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A 7000-year record of environmental change, including early farming impact, based on lake-sediment geochemistry and pollen data from County Sligo, western Ireland

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ABSTRACT

Detailed, chronologically tightly constrained, lake-sediment-based geochemical and pollen records have enabled local changes in soil erosion, woodland cover and composition, and prehistoric farming impact to be reconstructed in considerable detail. The profile opens shortly after 7800 BC when tall canopy trees were well-established and presumably in equilibrium with their environment. A distinct perturbation that involved an increase in pine and birch, a decrease in oak and a minor opening-up of the woodland is regarded as the local expression of the 8.2 ka climate anomaly. Lack of response in the geochemical erosional indicators is interpreted as evidence for drier conditions. A short-lived, over-compensation in climate recovery followed the 8.2 ka event. Neolithic farming impact is clearly expressed in both the pollen and geochemical data. Both datasets indicate that Neolithic impact was concentrated in the early Neolithic (3715–3440 BC). In the interval 3000–2700 BC there appears to have been a break in farming activity. The pollen data suggest substantially increased farming impact (both arable and pastoral) in the Bronze Age, with maximum farming and woodland clearances taking place in the late Bronze Age (1155–935 BC). These developments are poorly expressed in the geochemical record, possibly due to within-lake changes.

Introduction

Multi-proxy records from lake sediments are one of the main sources of evidence for long-term environmental change. While Holocene lake sediments have been widely used in Ireland for pollen investigations, a multi-proxy approach that involves investigations of the elemental chemistry of lake sediments is less common (cf. Hirons and Thompson, 1986; O'Connell, 1990; Schettler et al., 2006; Murnaghan et al., 2012; Stolze et al., 2012). In this paper we present the results of detailed pollen and geochemical analyses of lake sediments from Cooney Lough, a small lake in north Co. Sligo, western Ireland. The investigations form part of a larger research programme with focus on the Holocene and especially early farming impact and environmental change in Co. Sligo (Stolze et al., 2012; Ghilardi and O'Connell, 2013a, 2013b, 2013c; Stolze et al., 2013a, 2013b).

Cooney Lough was selected on account of its proximity to Cúil Irra, which is one of the most important regions in Ireland as regards to the Neolithic. It has the highest concentration of passage tombs (Ó Nualláin, 1989; Bergh, 1995, 2002; Egan et al., 2005). In all there are about 80 passage tombs, some 60 of which are in a cluster commonly known as the Carrowmore passage-tomb cemetery. The dominant geographical feature is Knocknarea, a large, flat-topped hill that rises in the western part of the peninsula to 327 m asl (Figs. 1B, S1). This hill has seven passage tombs, an exceptionally large cairn on its summit (*Miosgán Meadhbha*; Maeve's Tomb) that probably contains a passage tomb and there are also several other features that relate to the Neolithic (Bergh, 2002). The north-east extension of the Ox Mountains into Co. Sligo forms the southern and much of the eastern boundary of the Cúil Irra region and Cooney L. lies within the region so defined. Six cairns, ascribable to the passage tomb tradition, are recorded from these uplands (Bergh, 1995). The nearer cairns are those on the peaks Croaghaun and Doomore, 1.6 km and 4 km west of Cooney L., respectively (Fig. 1C; Doomore is ca. 3 km west of the area shown).

The passage tombs of this part of Sligo have been the subject of archaeological survey and excavation including major excavations led by Burenhult (Burenhult, 1984, 2009) and other detailed studies in more recent times (Bergh, 1995; Hensey and Bergh, 2013). There has been considerable debate regarding the chronology of the tombs (Caulfield, 1983; Cooney et al., 2011). The most recent evidence, based on AMS ^{14}C dates from antler and bone pins recovered from two tombs at Carrowmore, suggests that the start of use was in the interval ca. 3775–3520 BC and that by ca. 3000 BC, or possibly earlier, the tombs were no longer in use by Neolithic peoples (Hensey and Bergh, 2013) (BC indicates calibrated ages).

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As regards to early Neolithic activity, the recently discovered and partially excavated large enclosure at Magheraboy (Fig. 1B) has yielded ^{14}C dates indicative of Neolithic activity that may have started particularly early in the Neolithic and possibly before 4000 BC (Danaher, 2007). Some of the ^{14}C dates, however, on which this is based are so early that their validity as in indication of date of construction has been questioned (Cooney et al., 2011). Nevertheless, there is a consensus that the enclosure was particularly early in the context of the Neolithic not only in Ireland but also in Great Britain (Whittle et al., 2011).

While general proximity to the archaeology described above was one of the chief reasons for selection of Cooney L. for detailed paleoecological investigations, the lake itself had much to recommend it. It lies in a distinct depression that is sheltered from the prevailing westerlies (Figs. 1C, E, S1 and S2). This, and the lack of inflowing and outflowing streams and the overall bathymetry (see site description), suggest that the lake contains a continuous Holocene sediment sequence and there is no reason to suspect, either from a priori considerations or indeed the results obtained, that sediment focusing or slumping complicates the record.

Pollen analysis was the main method employed as it facilitated detailed reconstruction of vegetation and land-use that, in turn, can give important insights into pedogenesis, climate change and human impact. Reconstruction of climate change in the early Holocene, and especially the 8.2 ka anomaly, based on pollen data and the reconstructed vegetation dynamics at Cooney L. is described by Ghilardi and O'Connell (2013a). This, and the later part of the pollen record (the record extends to ca. 790 BC, i.e. the end of the Bronze Age), are here evaluated in the light of geochemical (elemental) data from the same sediment core. Mackereth (1966), in his pioneering investigations of lake sediments from the Lake District, north-west England, showed that sediment geochemistry reflects mainly changes in the lake catchment and especially erosion events. The geochemical record, however, may also be considerably influenced by within-lake processes, including development of meromictic conditions, changes in lake levels, and shifts in pH and redox potential at the top of the sediment

