest compared to various coastal and terrestrial habitats in the UK, our results demonstrate the importance of lakes as long-term OC stores as compared to ponds and woodlands. While more lake sediment records could be incorporated into the estimation for better spatiotemporal representation of UK lakes, our estimates based on available data improve the current understanding of terrestrial carbon storage in the UK and OC accumulation in European temperate lakes. Our results may contribute important information for understanding how lake carbon budgets would change in the future, as well as for implementing a more comprehensive carbon accounting for better-informed Nature-based Solutions and land management practices.

Moreover, our results indicate that the first-order response of lake OCAR was to climate amelioration during the early Holocene, initiating organic matter production in terrestrial landscapes and its burial in lake sediments. The second major driver of OCAR since the middle Holocene has been the anthropogenic impact on the landscape, which has resulted in enhanced transport and erosion of OC from the deforested landscapes into lakes and also increased aquatic productivity due to a greater nutrient supply. Further work using geochemical analyses is required to distinguish the type or source of OC that reaches lakes during the middle-late Holocene.

Acknowledgements

Radiocarbon chronologies for three new sediment records analyzed in this study were provided by NEIF (NF/2019/1/11 and NEIF 2364.0321), and the PhD studentship for Louisa Matthews was provided by NERC-UKRI (IAP-17-91). Data for the average sediment focusing factor based on 90 UK lakes was provided by Handong Yang. We would like to sincerely thank Neil Rose and the two anonymous reviewers for their helpful comments and suggestions.

References

Alin SR and Johnson TC (2007) Carbon cycling in large lakes of the world: A synthesis of production, burial, and lake-atmosphere exchange estimates: carbon cycling in large lakes. *Global Biogeochemical Cycles* 21(3): GB3002.

Anderson NJ, Bennion H and Lotter AF (2014) Lake eutrophication and its implications for organic carbon sequestration in Europe. *Global Change Biology* 20(9): 2741–2751.

Anderson NJ, D'Andrea W and Fritz SC (2009) Holocene carbon burial by lakes in SW Greenland. *Global Change Biology* 15(11): 2590–2598.

Anderson NJ, Heathcote AJ, Engstrom DR, et al. (2020) Anthropogenic alteration of nutrient supply increases the global freshwater carbon sink. *Science Advances* 6(16): eaaw2145.

Beales PW (1980) The Late Devensian and Flandrian vegetational history of Crose Mere, Shropshire. *New Phytologist* 85(1): 133–161.

Bennett KD, Boreham S, Sharp MJ, et al. (1992) Holocene history of environment, vegetation and human settlement on Catta Ness, Lunnasting, Shetland. *The Journal of Ecology* 80(2): 241–273.

Bennett KD, Fossitt JA, Sharp MJ, et al. (1990) Holocene vegetational and environmental history at Loch Lang, South Uist, Western Isles, Scotland. *New Phytologist* 114(2): 281–298.

Blaauw M and Christen JA (2011) Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis* 6(3): 457–474.

Buffam I, Turner MG, Desai AR, et al. (2011) Integrating aquatic and terrestrial components to construct a complete carbon budget for a north temperate lake district: Carbon budget in lake-rich region. *Global Change Biology* 17(2): 1193–1211.

Carey, PD, Wallis SM, Emmett B et al. (2008) *Countryside survey: UK results from 2007*. Report for the Natural Environment Research Council, 10 December. Swindon: Natural Environment Research Council.

Chmiel HE, Niggemann J, Kokic J, et al. (2015) Uncoupled organic matter burial and quality in boreal lake sediments over the Holocene. *Journal of Geophysical Research: Biogeosciences* 120(9): 1751–1763.

Cole JJ, Caraco NF, Kling GW, et al. (1994) Carbon dioxide supersaturation in the surface waters of lakes. *Science* 265(5178): 1568–1570.

Cole JJ, Prairie YT, Caraco NF, et al. (2007) Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems* 10(1): 172–185.

Cole J (2013) Freshwater in flux. *Nature Geoscience* 6(1): 13–14.

Collard M, Edinborough K, Shennan S, et al. (2010) Radiocarbon evidence indicates that migrants introduced farming to Britain. *Journal of Archaeological Science* 37(4): 866–870.

Dalton C, Birks HJB, Brooks SJ, et al. (2005) A multi-proxy study of lake-development in response to catchment changes during the Holocene at Lochnagar, north-east Scotland. *Palaeogeography, Palaeoclimatology, Palaeoecology* 221(3–4): 175–201.

Davis BAS, Brewer S, Stevenson AC, et al. (2003) The temperature of Europe during the Holocene reconstructed from pollen data. *Quaternary Science Reviews* 22(15–17): 1701–1716.

Dean WE and Gorham E (1998) Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. *Geology* 26(6): 535–538.

Dean, WE Jr (1974) Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: Comparison with other methods. *SEPM Journal of Sedimentary Research* 44(1): 242–248.

Dearing JA and Jones RT (2003) Coupling temporal and spatial dimensions of global sediment flux through lake and marine sediment records. *Global and Planetary Change* 39(1–2): 147–168.

Downing JA, Cole JJ, Middelburg JJ, et al. (2008) Sediment organic carbon burial in agriculturally eutrophic impoundments over the last century: Sediment organic carbon burial. *Global Biogeochemical Cycles* 22(1): GB1018.

Downing JA, Prairie YT, Cole JJ, et al. (2006) The global abundance and size distribution of lakes, ponds, and impoundments. *Limnology and Oceanography* 51(5): 2388–2397.

Edwards KJ and Whittington G (1998) The palaeoenvironmental background: Pollen studies at Rae Loch. In: Barclay GJ and Maxwell GS (eds) *The Cleaven Dyke and Littleour: Monuments in the neolithic of Tayside.* Edinburgh: Society Antiquaries Scotland Monograph 13, pp.5–12.

Edwards KJ and Whittington G (2001) Lake sediments, erosion and landscape change during the Holocene in Britain and Ireland. *Catena* 42(2–4): 143–173.

Einsele G (2001) Atmospheric carbon burial in modern lake basins and its significance for the global carbon budget. *Global and Planetary Change* 30(3–4): 167–195.

Engstrom DR and Rose NL (2013) A whole-basin, mass-balance approach to paleolimnology. *Journal of Paleolimnology* 49(3): 333–347.

Ferland ME, Prairie YT, Teodoru C, et al. (2014) Linking organic carbon sedimentation, burial efficiency, and long-term accumulation in boreal lakes. *Journal of Geophysical Research: Biogeosciences* 119(5): 836–847.

Fossitt JA (1996) Late Quaternary vegetation history of the Western Isles of Scotland. *New Phytologist* 132(1): 171–196.

Gibson CE, Smith SJ and Wolfe-Murphy SA (1994) The Northern Ireland lake survey. In: Brian SR (ed.) *Irish Botanical News.* The Committee for Ireland Botanical Society of the British Isles, pp.5–11.

Girardin CAJ, Jenkins S, Seddon N, et al. (2021) Nature-based solutions can help cool the planet — if we act now. *Nature* 593(7858): 191–194.

Green AE, Unsworth RKF, Chadwick MA, et al. (2021) Historical analysis exposes catastrophic seagrass loss for the United Kingdom. *Frontiers in Plant Science* 12: 629962.

Gregg R, Elias JL, Alonso I, et al. (2021) *Carbon storage and sequestration by habitat: a review of the evidence (second edition).* Natural England Research Report no. NERR094, 20 April. York: Natural England.

Gudasz C, Sobek S, Bastviken D, et al. (2015) Temperature sensitivity of organic carbon mineralization in contrasting lake sediments. *Journal of Geophysical Research: Biogeosciences* 120(7): 1215–1225.

Hanson PC, Pace ML, Carpenter SR, et al. (2015) Integrating landscape carbon cycling: Research needs for resolving organic carbon budgets of lakes. *Ecosystems* 18(3): 363–375.

Heiri O, Lotter AF and Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25(1): 101–110.

Hughes M, Hornby DD, Bennion H, et al. (2004) The development of a GIS-based inventory of standing waters in Great Britain together with a risk-based prioritisation protocol. *Water, Air and Soil Pollution: Focus* 4(2–3) 73–84.

Jones R, Benson-Evans K and Chambers FM (1985) Human influence upon sedimentation in Llangorse Lake, Wales. *Earth Surface Processes and Landforms* 10(3): 227–235.

Kastowski M, Hinderer M and Vecsei A (2011) Long-term carbon burial in European lakes: Analysis and estimate. *Global Biogeochemical Cycles* 25(3): GB3019.

Keith H, Vardon M, Obst C, et al. (2021) Evaluating nature-based solutions for climate mitigation and conservation requires comprehensive carbon accounting. *Science of The Total Environment* 769: 144341.

Kortelainen P, Pajunen H, Rantakari M, et al. (2004) A large carbon pool and small sink in boreal Holocene lake sediments: Carbon stock in boreal lakes. *Global Change Biology* 10(10): 1648–1653.

Lang B, Bedford A, Brooks SJ, et al. (2010) Early-Holocene temperature variability inferred from chironomid assemblages at Hawes Water, northwest England. *The Holocene* 20(6): 943–954.

Loisel J, Yu Z, Beilman DW, et al. (2014) A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. *The Holocene* 24(9): 1028–1042.

Mackie EAV, Lloyd JM, Leng MJ, et al. (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.

Matthews L (2022) *Iron age palaeoenvironments of Northwest Scotland*. Unpublished PhD Thesis, Newcastle University, UK.

McGowan S, Anderson NJ, Edwards ME, et al. (2016) Long-term perspectives on terrestrial and aquatic carbon cycling from palaeolimnology. *WIREs Water* 3(2): 211–234.

Mcleod E, Chmura GL, Bouillon S, et al. (2011) A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment* 9(10): 552–560.

Met Office (2022) UK climate averages. Available at: https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-averages (accessed 12 June 2022).

Moyle M, Boyle JF and Chiverrell RC (2021) Towards a history of Holocene P dynamics for the Northern Hemisphere using lake sediment geochemical records. *Biogeosciences* 18(20): 5609–5638.

Mulder YLA (1999) *Aspects of vegetation and settlement history in the Outer Hebrides*, *Scotland*. PhD Thesis, University of Sheffield, UK.

Mulholland PJ and Elwood JW (1982) The role of lake and reservoir sediments as sinks in the perturbed global carbon cycle. *Tellus* 34(5): 490–499.

Pajunen H (2000) Lake sediments: their carbon store and related accumulation rates. *Geological Survey of Finland, Special Paper*, 29: 39–69.

Parker AG, Goudie AS, Anderson DE, et al. (2002) A review of the mid–Holocene elm decline in the British Isles. *Progress in Physical Geography: Earth and Environment* 26(1): 1–45.

Phelan N, Shaw A and Baylis A (2011) *The extent of saltmarsh in England and Wales: 2006–2009*. Report for the Environment Agency, 1 August. Bristol: Environment Agency.

Pollard J (2008) The construction of prehistoric Britain. In: Pollard J (ed.) *Prehistoric Britain*. Oxford: Blackwell, pp.1–17.

Prairie YT (2008) Carbocentric limnology: Looking back, looking forward. *Canadian Journal of Fisheries and Aquatic Sciences* 65(3): 543–548.

Radbourne AD, Ryves DB, Anderson NJ, et al. (2017) The historical dependency of organic carbon burial efficiency. *Limnology and Oceanography* 62(4): 1480–1497.

Rantala MV, Luoto TP and Nevalainen L (2016) Temperature controls organic carbon sequestration in a subarctic lake. *Scientific Reports* 6(1): 34780.

Ratcliffe JL, Payne RJ, Sloan TJ, et al. (2018) Holocene carbon accumulation in the peatlands of northern Scotland. *Mires and Peat* (23): 1–30.

Reimer PJ, Austin WEN, Bard E, et al. (2020) The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0-55 cal kBP). *Radiocarbon* 62(4): 725–757.

Scott DR (2014) *Carbon fixation, flux and burial efficiency in two contrasting eutrophic lakes in the UK (Rostherne Mere & Tatton Mere)*. PhD Thesis, Loughborough University, UK.

Smeaton C, Austin WEN, Davies AL, et al. (2017) Scotland's forgotten carbon: A national assessment of mid–latitude fjord sedimentary carbon stocks. *Biogeosciences* 14(24): 5663–5674.

Snowball I and Thompson R (1990) A mineral magnetic study of Holocene sedimentation in Lough Catherine, Northern Ireland. *Boreas* 19(2): 127–146.

Sobek S, Durisch-Kaiser E, Zurbrügg R, et al. (2009) Organic carbon burial efficiency in lake sediments controlled by oxygen exposure time and sediment source. *Limnology and Oceanography* 54(6): 2243–2254.

Stallard RF (1998) Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial. *Global Biogeochemical Cycles* 12(2): 231–257.

Taylor S, Gilbert PJ, Cooke DA, et al. (2019) High carbon burial rates by small ponds in the landscape. *Frontiers in Ecology and the Environment* 17(1): 25–31.

Tranvik LJ, Downing JA, Cotner JB, et al. (2009) Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology and Oceanography* 54(6part2): 2298–2314.

UK Centre for Hydrology and Ecology (2016) UK Lakes Portal. Available at: https://eip.ceh.ac.uk/apps/lakes/index.html (accessed 2 November 2021).

Van Vliet-Lanoë B, Helluin M, Pellerin J et al. (1992) Soil erosion in western Europe: From the last interglacial to the present. In: Bell M and Boardman J (eds) *Past and present soil erosion*. Oxford: Oxbow Monograph 22, pp.101–114.

Verpoorter C, Kutser T, Seekell DA, et al. (2014) A global inventory of lakes based on high-resolution satellite imagery. *Geophysical Research Letters* 41(18): 6396–6402.

Watkins R, Scourse JD and Allen JRM (2007) The Holocene vegetation history of the Arfon Platform, North Wales, UK. *Boreas* 36(2): 170–181.

Woodbridge J, Fyfe RM, Roberts N, et al. (2014) The impact of the Neolithic agricultural transition in Britain: A comparison of pollen–based land–cover and archaeological ^{14}C date–inferred population change. *Journal of Archaeological Science* 51: 216–224.

How much organic carbon have UK lakes stored in the Holocene?

A preliminary estimate

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Supplementary information contents:

This file contains age models for the 30 lake sediment records included in this study (Figures S1-S30). These age models were produced using rbacon (Blauuw and Christen, 2011) in R with the radiocarbon dates (re)calibrated against the IntCal 20 curve (Reimer et al. 2020). Please refer to the original publications for the radiocarbon dates. Figure S31 shows the comparison between empirical loss on ignition-dry bulk density relationships derived from this study and previous publications. Tables S1-S3 show the radiocarbon dates for the three new sediment records (Loweswater, Loch an Aigeil and Loch na Claise).

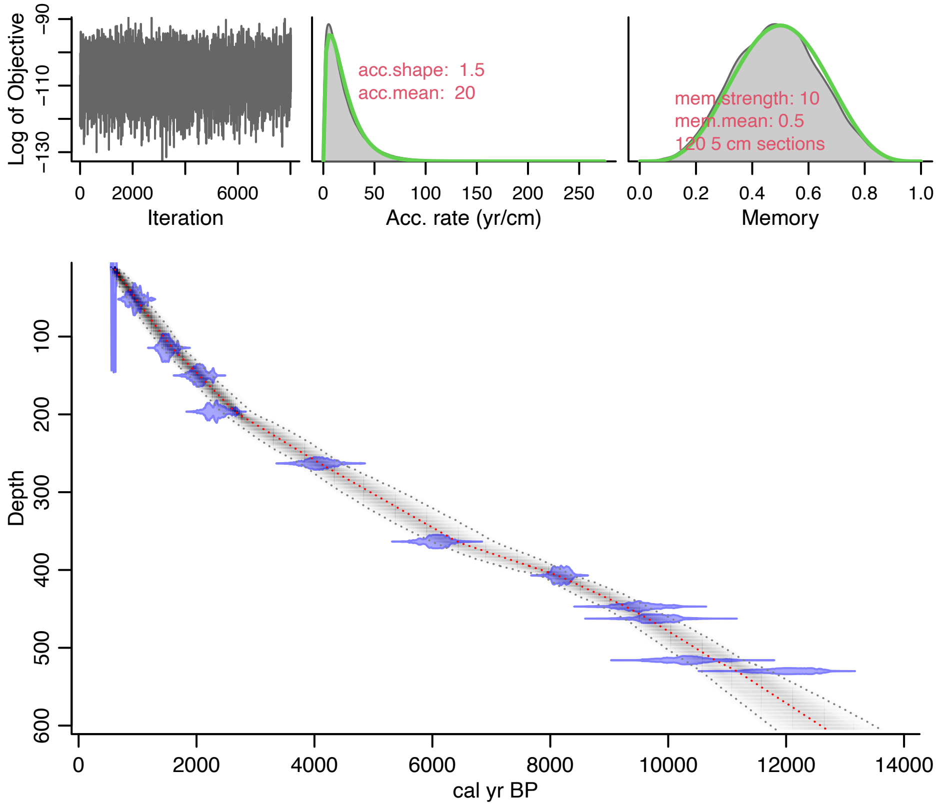

Figure S1. Revised age model for Crose Mere.

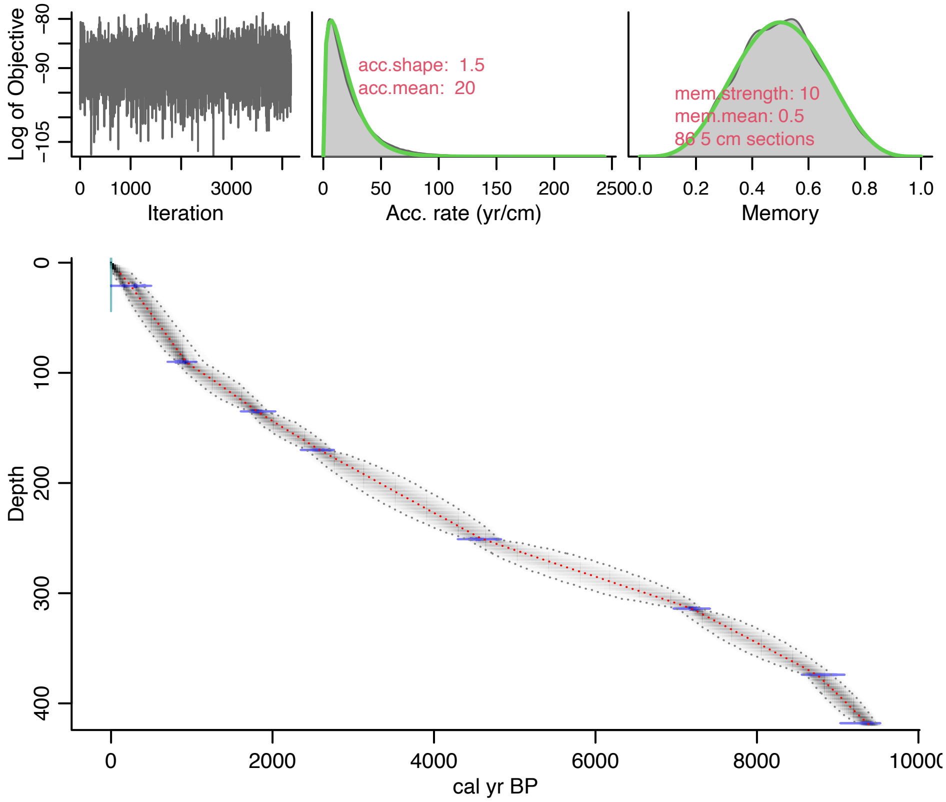

Figure S2. Revised age model for Crummock Water.

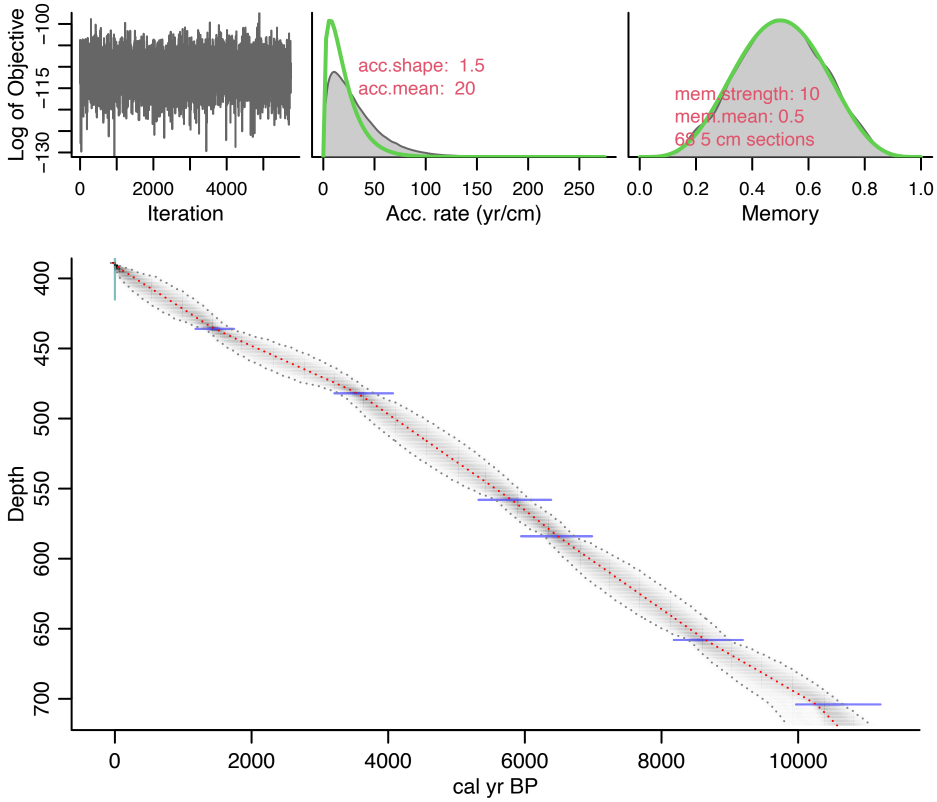

Figure S3. Revised age model for Dallican Water.

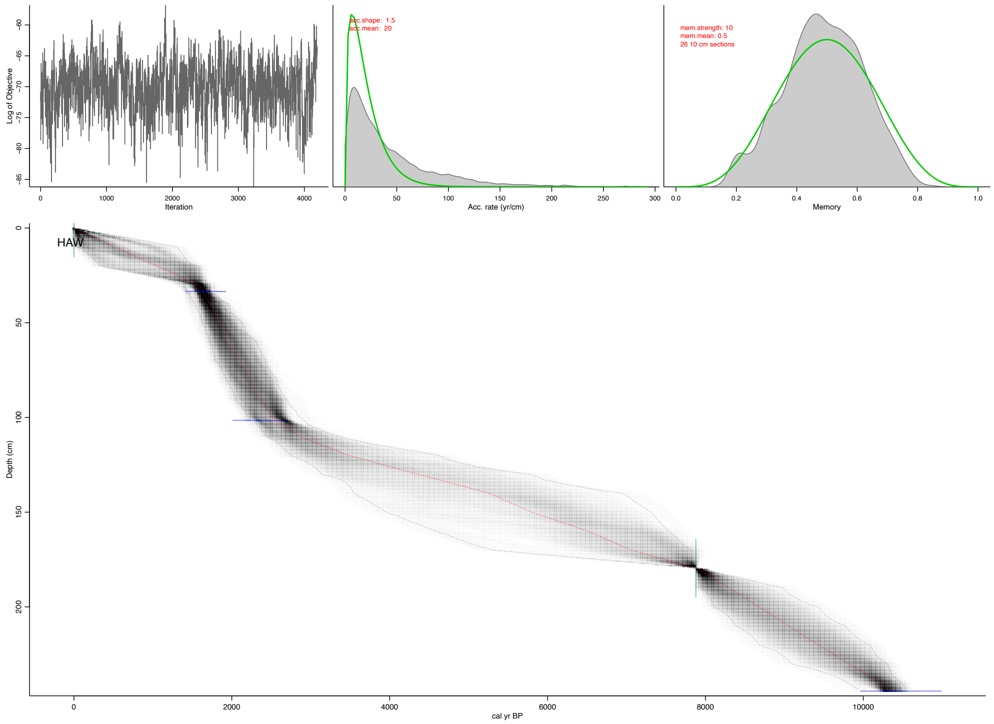

Figure S4. Revised age model for Hawes Water.