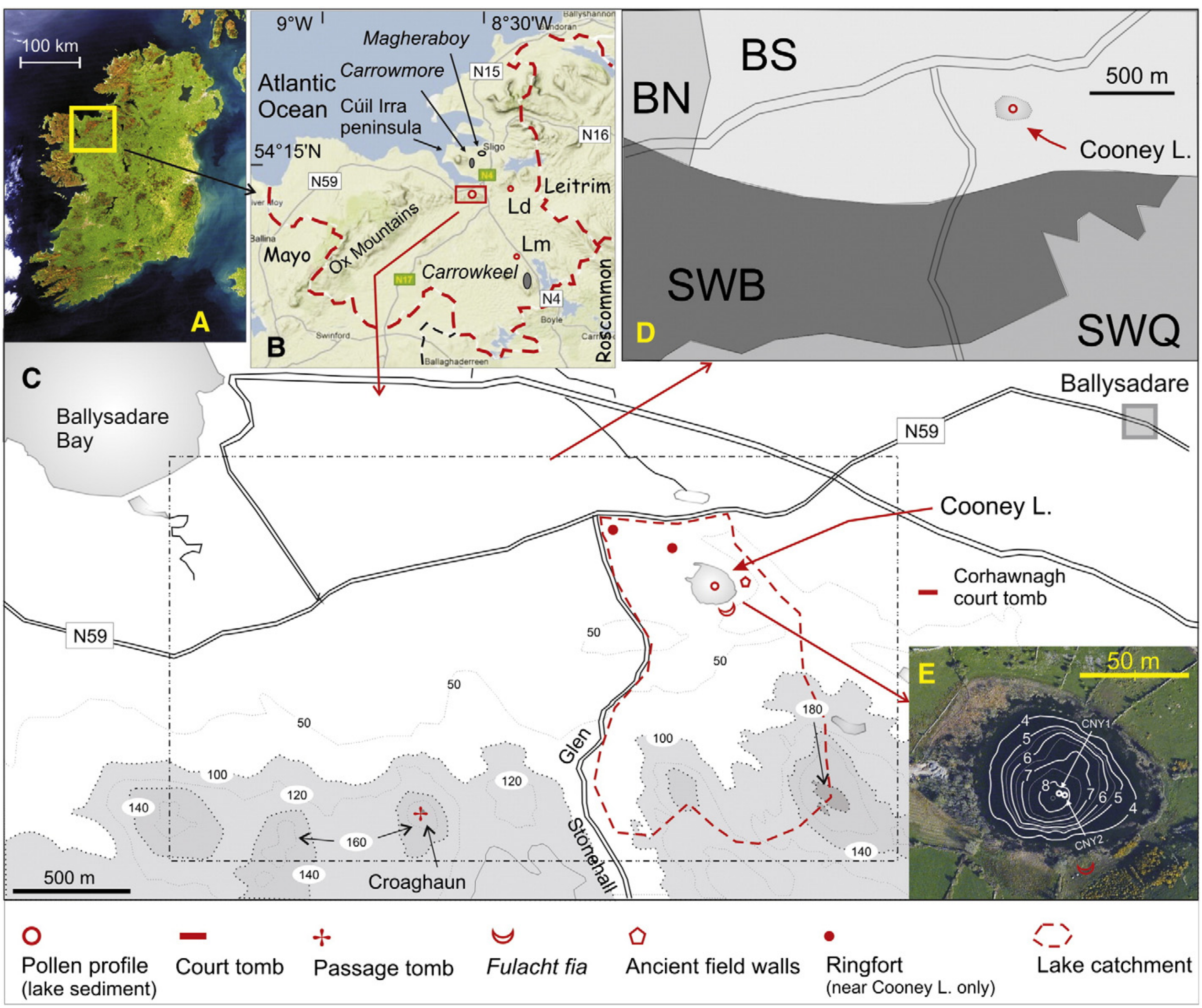

Figure 1. Maps showing the geographical location of Cooney Lough and other details relating to the study area. A. Map of Ireland showing Co. Sligo and adjacent counties; details shown in B include location of study area (enclosed by square) and selected sites of archaeological and palaeoecological interest (details in text; Carrowkeel indicates the Carrowkeel/Keshcorran area). C. Map of study area including main roads, megalithic tombs and main archaeological features beside Cooney Lough. Contours are indicated in m above sea level (asl) and the catchment of Cooney L. (approximate) is also shown. D. Bedrock geology of the area enclosed by the rectangle in C. BN, Bundoran Shale Formation and BS, Ballyshannon Limestone Formation (both Carboniferous). SWB, Slishwood Division (semi-pelitic biotite schists) and SWQ (psammitic paragneiss; both north-east Ox Mountain inlier; Dalradian or older). Geology is after MacDermot et al. (1996). E. Aerial view of Cooney L. (Bing Maps; downloaded 1/02/2013) with bathymetry (m) and coring locations CNY1 and CNY2.

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column. These factors must also be given due consideration as they can greatly influence the record, and especially the behaviour of key elements such as Fe, Mn, and P (cf. Mackereth, 1966). For more recent overviews of methodologies and especially interpretation consult Engstrom and Wright (1984) and Boyle (2001).

Site description

Cooney Lough lies 2 km west of Ballysadare, Co. Sligo in a sheltered depression within the fertile lowland coastal strip that lies between the Ox Mountains to the south and Ballysadare Bay to the north (Fig. 1). The coastal strip consists of drift-covered Carboniferous limestone (Ballyshannon Limestone (BS) is the local formation; Fig. 1D) that today supports mainly pastoral farming. This contrasts with the uplands to the south that consist of Dalradian (or older) metamorphic rocks, geologically classified as Slishwood Division and consisting of semi-pelitic biotite schists (SWB) and psammitic paragneiss (SWQ). These rocks dominate in the north-east part of the Ox Mountain range (MacDermot et al., 1996; Fig. 1D). Here skeletal soils support mainly heathy vegetation that provides rough grazing (Walsh et al., 1976). Tall scrub, dominated by *Corylus*, survives in sheltered, scattered locations such as the nearby Stonehall/Glen gap (Fig. 1C). *Betula pubescens* and *Ulex europaeus* are locally common. Archaeological features of note in the general vicinity of the lake (Fig. 1C) include a court tomb (Corhawnagh), 700 m east of the lake. This tomb type is usually ascribed to the early Neolithic (Waddell, 2010). This view is supported by the results from recent limited but critical AMS ^{14}C dating that points to initial use and construction of court tombs taking place in the interval 3700–3570 BC (Schulting et al., 2012). A previously unrecorded *fulacht fiadh* (burnt mound) was noted beside the lake during fieldwork (ascribable to the Bronze Age, cf. Waddell, 2010). Linear features of unknown age that, in earlier times, may have served as field boundaries were also noted. There are two substantial ringforts in the catchment (Fig. 1C). These may relate to the Iron Age or medieval period, in which case they are younger than the records presented here. At Larkhill and Beltra, a short distance to the west of Cooney L., there are several *fulachta fiadh* while in the coastal area between Beltra and Inishcrone there is a high concentration of megaliths. These latter are mainly court tombs but there are also passage tombs, the closest being that at Barnabrack, 6 km west of Cooney L. (Ó Nualláin, 1989; http://www.archaeology.ie; for the Neolithic archaeology of the wider region see the Introduction).

The lake, which lies at 36 m asl, is small (2.5 ha; 180 × 150 m), closed (a large drumlin to the west effectively impedes drainage), relatively deep (maximum recorded depth: 8.6 m), and steep-sided and flat-bottomed, much of it being over 5 m deep (Fig. 1E). The lake catchment is about 75 ha and lies mainly to the south of the lake and extends to the Ox Mountain uplands where locally schist prevails; (Fig. 1C). The catchment to the south, and especially the steep-sided terrain adjoining the lake on three sides (Figs. S1 and S2), are presumed to be the main sources of water and also erosional material. The pollen, on the other hand, reflects mainly vegetation of the fertile limestone lowlands (especially if it assumed that winds were predominantly westerlies as at present), within a radius of ca. 1 km of the lake (cf. Sugita, 1994; Gaillard et al., 2008). There was undoubtedly also pollen input from the uplands, but, given the distance between the lake and these uplands, this was probably small, especially in the period spanned by the record during which woodland was always important.

The present-day climate is mild and oceanic, with average precipitation in the range 1200–1400 mm per annum and rather evenly distributed throughout the year mainly as rain. Mean annual air temperature is ca. 11°C. Mean daily air temperatures at Belmullet, north-west Mayo (nearest synoptic weather station) are 6.3°C and 15°C in January and August (coldest and warmest months), respectively, and winds at this exposed location vary between 11.1 knots (5.7 m sec^{-1}) and 15.4 knots (7.9 m sec^{-1}) (mean monthly speed for January and July, respectively). These data are from www.met.ie (accessed on 1.02.2013) and the values relate to the period 1981–2010.

Methods

Fieldwork

Prior to coring (August 2009), the bathymetry of Cooney L. was established using a GPS (Garmin GPSMAP 450 s) with a depth sounder attached (Garmin Transom transducer). Core CNY1 (grid. ref. N 54° 12.236′, W 08° 32.490′) was taken in April 2010 from near the centre of the lake in water depth of ca. 8.3 m, using an Usinger piston corer (Mingram et al., 2007) fitted with a 2-m-long, 80-mm-diameter, steel coring tube. The 6-m-long core reached the highly minerogenic basal sediments and is assumed to contain a complete Holocene sequence. The investigations reported on here relate to core segments CNY1-I and II (depths 300–495 cm; depths are cited with reference to the top of core CNY1 that is assumed to have included the sediment/water interface). The break between core segments at 400 cm has been bridged by using sediment from core CNY2 (the gap was estimated to be ca. 4 cm; this was established pollen analytically; details will be presented in the context of a full evaluation of the pollen record which is in preparation).

Stratigraphy and magnetic susceptibility

The split core segments were photographed in the field and subsequently also in the laboratory. Stratigraphical descriptions were made, and magnetic susceptibility was measured using a Bartington MS2E1 high resolution, surface-scanning sensor connected to an MS2 metre (so called split-core logging; the sensitive ×0.1 range setting was selected). The readings, taken every 2 cm, were not very informative (little overall pattern) and so are not presented.

Pollen analysis

Samples of ca. 1 cm^3 from 1-cm-thick slices of sediment were taken at regular intervals (every 2 cm; in parts, continuous sampling was carried out) between 302 and 500 cm. Standard procedures as implemented in the Palaeoenvironmental Research Unit (PRU), National University of Ireland Galway (NUIG) were used for pollen preparation. This included treatment with KOH, sieving using a 100-μm-mesh sieve, HF, acetolysis, and sieving in an ultra-sonicator at the end of the preparation procedure using a 5-μm-mesh sieve to remove small particles (Ghilardi and O'Connell, 2013a). The samples were weighed and *Lycopodium clavatum* spore tablets (three tablets, i.e. 55752 spores, were added; tablets supplied by the Department of Geology, University of Lund; batch no. 177745) were added at the commencement of preparation to facilitate estimation of pollen concentration. The samples, mounted in glycerol, were counted using a Leica DM LB2 microscope fitted with ×10 oculars. A ×50 objective was routinely used while counting, and phase-contrast ×40 and ×100 objectives — the latter an oil immersion lens — were used to check critical grains. In general, at least 1000 pollen and spores of terrestrial origin (excluding aquatic taxa, *Sphagnum*, etc.) were counted in each sample.

Pollen and spore identification followed mainly Moore et al. (1991). Other authorities consulted included Beug (2004), Fægri and Iversen (1989) and Reille (1992, 1995). Cereal-type pollen was distinguished following the criteria given by Beug (Beug, 1961, 2004) but 40 μm rather than 37 μm was taken as the cut-off minimum size for acceptance as cereal-type pollen (cf. Ghilardi and O'Connell, 2013b). Non-pollen palynomorphs (NPP) were also counted, including fungal spores, *Pinus* stomata and charcoal (fragments ≥37 μm counted; referred to as micro-charcoal). Percentage, concentration and pollen accumulation rate diagrams were constructed. Percentages are based on a total

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terrestrial pollen sum (TTP) from which aquatics, algae and non-pollen palynomorphs (NPP), were excluded (percentage values for these are based on TTP plus the sum of the particular category).

Loss-on-ignition

Sediment samples with a volume of ca. 5 cm^3 were taken from depths corresponding to those sampled initially for pollen (side A of split cores was used). The samples were dried for 24 h at 105°C, subsequently transferred to porcelain crucibles and ashed for four hours at 550°C (cf. Heiri et al., 2001). Water content and loss-on-ignition (LOI) values were calculated (referred to as LOI-1). After more samples were taken for pollen analysis to achieve a near continuous record, the core was again sampled for LOI, this time using larger volume samples (ca. 10 cm^3) from side B of the split cores, and LOI was determined as described above (referred to as LOI-2). The residues from LOI-2 were used for elemental analysis. LOI, as used below, refers to the second series of ashing unless otherwise indicated.