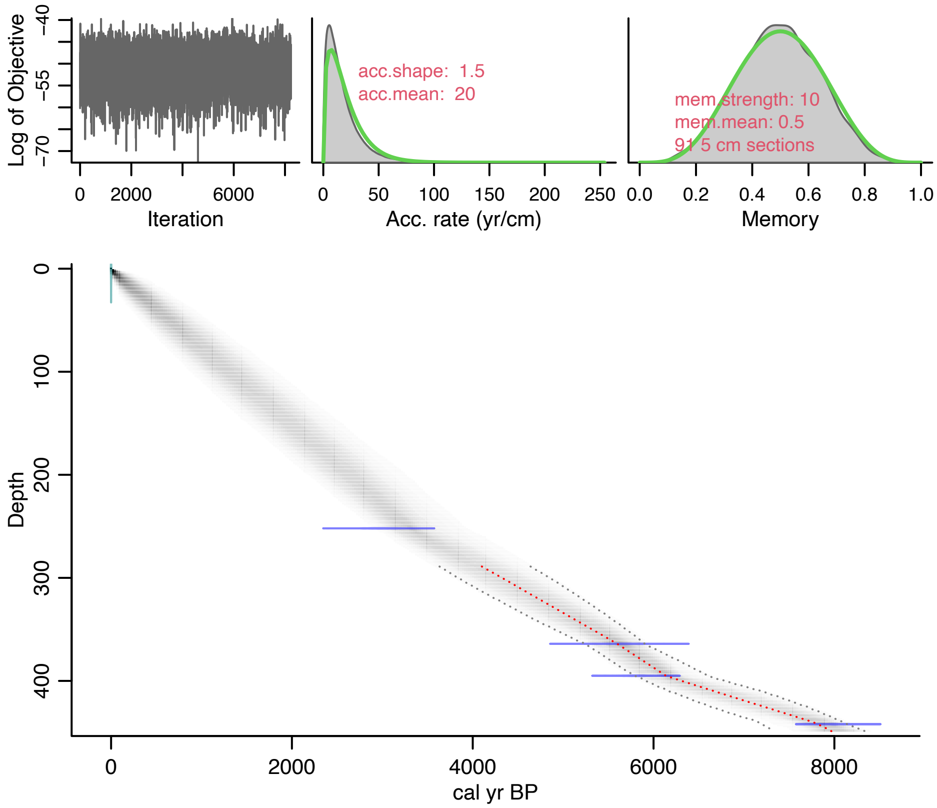

Figure S5. Revised age model for Killymaddy Lough.

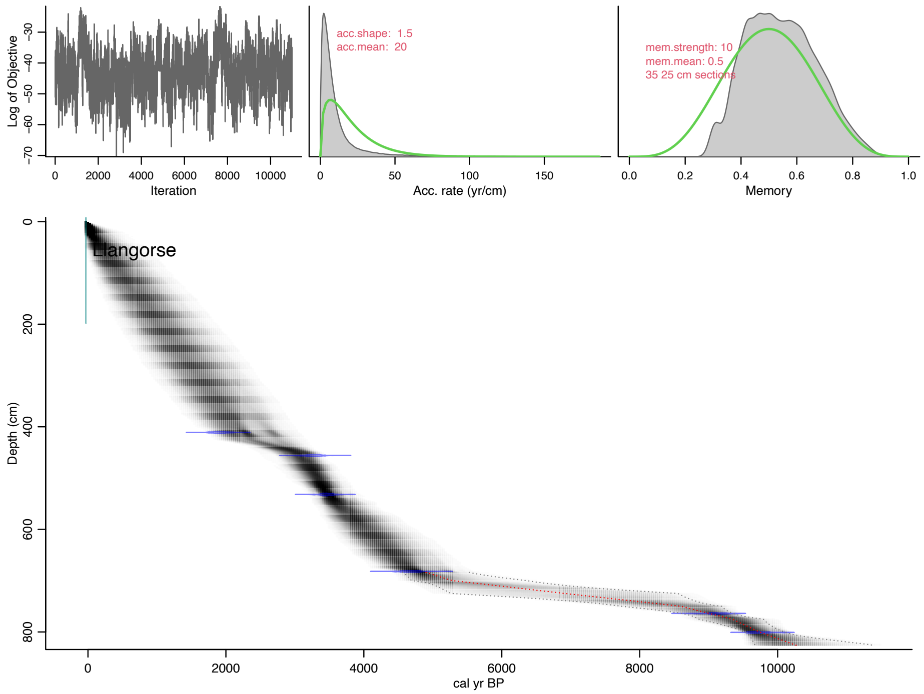

Figure S6. Revised age model for Llangorse Lake.

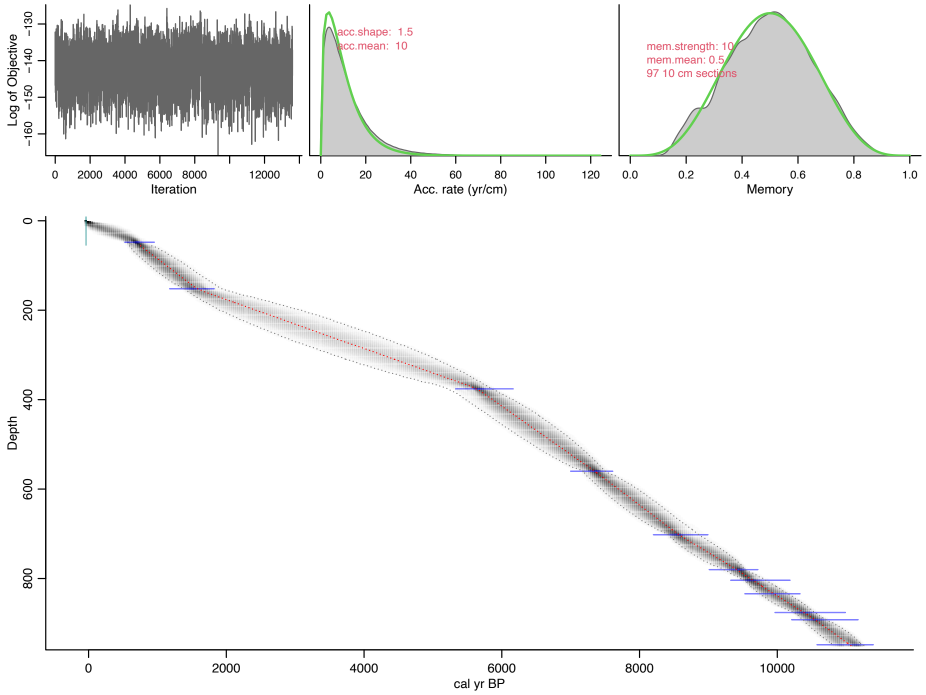

Figure S7. Revised age model for Llyn Cororion.

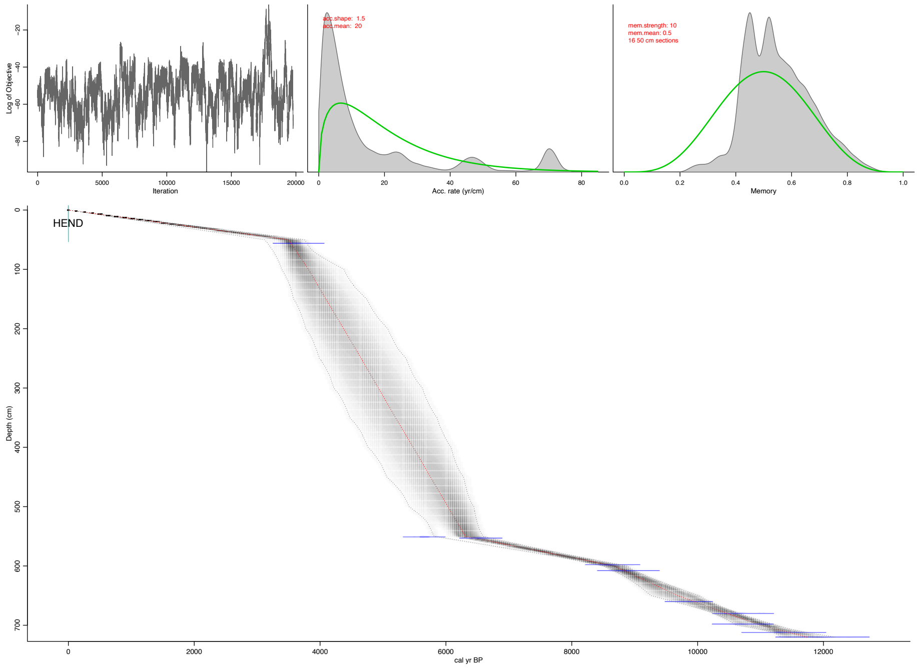

Figure S8. Revised age model for Llyn Hendref.

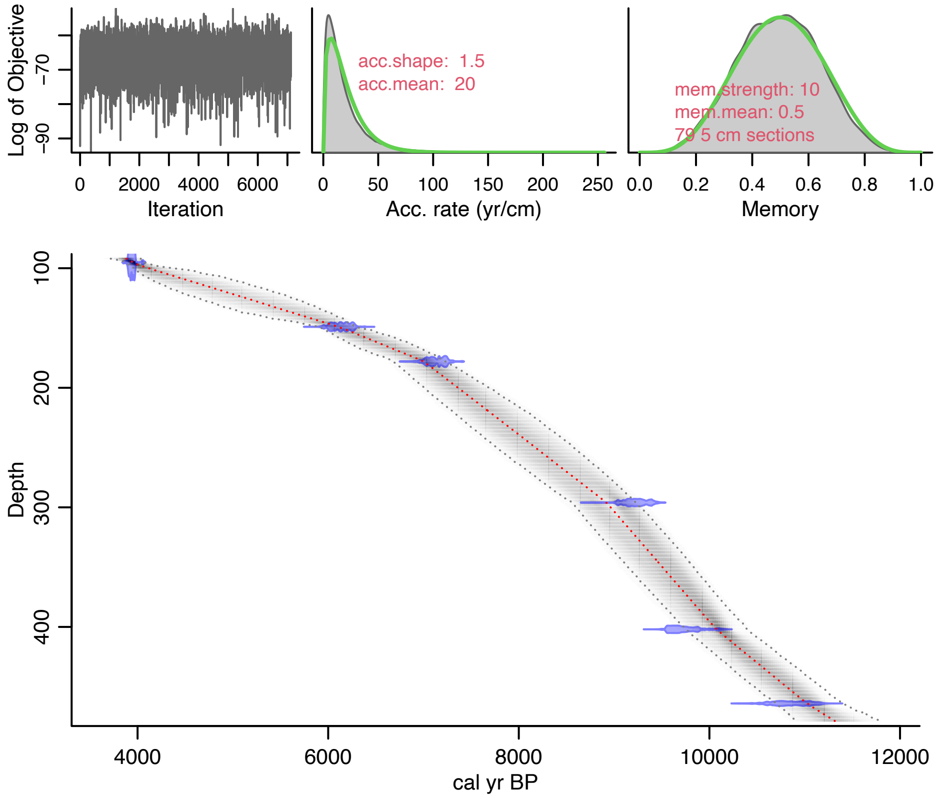

Figure S9. Revised age model for Loch a' Chabhain.