Elemental analysis

Samples were prepared and processed in a class 10,000 (ISO 7) cleanroom with a class 100 (ISO 5) laminar-flow fume cupboard at the Chemical Monitoring Facility (CMF), NUIG. Treatment involved a modified version of acid digestion procedures to determine element concentrations in lake sediments (Jarvis and Jarvis, 1985; Snäll and Liljefors, 2000; Boyle, 2001; Yafa and Farmer, 2006; Morrison et al., 2008; Selig and Leipe, 2008; Kamenov et al., 2009). Subsamples (approximately 150 mg) of the ashed residues from LOI-2 were weighed in pre-cleaned PTFE vessels (pre-cleaning involved soaking successively for seven days in each of the following: 20% HCL, 20% HNO_3 and Milli-Q water (18.2 mΩ, Milli-Q Element system, Millipore)), 4 cm^3 of hydrofluoric acid (HF) (Trace SELECT®, Sigma Aldrich) and 4 cm^3 of *aqua regia* (hydrochloric (HCL): nitric acid (HNO_3), ratio 3:1; reagents Trace Metal Grade, Fisher). The vessels were sealed and left at room temperature for 5 h, and then evaporated to dryness on a hotplate (150°C). After evaporation and cooling, 5 cm^3 of HNO_3 were added to the residue, the vessels were sealed and heated in an oven at 80°C for 24 h, and subsequently evaporated to dryness. When cool, 1 cm^3 of HNO_3 was added to the residue, which was then quantitatively transferred to trace-metal-free centrifuge tubes (Labcon, 50 cm^3) by the weighing liquids method using a macro balance, and diluted to 25 cm^3 using 1M HNO_3. Elemental concentrations of Al, Ba, Ca, Co, Cr, Cu, Fe, K, La, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sc, Sr, Th, Ti, U, V, Y, Zn and Zr were determined by inductively-coupled plasma optical emission spectrometry (ICP-OES; Varian 725-ES). Elemental concentrations were adjusted, using the LOI data, to facilitate reporting on a dry-weight basis. Quality control for method performance and digestion efficiency was evaluated using duplicates, reagent blanks and a lake-sediment reference material (LKSD-4, Natural Resources Canada). The recoveries of elements were in good agreement with the reference values (Table S1) and so we conclude that the methods employed, including the ashing, have not affected element concentrations as reported here.

Radiocarbon dating

Material for dating was obtained by taking 2-cm-thick slices with a wet weight of ca. 50 g. The samples were sieved through a 125 µm mesh and, as far as possible, material of terrestrial origin was selected for ^{14}C AMS dating. In all, 11 AMS ^{14}C dates are available. These relate to that part of the core from 486 to 302 cm, i.e. from ca. 6545 BC to the top of the pollen profile (ca. 790 BC). Depth 494 cm, i.e. 494–496 cm, was also sampled but yielded insufficient material for ^{14}C dating. The beginning of the Holocene, which is datable to 9700 ± 50 BC (cf. Walker et al., 2009), was placed at 515 cm, based on the lithology (highly minerogenic giving way to organic-rich sediments).

Results

Dating

Details regarding the ^{14}C dates are given in Table 1. The age/depth relationship for the complete core (see inset) and that part studied in detail here which spans the interval ca. 7760–770 cal yr BC is shown in Figure 2. The curve that is used, i.e. the same as that in Ghilardi and O'Connell (2013a), was obtained by fitting a cubic spline curve to the ^{14}C dates that were calibrated using OxCal ver. 4.1.7 (Ramsey, 2009) and IntCal09 calibration curve (Reimer et al., 2009). This curve is very similar to that obtained using OxCal and the P_Sequence model, the main difference being that the spline curve is smoother. This implies that there are no sharp changes in sedimentation rates which is what we expect given the rather uniform core lithology and the lake characteristics. The dates cited in this paper are derived from the cubic spline curve and are rounded to the nearest 5 yr.

Pollen data

Summary pollen and related data, including sediment accumulation time and LOI-1 and 2, are presented in Figure 3. The complete pollen dataset will be presented elsewhere.

Non-metric multidimensional scaling (NMS), carried out by PC-ORD (ver. 6.06), has been used to summarise the data (McCune and Mefford, 2011; for details regarding NMS carried out on the lower pollen spectra only, see Ghilardi and O'Connell, 2013a). For this paper, the analysis included all samples (114), characterised by 38 variables including pollen, spores, the algae *Pediastrum* and *Botryococcus*, and micro-charcoal. Most taxa that had <5 occurrences and low percentage values were excluded; non-transformed percentage values were used. Autopilot and the option 'slow and thorough' were selected (details in

Table 1
Radiocarbon dates, core CNY1 (Cooney Lough).

^{14}C lab. code	Depth (cm)	^{14}C date (^{14}C yr BP)	$\delta^{13}C$ (‰)	Age range[a] (1σ; 68.3%)	Age range[a] (2σ; 95.4%)	Median age[a]	Description (numbers in parentheses refer to the number of items included in the sample)
UBA-17011	302	2609 ± 34	−25.7	810–781	835–670	797	*Sphagnum* leaf and *Betula* fruit
UBA-15784	326	2846 ± 24	−26.2	1045–944	1112–924	1005	Fragments of leaves (cf. *Salix*)
UBA-15785	350	3001 ± 29	−32.2	1310–1135	1374–1129	1254	*Betula* fruits (2), *Betula* bud scales (4), *Betula* bract (1) and leaves (cf. *Salix*)
UBA-15786	372	3379 ± 26	−24.1	1730–1634	1742–1617	1674	*Salix* leaf, cf. *Salix* leaf, bud scales of *Betula* (2) and *Betula* fruits (3)
UBA-17010	394	3917 ± 32	−33.6	2470–2347	2479–2295	2405	Leaf fragments (ca. 20)
UBA-15787	420	4653 ± 30	−27.5	3500–3369	3518–3364	3456	Bud scales of *Betula* (8), big bud scales (2), *Pinus* scales (4) and *Betula* fruits (3)
UBA-17008	428	4928 ± 32	−31.8	3756–3654	3772–3650	3698	Large leaf fragments; Bud scales of *Betula* (4) and *Pinus* (2)

Sample depths are given with reference to the upper depth; e.g. 302 cm included sediment from 302 to 304 cm; radiocarbon dates were calibrated using OxCal ver. 4.1.7 (Ramsey, 2009) and IntCal09 calibration curve (Reimer et al., 2009). Details of four lowermost dates, i.e. 7792 ± 36 BP (486 cm), 7077 ± 38 (476 cm), 6481 ± 32 BP (464 cm) and 5502 ± 28 BP (444 cm), are given in Ghilardi and O'Connell (2013a).
[a] Age ranges and median range, as reported by OxCal, are quoted in calibrated yr BC.

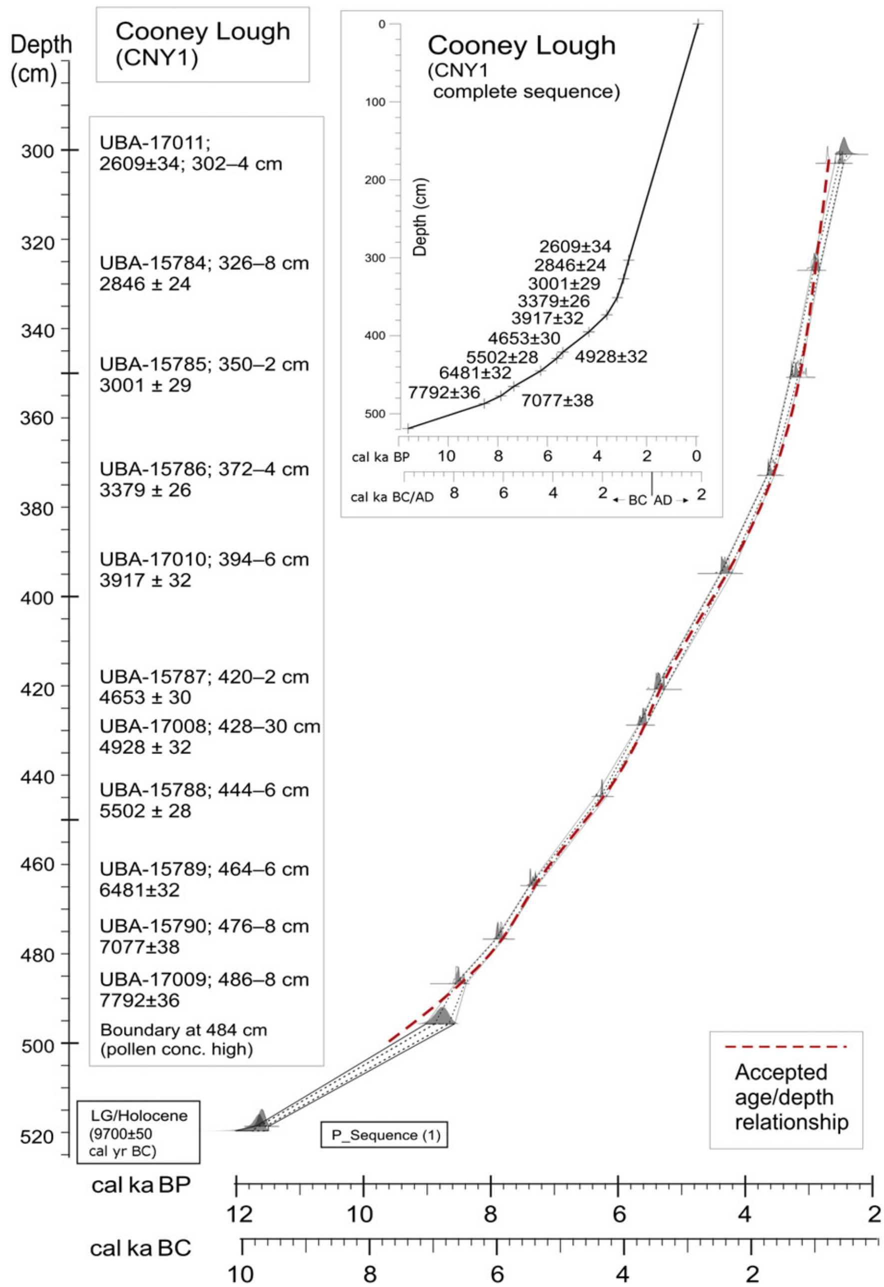

Figure 2. Age-depth model core CNY1, Cooney Lough, based on 11 AMS ^{14}C dates. The age-depth curve used is a spline curve fitted to the median values of the calibrated ^{14}C dates. Output from OxCal ver. 4.1.7 is also shown including (a) an envelope showing the 95% (solid line) and 68% (broken line) highest probability density ranges as given by OxCal and (b) likelihood distributions of the individual dates (solid line, no shading) and also the marginal posterior distributions that take into account the depth model (shaded; terminology follows Ramsey, 2008).

Peck, 2010; McCune and Mefford, 2011). The recommended two-dimensional solution was accepted. The scores of the pollen spectra on axes 1 and 2 are presented in Figure 3. Axis 1 accommodates most of the stress and so it is assumed that the trends suggested by the plot of scores on that axis are of greater importance for evaluation of the changes recorded.

Pollen assemblage zones (PAZs) were distinguished by careful visual inspection of the percentage, concentration and pollen accumulation rate diagrams. In general there is a good correspondence between the changes as highlighted by the NMS curves and the zonation as presented here. An overview of the pollen zonation and a summary interpretation of the pollen data are provided in Table 2.

PAZs 1–3 reflect mainly the changes during the early Holocene in the contribution by the various trees and tall shrubs to the woodlands that dominated in the general vicinity of the lake, i.e. within about 1 km radius. Oak, elm and pine were the main tall canopy trees. A more or less continuous record for *Pinus* stomata up to mid zone 3 (not shown) points to pine growing in the lake catchment. Pollen features of note include the expansion of *Betula* and *Pinus*, and decrease in *Corylus* and *Quercus*, in subzone 1c. The upper part of this subzone is regarded as reflecting the 8.2 ka climate anomaly (CA). In Ghilardi and O'Connell (2013a) this is referred to as CA 3b (Figs. 3, 4 and 6). There follows a series of changes, including a substantial increase in pollen input and the beginning of an *Alnus* curve (PAZ 2a) that consists mainly of single *Alnus* pollen records until the base of PAZ 2d where there is a minor increase. A further increase does not occur until the base of PAZ 3 but, even then, *Alnus* representation is such (it averages 5% in zone 3) that it can be assumed that alder, though present, was unimportant.