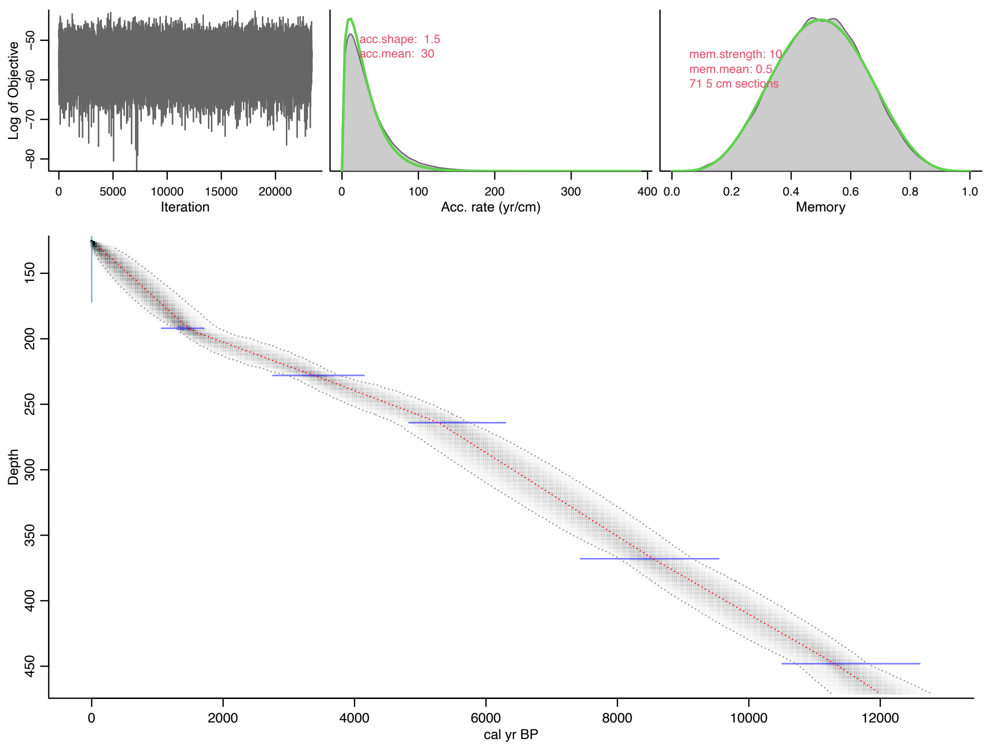

Figure S10. Revised age model for Loch Airigh na h-Achlais.

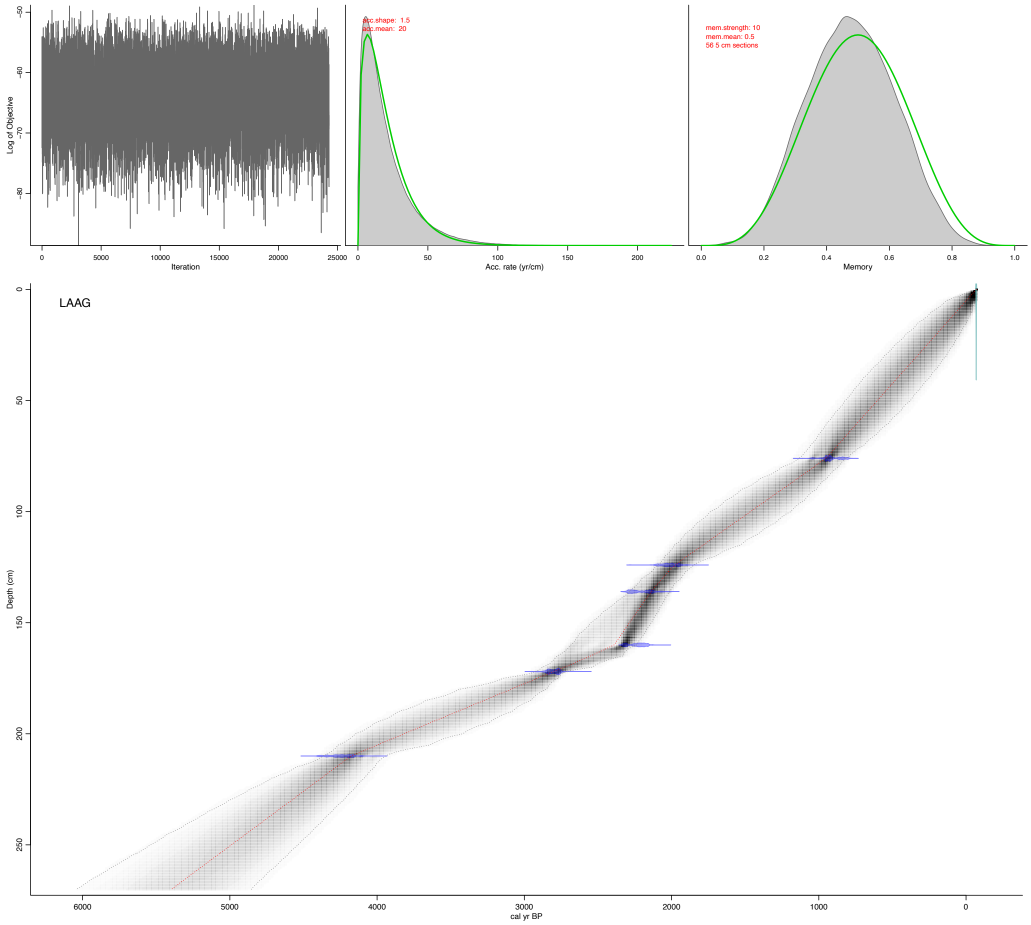

Figure S11. Age model for Loch an Aigeil.

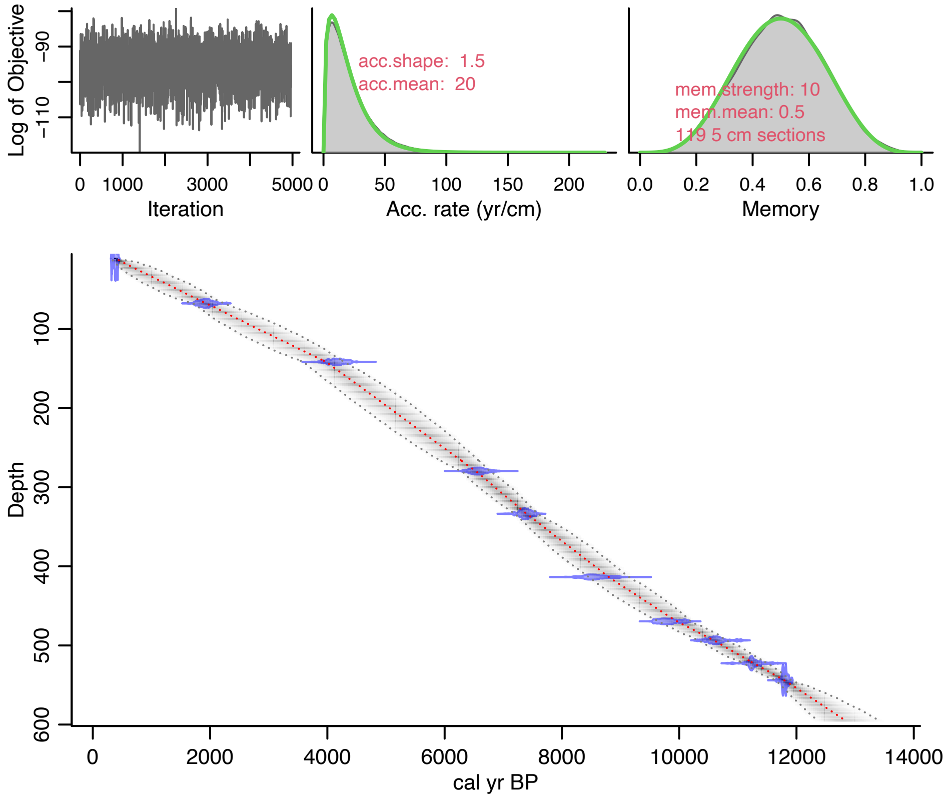

Figure S12. Revised age model for Loch Bharabhat.

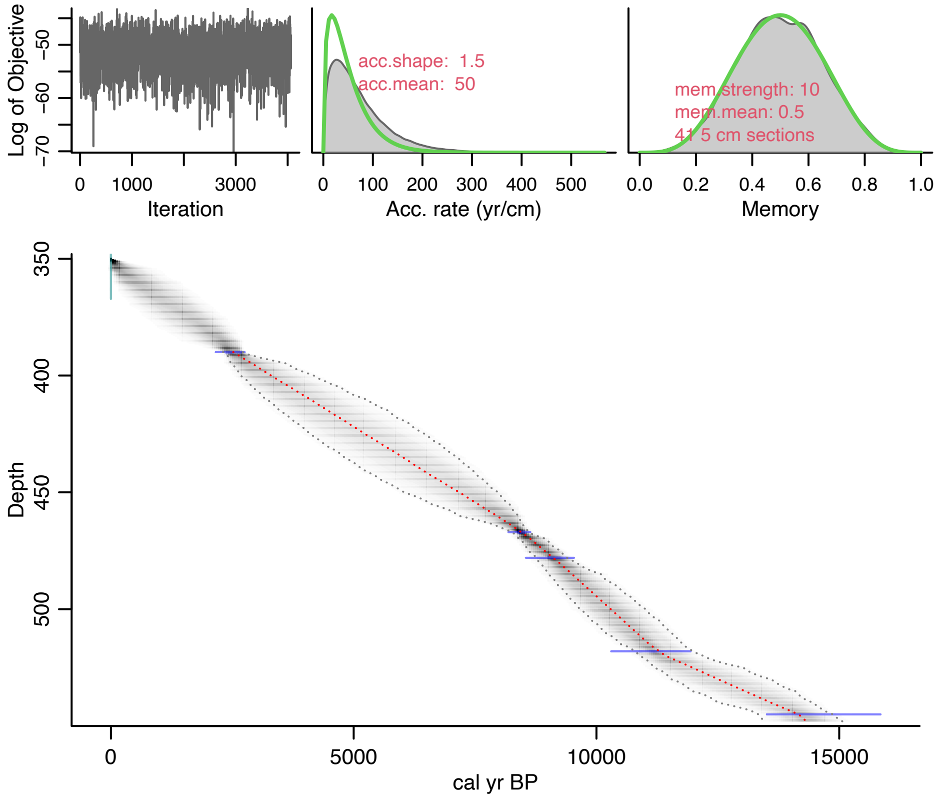

Figure S13. Revised age model for Loch Buailaval Beag.

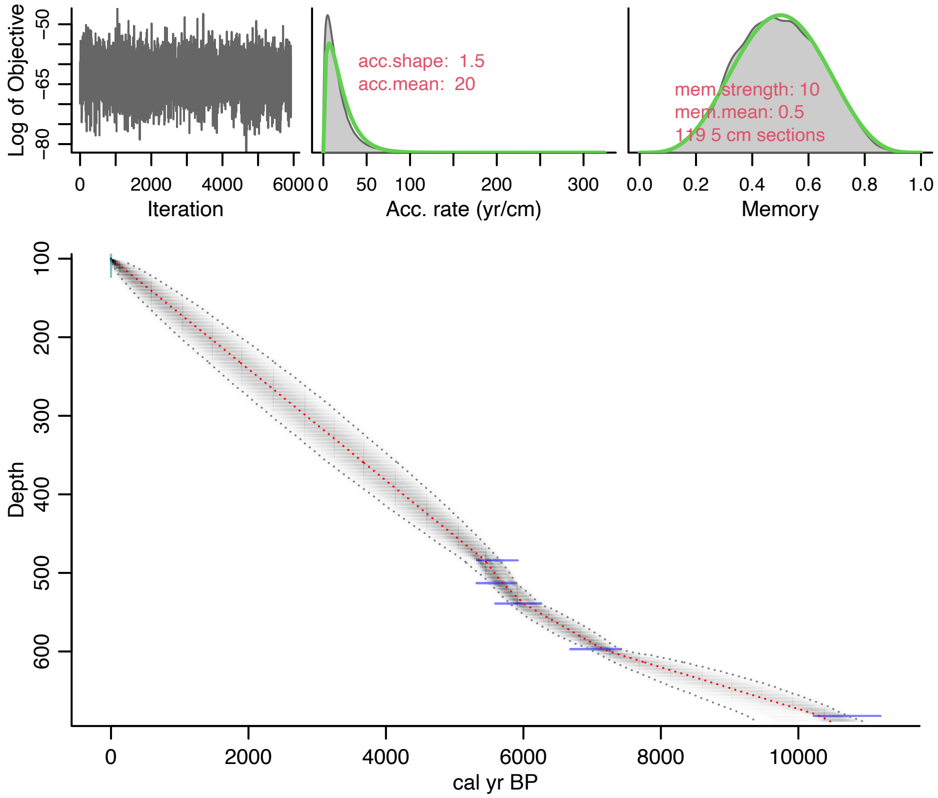

Figure S14. Revised age model for Loch Coulavie.