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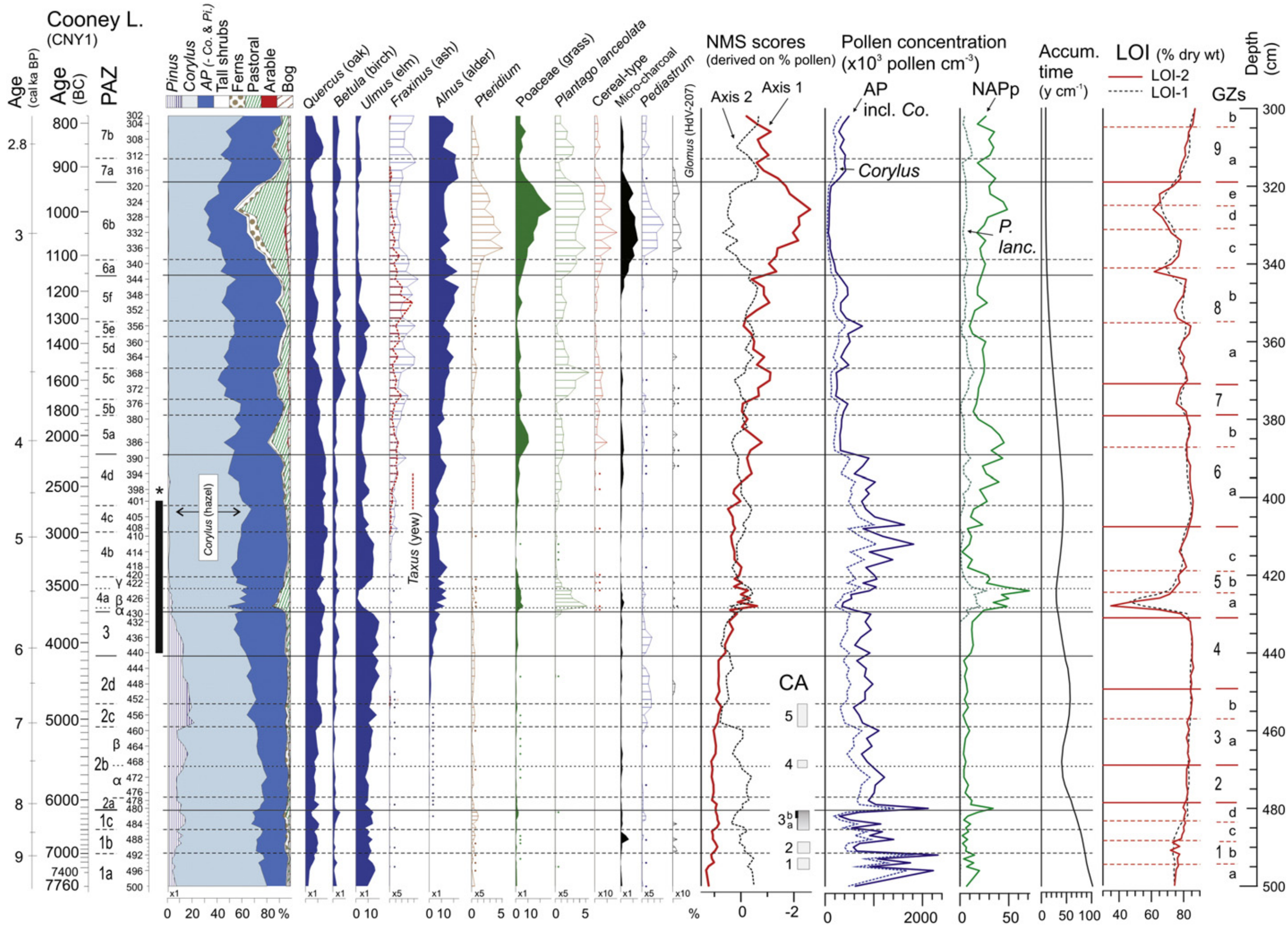

Figure 3. Selected pollen and related data, profile CNY1, Cooney Lough, plotted to a depth scale. The following are shown (left to right): timescales, pollen assemblage zones (PAZ), composite and individual percentage pollen curves, NMS scores on axes 1 and 2 based on percentage pollen data, climate anomalies (CA) as in Ghilardi and O'Connell (2013a), pollen concentration data (summary curves), sediment accumulation time, and LOI (data sets 1 and 2) and geochemical zones (GZs). GZs are shown in the LOI plot; otherwise PAZs are indicated. In the pollen curves, a small dot serves to highlight a low value. A solid bar with an asterisk indicates the interval plotted in Fig. 7. Main abbreviations: *Co.*, *Corylus*; NAPp, non-arboreal pollen indicative of grassland, as distinct from disturbed biotopes which is referred to as NAPa; *P. lanc. P. lanceolata*.

Other major features include a general decrease in *Corylus* from sub-subzone 2bβ onwards (*Corylus* concentration values decline at the base of subzone 2c) and there is a steep decline in *Pinus* in mid zone 3 (Fig. 3). Early in subzone 4a (ca. 3650 BC), *Pinus* values are low (<4%) and the stomatal record ceases so it may be assumed that pine is either locally extinct or rare.

In PAZs 4–7 changes in the relative contributions of arboreal pollen (AP) to non-arboreal pollen (NAP) and curves for Poaceae, *Plantago lanceolata*, cereal-type pollen and other NAP suggest varying levels of farming activity. During the Neolithic (cf. PAZ 4), farming was mainly pastoral based (cereal-type pollen and pollen of weeds associated with disturbed/arable situations are poorly represented; Figs. 3 and 7). The main activity was concentrated in the early Neolithic (subzone 4a; this subzone includes the Elm Decline and Landnam, namely woodland clearance by early farmers) and the later Neolithic (subzone 4d). Shifts in woodland composition result from decline and demise of pine (subzone 4a), an initial weak increase in ash (from mid subzone 4b) followed by a somewhat stronger expansion (subzone 4c) that was accompanied by the first continuous *Taxus* pollen records. Ash and yew achieved maximum expansion in subzone 5f but never made major contributions.

PAZs 5–7 span an interval that corresponds closely with the Bronze Age. In subzones 5a, 5c and zone 6, the pollen data suggest substantial farming activity, with a rather important arable component. Zone 6 reflects maximum woodland clearance and human impact for the profile as a whole (cf. NAP and micro-charcoal curves); this is followed by much lower human impact and woodland regeneration (especially subzone 7a).

Geochemistry

Numerical zonation of the geochemical profile was carried out by CONISS, a stratigraphically constrained cluster analysis by sum-of-squares (Grimm, 1987), using psimpoll ver. 4.27 (Bennett, 2007). Seventeen elements, i.e. the most abundant, were included in the analyses (the five elements (REEs)), and minor elements Ba, Mo, Sr and Th, were omitted). In several samples in the upper part of the profile REEs were at such low concentrations as to be below detection levels (see also below). Separate runs were performed with variables root-square transformed, and standardised to zero mean and unit variance. In each case 15 zones were specified. Output, using variables standardised to zero mean and unit variance, was regarded as giving the optimum result. The resulting dendrogram is presented in Figure 4, which includes curves for the main elements and groups of elements. The geochemical profile was then zoned by careful visual inspection of the curves and particularly movement in curves regarded as indicative of erosion. The zonation suggested by the dendrogram produced by CONISS was also taken into consideration. Nine

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Table 2
Summary of pollen data, profile CNY1, Cooney Lough.

PAZs	Spectra[a]	Age range[b]	Main features	Interpretation with (age)[c]
7	318–302	935–790	AP recovers; Poaceae and *Plantago lanceolata* decline	Subpaz 7b (885–790): modest increase in farming Subpaz 7a (935–885): woodland regeneration in response to decline in farming
6	432–320	1155–935	Major decline in AP and increase in NAP; micro-charcoal and *Pediastrum* rise	Major increase in farming, incl. arable. Subpaz 6b (1095–935): major farming impact involving substantial woodland clearance Subpaz 6a (1155–1095): initial expansion in farming
5	388–344	2175–1155	AP remain high (average: 91%); NAP and esp. taxa indicative of farming (e.g. Poaceae, *P. lanceolata* and cereal-type) better represented than heretofore	Overall increased, but oscillating, levels of human impact; cereal growing important. Subpaz 5f (1310–1155): increased farming Subpaz 5e (1375–1310): distinct lull in farming Subpaz 5d (1530–1375): farming declines; woodlands regenerate Subpaz 5c (1725–1530): most intense farming in PAZ 5 Subpaz 5b (1840–1725): distinct lull in farming Subpaz 5a (2175–1840): substantial increase in farming, incl. arable; cf. beginning of Bronze Age
4	429–390	3715–2175	*Ulmus* decline and increase in *P. lanceolata* already began at top of previous zone. Curves for *Fraxinus* and *Taxus* begin in mid 4b and base of 4c, resp. *Pinus* values very low	Subpaz 4d (2700–2175): farming resumes but does not impact greatly on woodlands that now include minor amounts of ash and yew Subpaz 4c (3000–2700): interruption in farming Subpaz 4b (3440–3000): woodland regeneration incl. elm; farming impact weak Subpaz 4a (3715–3440): a pronounced Elm Decline and a modest Neolithic Landnam
3	440–430	4155–3715	*Alnus* begins a consistent rise; *Pinus* and *Corylus* decrease	Alder begins to noticeably increase and hazel decreases from the beginning of the zone. The main changes register towards the top of the zone, incl. decline in *Pinus*, then *Ulmus* and *P. lanceolata* curves are initiated
2 1	480–442; 500–481	6155–4155 7760–6155	AP dominant; main contributors *Corylus* (63%), *Ulmus* (12.3%), *Quercus* (8.6%) and *Pinus* (10.6%)[b]	Full woodland cover with elm, oak and pine. Hazel important probably as an undershrub and possibly also forming hazel-dominated stands. Boreal and possibly early Atlantic periods are represented[c]. Low but consistent records for *Alnus* from subzone 2a upwards with first notable increase at 2c/2d boundary

[a] Spectra are cited as depths (cm); age ranges in cal yr BC, rounded to the nearest 5 yr.
[b] Averages for zones 1 and 2 together are cited.
[c] Classical pollen zones are as defined by Mitchell (1956). Zones 1 (excluding pollen spectrum from 500 cm) and 2 are discussed in Ghilardi and O'Connell (2013a) where the climate implications are considered. CA 3b (upper part of subzone 1c) is regarded as reflecting the effects of the 8.2 ka climate anomaly when *Pinus* and *Betula* increase and *Corylus* and *Quercus* decline.

geochemical zones (GZs) (Table 3) and, in some instances, subzones were differentiated. Overall, the divisions are similar to those suggested by CONISS (Fig. 4).

To explore the relationships between the more important elements and groups of elements, biplots were constructed (Fig. 5). As expected, the alkalis, i.e. Na, K and Mg, show strong positive correlations, with Mg/Na and K/Na showing the strongest correlations (Fig. 5B). The basal samples (GZ 1a and 1b) are distinctive on account of high Mg and K values. Of the three alkalis, K appears to be a particularly sensitive indicator of erosion, especially in the early and mid Holocene. Fe shows a rather weak correlation with the alkalis ($r^2 = 0.37$ for linear fit; Fig. 5A) due partly to three outliers, 420, 421 and 423 cm (GZ 5b) in which Fe is particularly high but the alkalis have only average values. The Fe/Mn ratio is also elevated at this time (Fig. 4) which suggests that reduced redox potential in the soils of the catchment facilitated the movement of both Fe and Mn to the lake (Mackereth, 1966; Engstrom and Wright, 1984; see also Discussion). The Fe/Mn plot also serves to highlight the low Mn values in the lower part of the profile (GZ 1 and 2) where Fe (also the alkalis) has high concentrations. This may be the result of erosion combined with strong reducing conditions in the catchment, though changes in redox conditions in the lake and its uppermost sediments as well as lake-water stratification may have also contributed (Schaller et al., 1997).

Al and Ti are positively correlated ($r^2 = 0.32$ for linear fit; Fig. 5D) as expected given that these elements are generally assumed to derive from clastic material eroded from the catchment and are considered to behave conservatively in the limnic environment (cf. Engstrom and Wright, 1984). Positive correlation, especially in the case of Ti, with the alkalis supports this conclusion (see especially GZ 1; Fig. 4). Samples 428–425 cm are distinct outliers (GZ 5a; on removing these three samples r^2 for Al/Ti = 0.56), in that Ti concentration is particularly high and Al concentration is low. This may be connected with within-lake changes (cf. decrease in LOI values which is regarded as a proxy for organic content, an assumption that is justified on the basis of overall high organic content (Mackereth, 1966)).