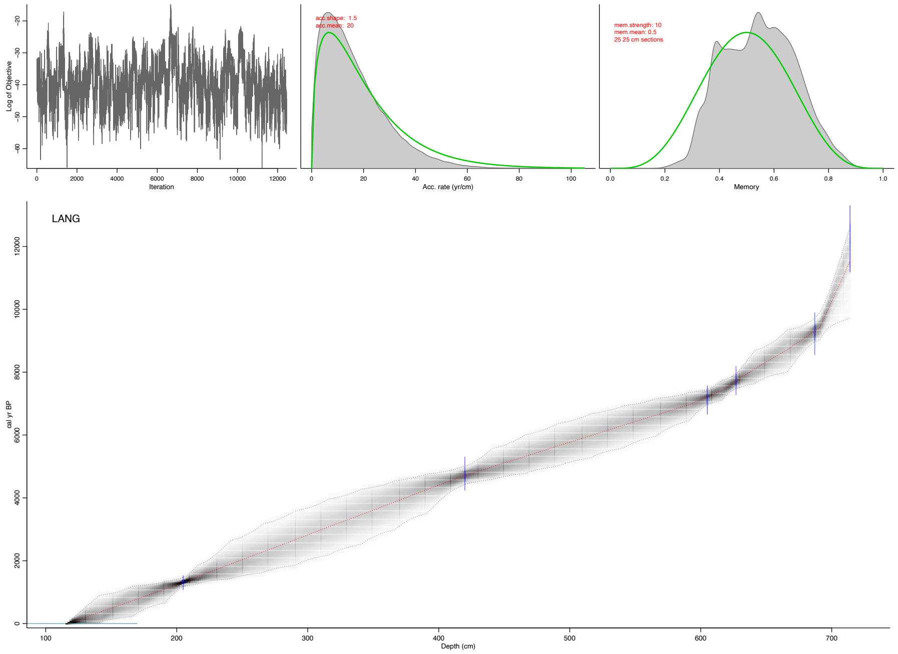

Figure S15. Revised age model for Loch Lang.

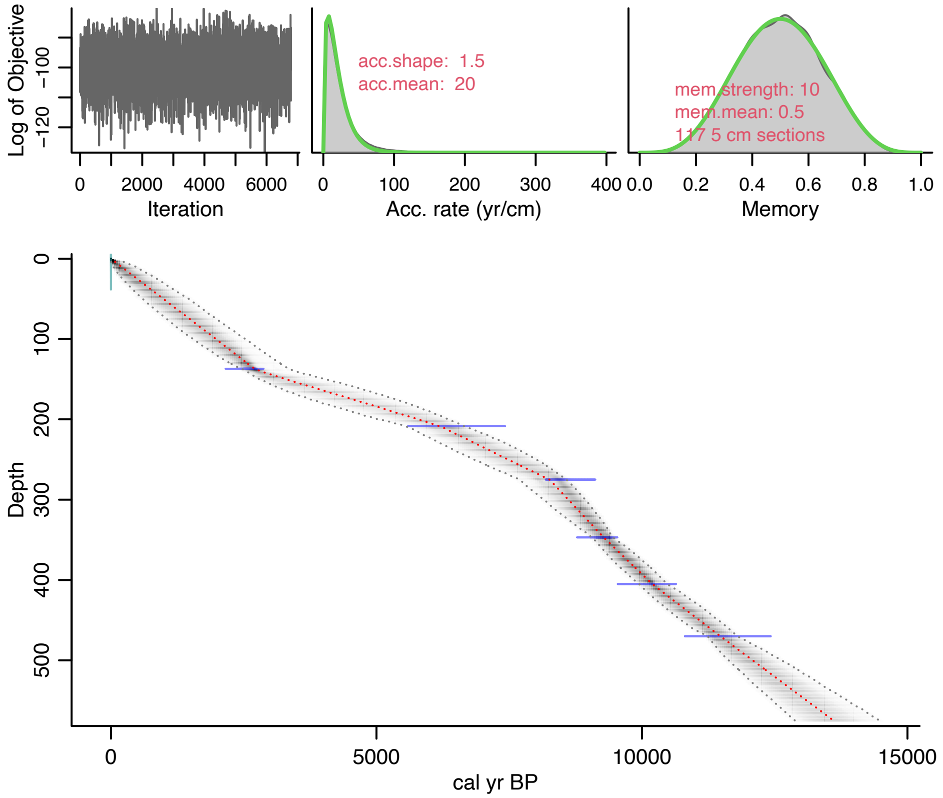

Figure S16. Revised age model for Loch na Beinne Bige.

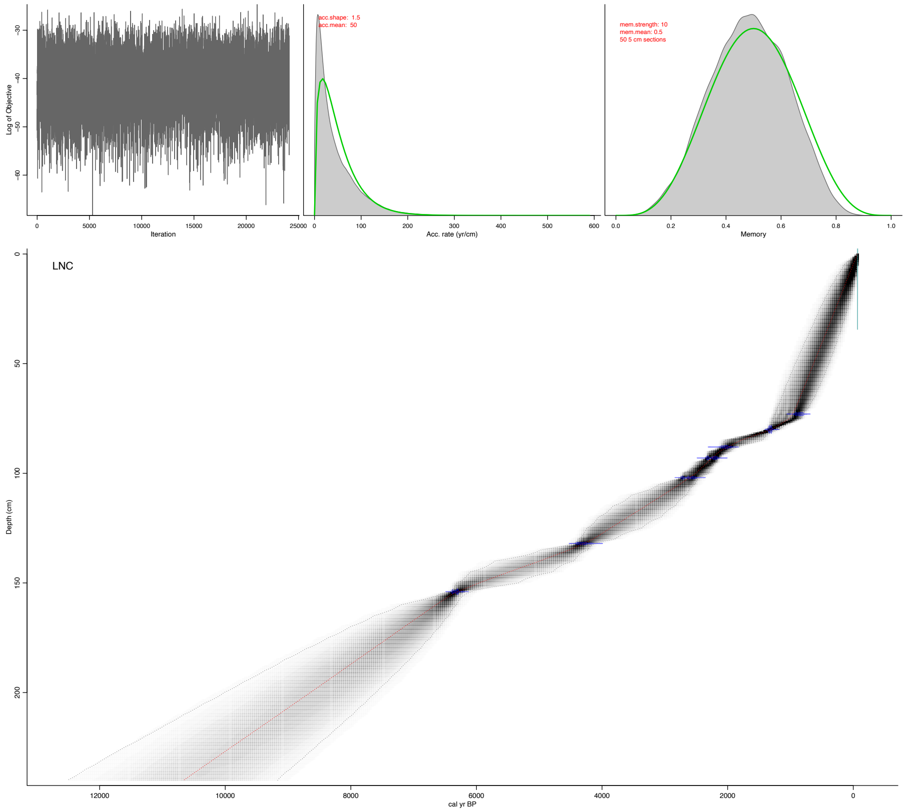

Figure S17. Age model for Loch na Claise.

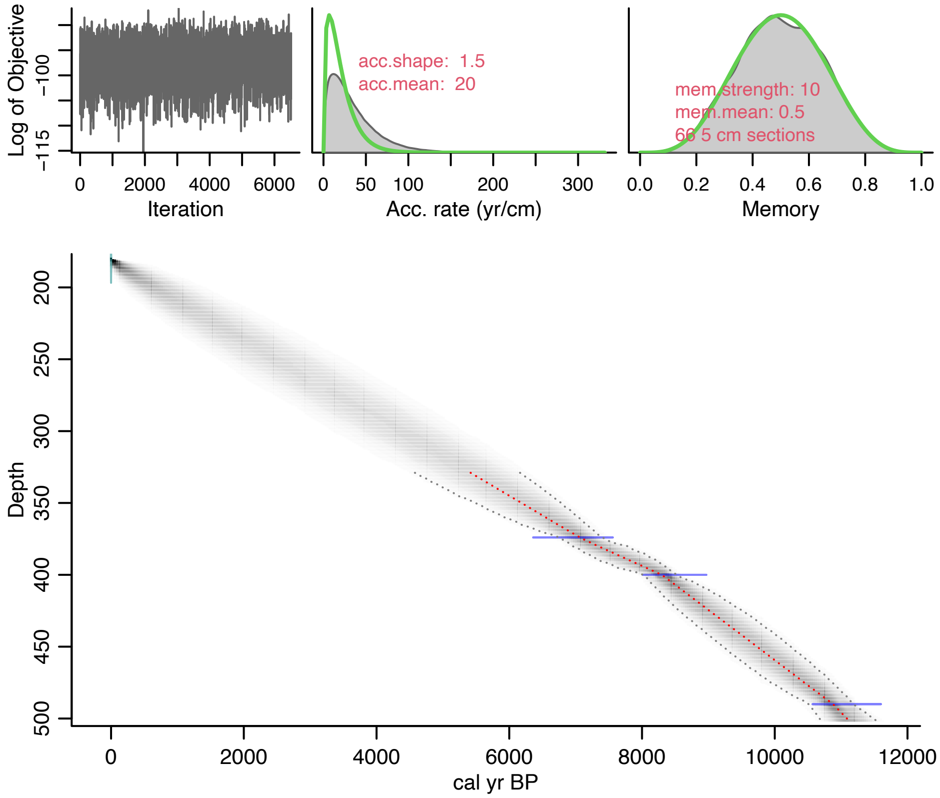

Figure S18. Revised age model for Loch na Muilne.

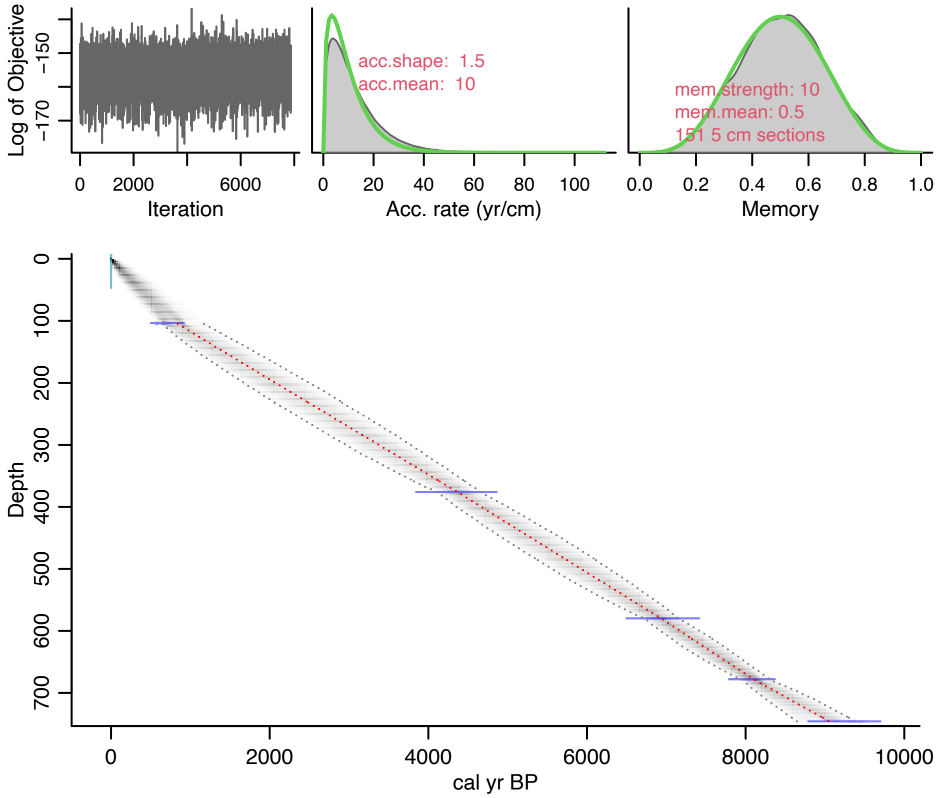

Figure S19. Revised age model for Loch nan Corr.

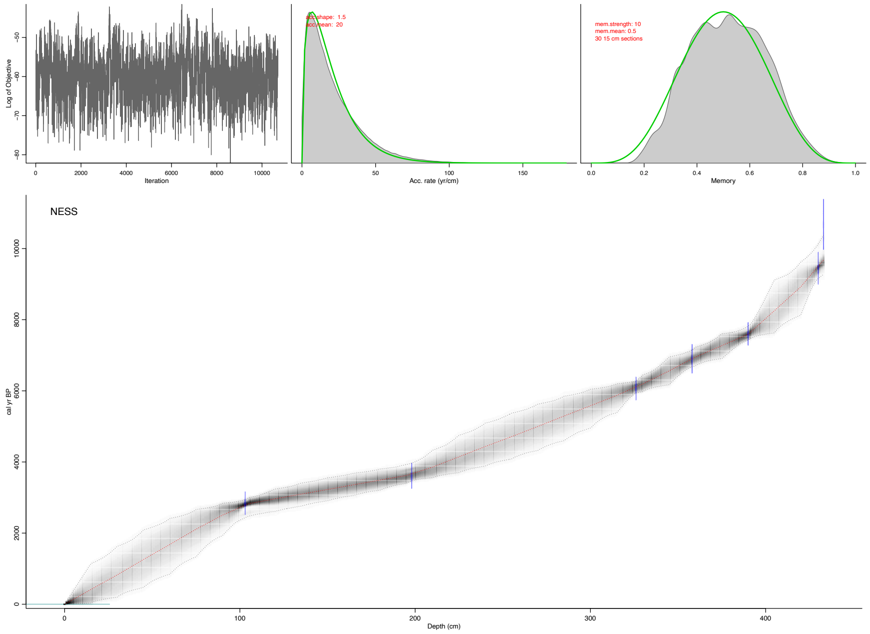

Figure S20. Revised age model for Loch Ness.

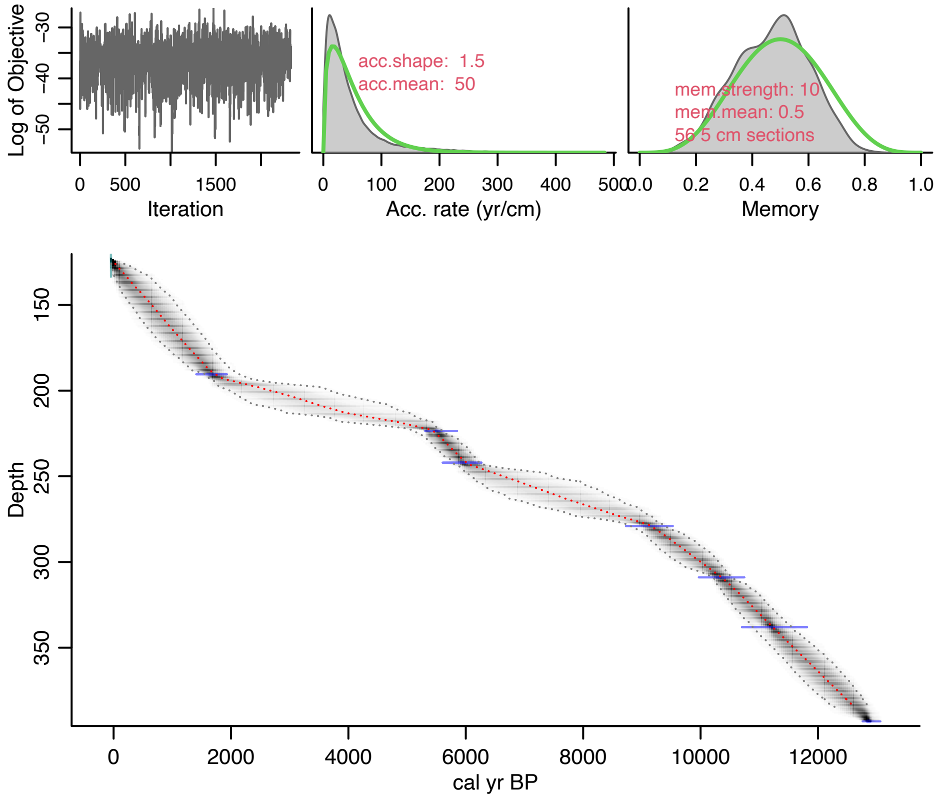

Figure S21. Revised age model for Loch Olabhat.

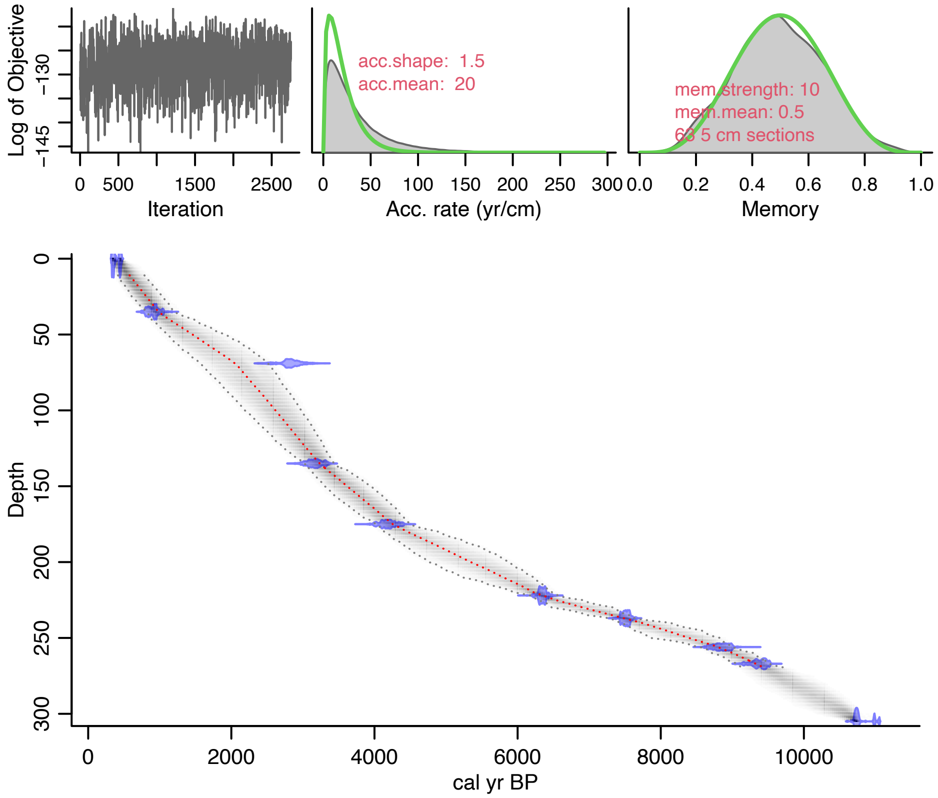

Figure S22. Revised age model for Loch Pityoulish.

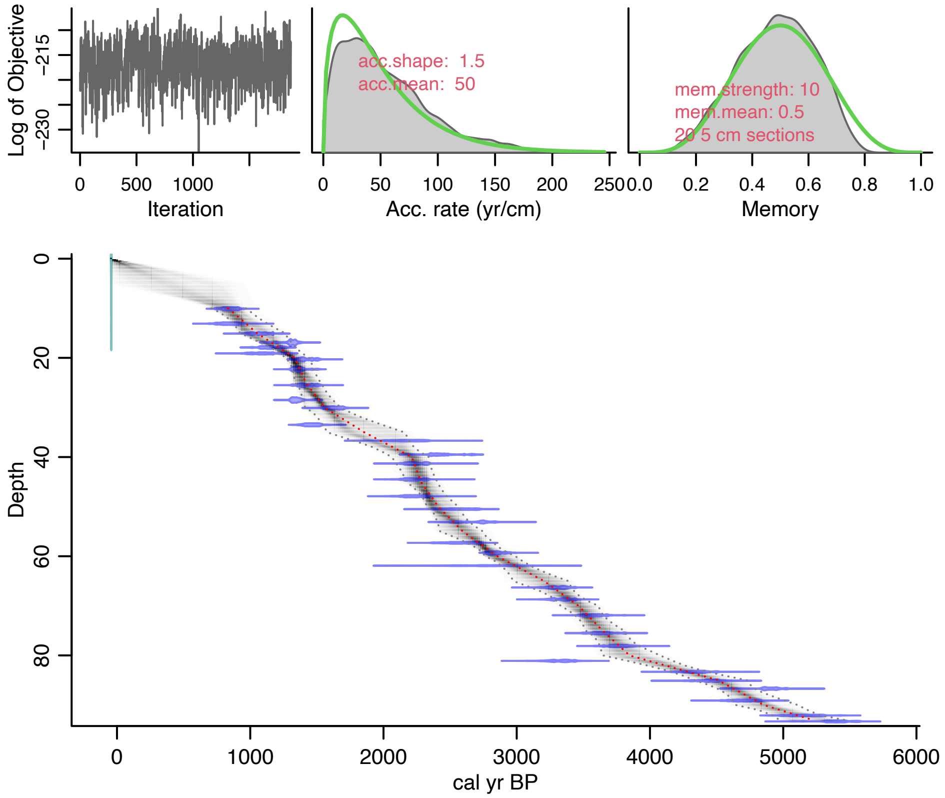

Figure S23. Revised age model for Lochan Uaine.

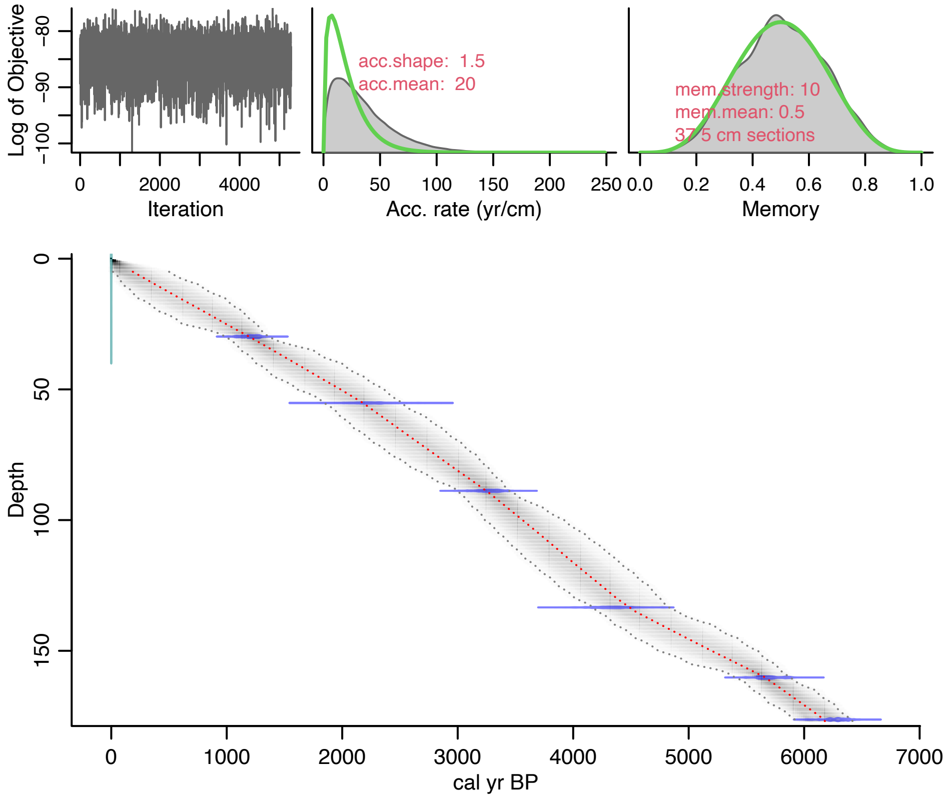

Figure S24. Revised age model for Lochnagar.

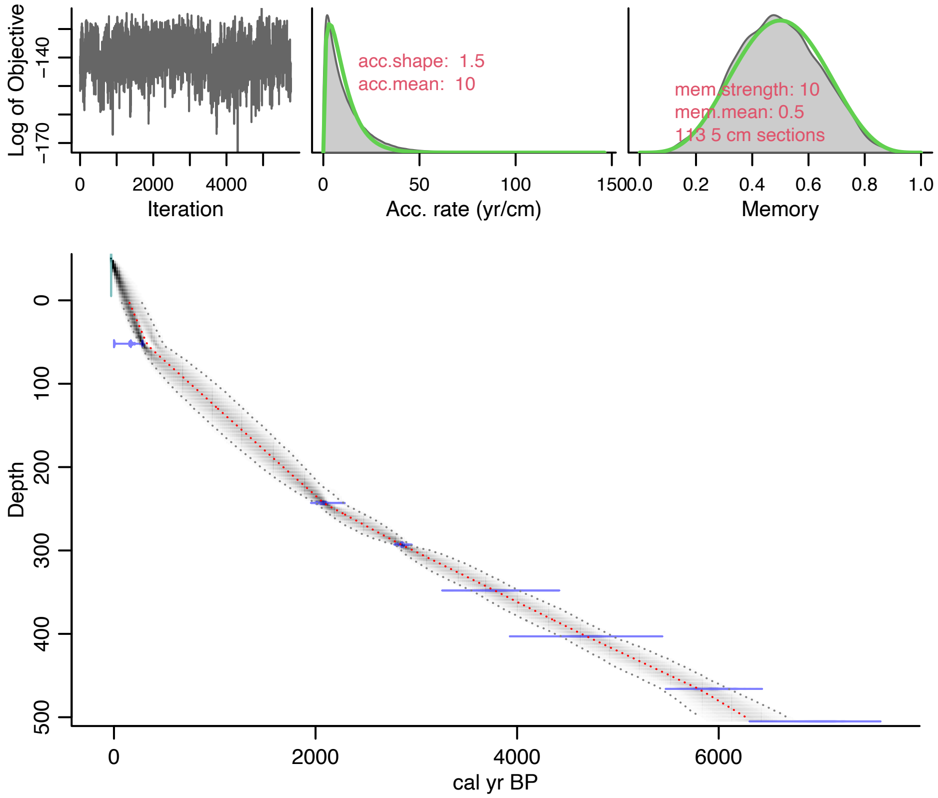

Figure S25. Revised age model for Lough Catherine.

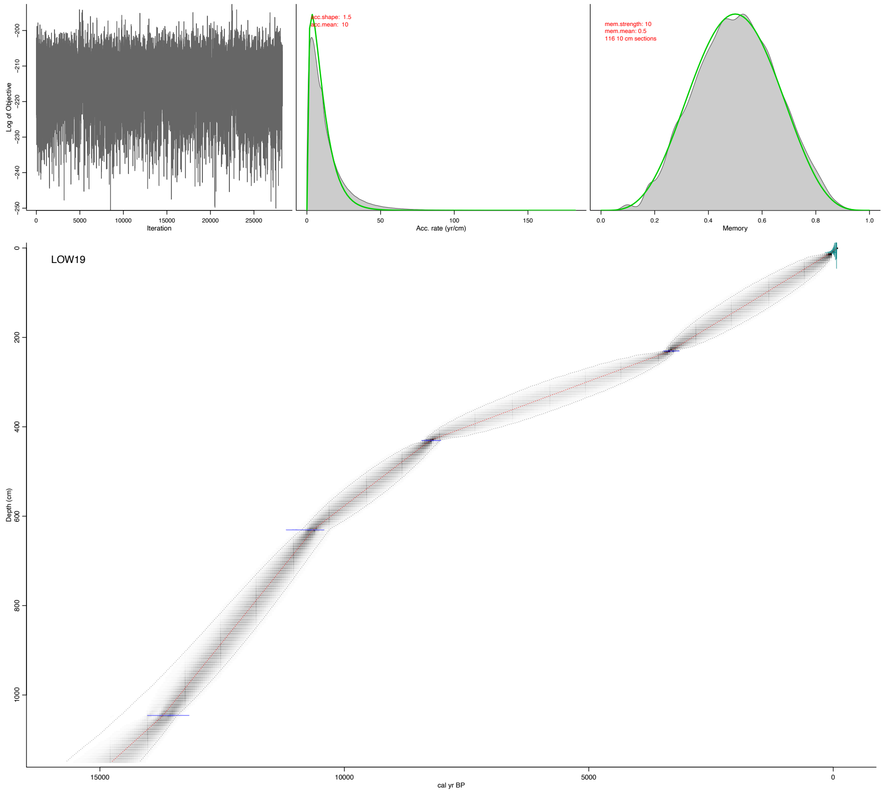

Figure S26. Mixed age model for Loweswater, including both ^{14}C and ^{210}Pb dates.

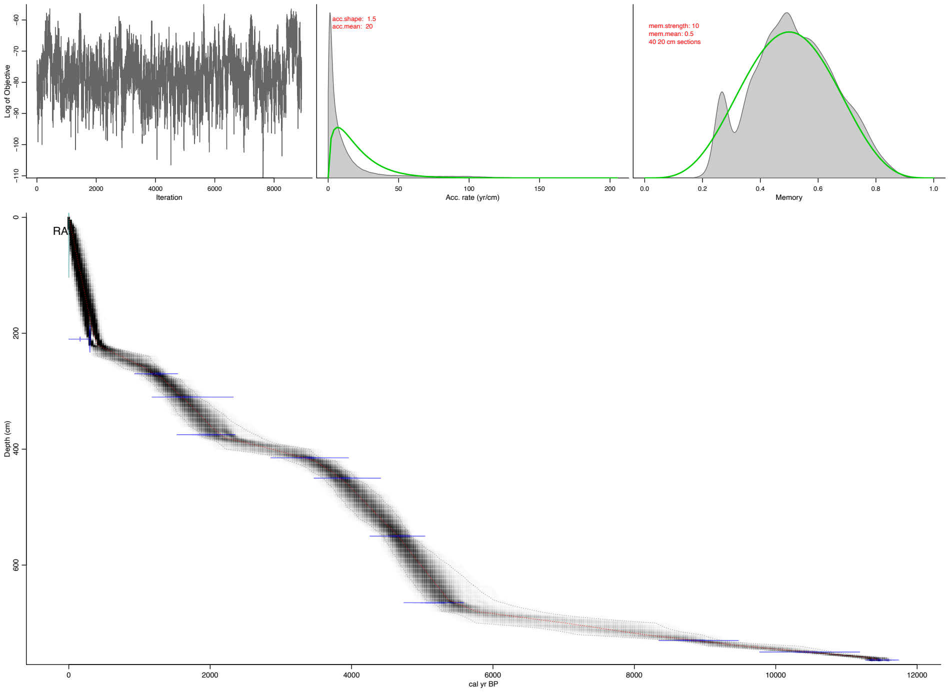

Figure S27. Revised age model for Rae Loch.

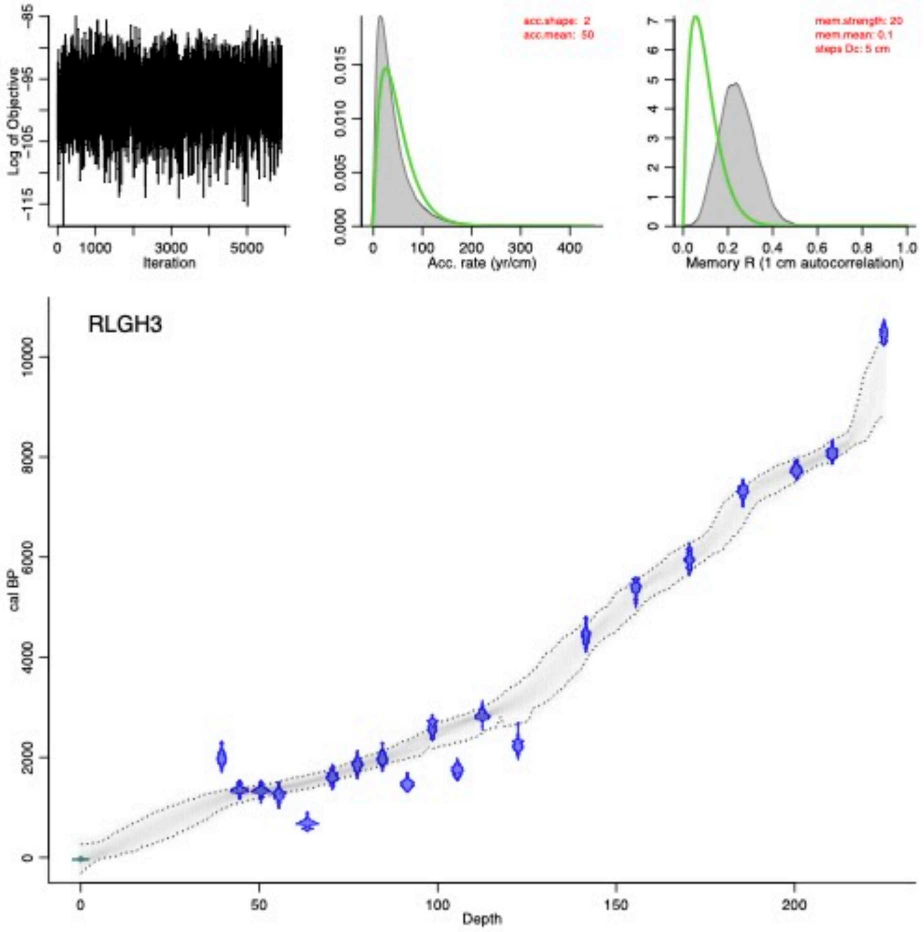

Figure S28. Revised age model for Round Loch of Glenhead.

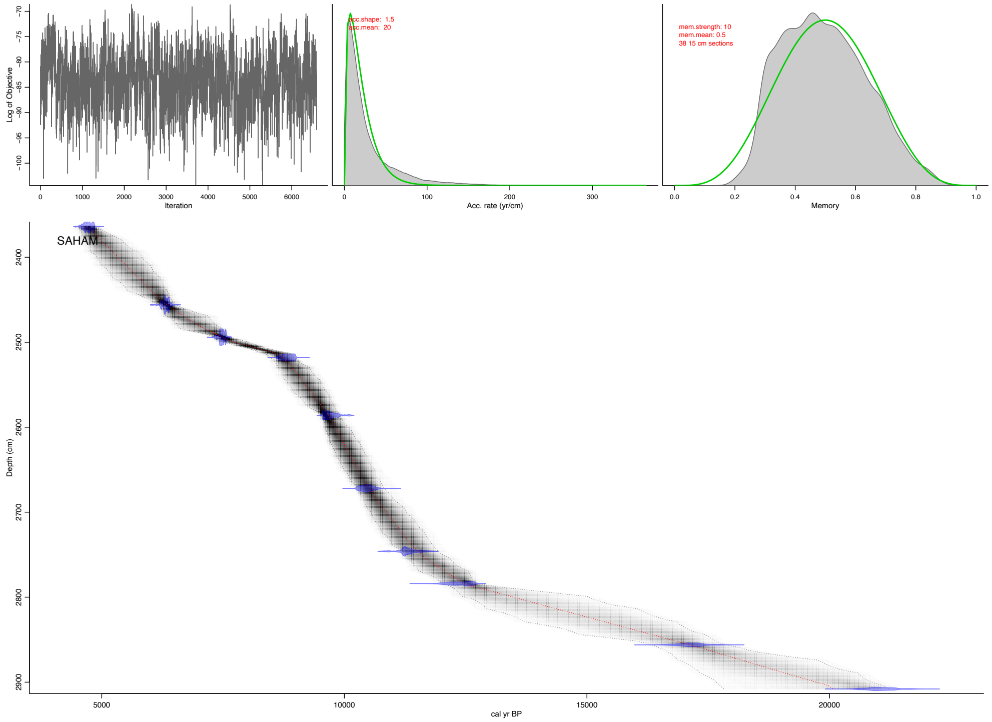

Figure S29. Revised age model for Saham Mere.

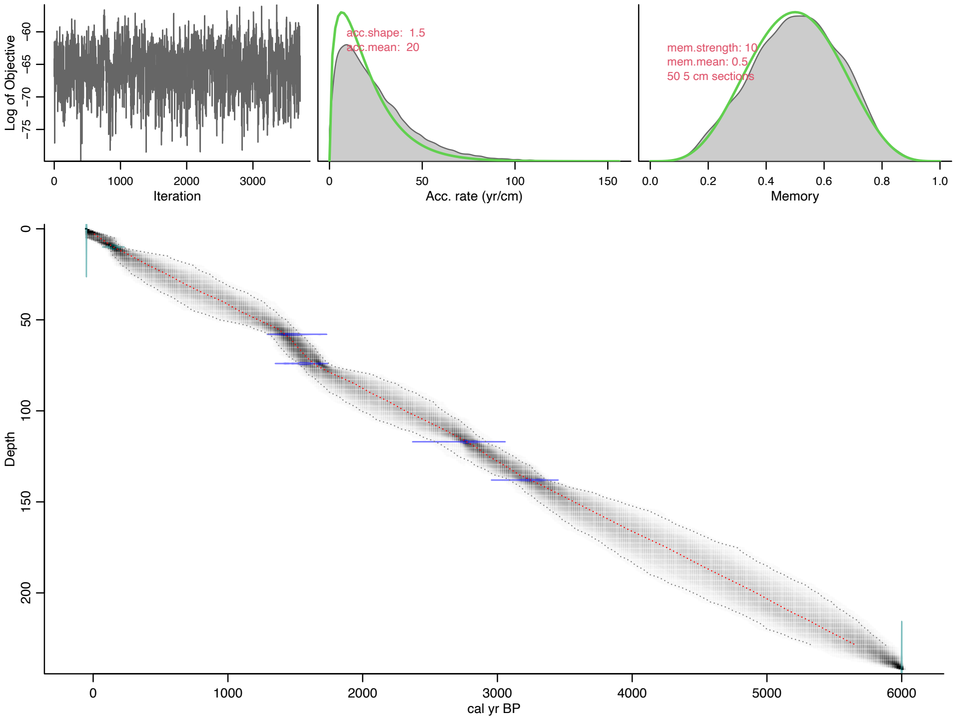

Figure S30. Revised age model for Talkin Tarn.

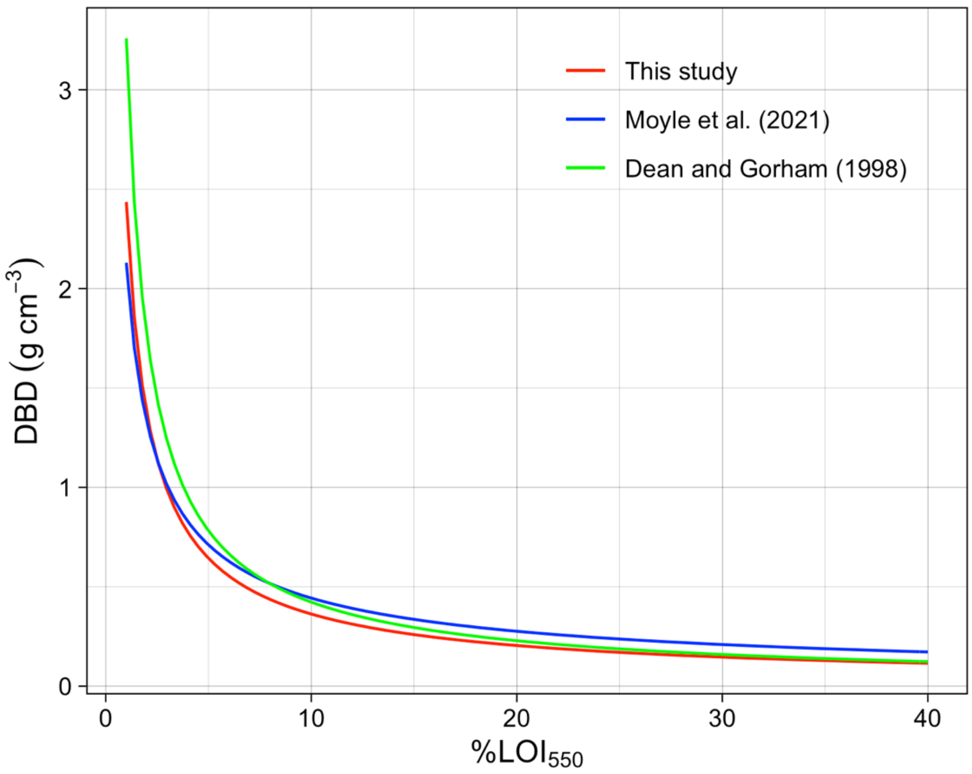

Figure S31. Comparison of empirical loss on ignition (%LOI$_{550}$) - dry bulk density (DBD) relationships derived from this study (DBD=2.4355*%LOI$_{550}^{-0.827}$, r^2=0.6, p<2.2*10^{-16}), Moyle et al., (2021) (DBD=2.13*%LOI$_{550}^{-0.682}$) and Dean and Gorham (1998) (DBD=1.665*%OC$^{-0.887}$). For ease of comparison, %OC in the Dean and Gorham (1998) relationship was multiplied by 0.469 and converted into %LOI$_{550}$ following Dean (1974) for ease of comparison.

Table S1. Radiocarbon (^{14}C) dates for Loweswater.

Sample ID	Lab ID	Depth (cm)	^{14}C age (year BP)	^{14}C error (year)
LOW19 230-231	Poz-140857	230.5	3125	30
LOW19 430-431	Poz-140900	430.5	7470	40
LOW19 630-631	Poz-140901	630.5	9490	50
LOW19 830-832	Poz-140902	831	18520	140
LOW19 1044-1047	Poz-135822	1045.5	11690	80

Table S2. Radiocarbon (^{14}C) dates for Loch an Aigeil (Matthews 2022).

Sample ID	Lab ID	Depth (cm)	^{14}C age (year BP)	^{14}C error (year)
LAAG_008 (75-76cm)	SUERC-98655	75.5	1017	37
LAAG_007 (124cm)	SUERC-98651	124	2057	35
LAAG4-136cm	BETA-609264	136	2180	30
LAAG4-160cm	BETA-609265	160	2240	30
LAAG_003 (172cm)	SUERC-98656	172	2690	37
LAAG_006 (210cm)	SUERC-98650	210	3836	38

Table S3. Radiocarbon (^{14}C) dates for Loch na Claise (Matthews 2022).

Sample ID	Lab ID	Depth (cm)	^{14}C age (year BP)	^{14}C error (year)
LNC_010 (73cm)	SUERC-98648	73	961	37
LNC19-80cm	BETA-609263	80	1420	30
LNC_011 (88cm)	SUERC-98649	88	2073	35
LNC_009 (93cm)	SUERC-98647	93	2264	35
LNC19_008 (102cm)	SUERC-98646	102	2539	35
LNC19_007 (132cm)	SUERC-98645	132	3876	36
LNC19_006 (153-154cm)	SUERC-98641	154	5524	35

References

Battarbee RW, Cameron NG, Golding P, et al. (2001) Evidence for Holocene climate variability from the sediments of a Scottish remote mountain lake. *Journal of Quaternary Science* 16(4): 339–346.

Bennett KD, Fossitt JA, Sharp MJ, et al. (1990) Holocene vegetational and environmental history at Loch Lang, South Uist, Western Isles, Scotland. *New Phytologist* 114(2): 281–298.

Bennett KD (1988) Holocene pollen stratigraphy of central East Anglia, England, and comparison of pollen zones across the British Isles. *New Phytologist* 109(2): 237–253.

Bennett KD, Boreham S, Sharp MJ, et al. (1992) Holocene history of environment, vegetation and human settlement on Catta Ness, Lunnasting, Shetland. *The Journal of Ecology* 80(2): 241–273.

Beales PW (1980) The Late Devensian and Flandrian vegetational history of Crose Mere, Shropshire. *New Phytologist* 85(1): 133–161.

Blaauw M and Christen JA (2011) Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis* 6(3): 457–474.

Blaauw M and Heegaard E (2012) Estimation of age-depth relationships. In: Birks HJB, Lotter AF, Juggins S and Smol JP (eds) *Tracking environmental change using lake sediments: Data handling and numerical techniques*. Dordrecht: Springer.

Cooper MC (1999) *Laminated sediments of Loch Ness, Scotland: Indicators of Holocene environmental change*. PhD Thesis, University of Plymouth, UK.

Dalton C, Birks HJB, Brooks SJ, et al. (2005) A multi-proxy study of lake-development in response to catchment changes during the Holocene at Lochnagar, north-east Scotland. *Palaeogeography, Palaeoclimatology, Palaeoecology* 221(3–4): 175–201.

Dean WE and Gorham E (1998) Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. *Geology* 26(6): 535–538.

Dean, WE Jr (1974) Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: Comparison with other methods. *SEPM Journal of Sedimentary Research* 44(1): 242–248.

Edwards KJ and Whittington G (1998) The palaeoenvironmental background: Pollen studies at Rae Loch. In: Barclay GJ and Maxwell GS (eds) *The Cleaven Dyke and Littleour:*

Monuments in the neolithic of Tayside. Edinburgh: Society Antiquaries Scotland Monograph 13, pp.5–12.

Fossitt JA (1996) Late Quaternary vegetation history of the Western Isles of Scotland. *New Phytologist* 132(1): 171–196.

Hirons KR and Edwards KJ (1986) Events at and around the first and second ulmus declines: palaeoecological investigations in Co. Tyrone, Northern Rreland. *New Phytologist* 104(1): 131–153.

Jones R, Benson-Evans K and Chambers FM (1985) Human influence upon sedimentation in Llangorse Lake, Wales. *Earth Surface Processes and Landforms* 10(3): 227–235.

Jones RT, Marshall JD, Fisher E, et al. (2011) Controls on lake level in the early to mid Holocene, Hawes Water, Lancashire, UK. *The Holocene* 21(7): 1061–1072.

Langdon PG, Barber KE and Lomas-Clarke (previously Morriss) SH (2004) Reconstructing climate and environmental change in northern England through chironomid and pollen analyses: evidence from Talkin Tarn, Cumbria. *Journal of Paleolimnology* 32(2): 197–213.

Lomax TM (1997) *Holocene vegetation history and human impact in Western Lewis, Scotland.* PhD Thesis, University of Birmingham, UK.

Mackie EAV, Lloyd JM, Leng MJ, et al. (2007) Assessment of δ13C 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.

Matthews L (2022) *Iron age palaeoenvironments of Northwest Scotland*. Unpublished PhD Thesis, Newcastle University, UK.

Moyle M, Boyle JF and Chiverrell RC (2021) Towards a history of Holocene P dynamics for the Northern Hemisphere using lake sediment geochemical records. *Biogeosciences* 18(20): 5609–5638.

Mulder YLA (1999) *Aspects of vegetation and settlement history in the Outer Hebrides, Scotland.* PhD Thesis, University of Sheffield, UK.

O'Sullivan PE (1976) Pollen analysis and radiocarbon dating of a core from Loch Pityoulish, Eastern Highlands of Scotland. *Journal of Biogeography* 3(3): 293.

Reimer PJ, Austin WEN, Bard E, et al. (2020) The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0-55 cal kBP). *Radiocarbon* 62(4): 725–757.

Shen Z, Bloemendal J, Mauz B, et al. (2008) Holocene environmental reconstruction of sediment-source linkages at Crummock Water, English Lake District, based on magnetic measurements. *The Holocene* 18(1): 129–140.

Snowball I and Thompson R (1990) A mineral magnetic study of Holocene sedimentation in Lough Catherine, Northern Ireland. *Boreas* 19(2): 127–146.

Thompson R and Edwards KJ (2008) A Holocene palaeomagnetic record and a geomagnetic master curve from Ireland. *Boreas* 11(4): 335–349.

Tisdall EW (2000) *Holocene climate change in Glen Affric, Northern Scotland: a multi-proxy approach.* PhD Thesis, University of Stirling, UK.

Watkins R (1991) *Postglacial vegetational dynamics in lowland North Wales.* PhD Thesis, University of Wales, UK.

Watkins R, Scourse JD and Allen JRM (2007) The Holocene vegetation history of the Arfon Platform, North Wales, UK. *Boreas* 36(2): 170–181.