Ca shows little relationship overall to the erosional indicators. A major spike in Ca occurs at 429 cm, the second sample from the base of GZ 5 and the first sample of PAZ 4. The Ca peak presumably reflects increased precipitation of calcium carbonate due to higher lake productivity triggered by increased soil erosion. The maximum change in LOI, i.e. LOI-2, is recorded at 428 cm where values fall to 35% (Figs. 3 and 4). The LOI-1 values also show a sharp decline but the minimum (37%) registers at 427 cm. This minor upwards displacement of the minimum value may be attributable, at least in part, to a small displacement during subsampling (sampling for LOI-1 and pollen, and sampling for LOI-2 and the chemical analyses were from sides A and B, respectively, of the split cores). The decrease in LOI points to increased mineral input. Within-lake changes, such as a diatom bloom, may also be involved but this is considered unlikely. The alga, *Pediastrum*, which is usually responsive to changes in the limnic environment, shows little response (Fig. 4; see also Discussion).

The plot of Cu + Cr + Co versus the alkalis indicates rather strong positive correlation (Fig. 5F). This is as expected, given that the latter metals are regarded as being firmly bound in mineral lattices (cf. Boyle, 2001). Cu is the main element especially in the lower part of the profile, i.e. from top of GZ 3b downwards but, overall, the individual curves show strong correlation (Fig. 4). These metals (also Ni; it shows a broadly similar pattern) seem to be generally indicative of soil erosion.

Sulphur and zinc have rather similar profiles (Fig. 4; biplots are not shown). Notable are the peaks in both curves in the basal part of the profile (GZ 1b) and the generally elevated values recorded in GZ 5 and 9a (Fig. 4). There is a general correspondence with Fe (S is often regarded as indicative of iron sulphide which forms under strongly reducing conditions; cf. Boyle, 2001), the main exception being in GZ 1c where Fe and Fe/Mn are high but S and Zn decrease. This may be due to redox changes at the sediment/water interface, possibly brought about by lower water–table levels and increased oxygen supply at the base of the water column. Redox changes may also have a direct bearing on the shape of the molybdenum (Mo) curve which generally parallels that of Fe and S as it tends to co-precipitate with compounds formed by these elements (Schaller et al., 1997).

Phosphorus values are generally at or below 800 mg kg^{-1}. This general pattern is interrupted by a major peak (6219 mg kg^{-1}) at 376 cm (GZ 7). Adjacent samples, 378 and 374 cm, also show elevated

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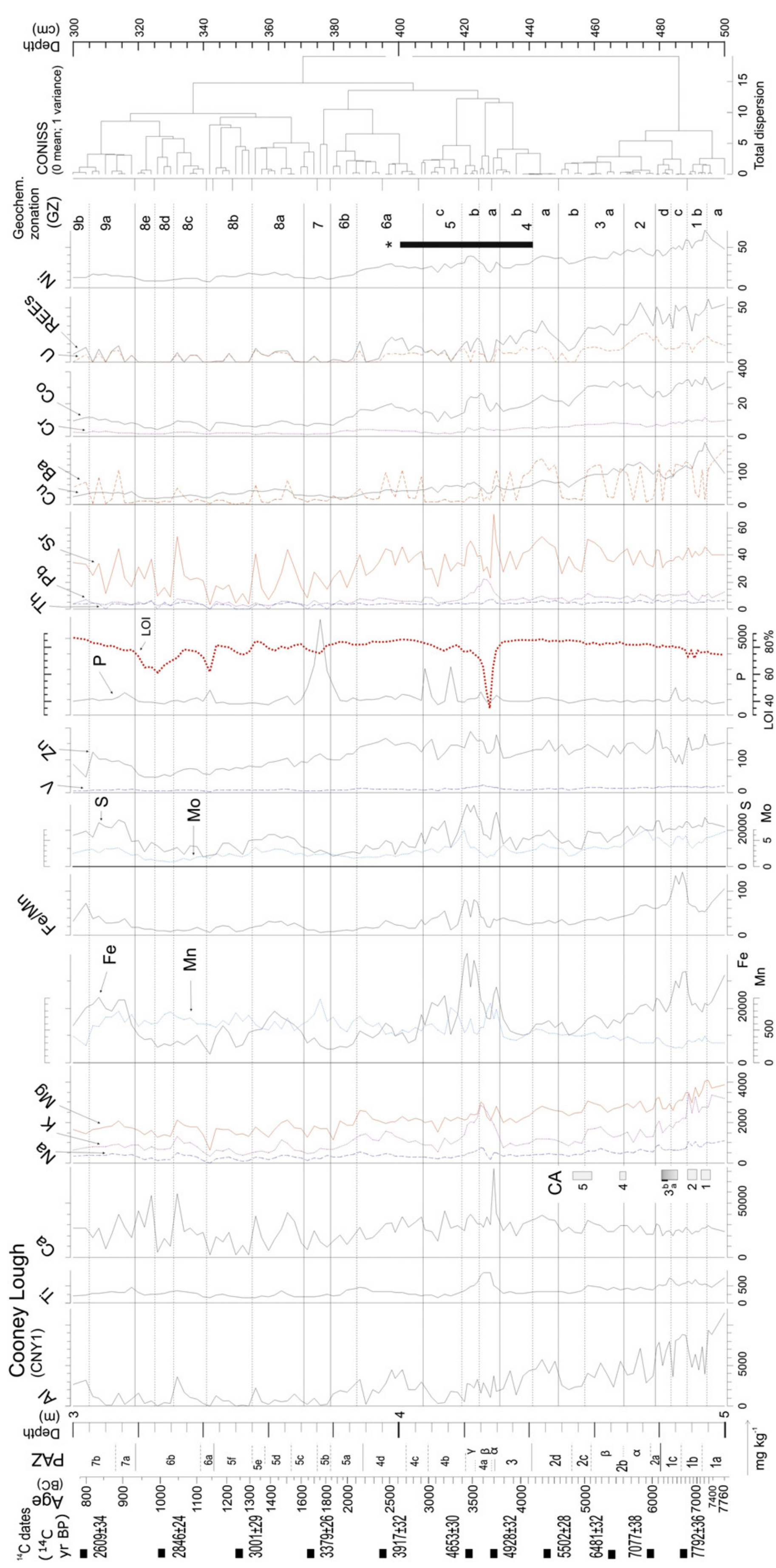

Figure 4. Geochemical data (individual elements expressed as mg kg^{-1} dry weight) plotted to a depth scale. Also indicated: ages based on the age-depth model, pollen assemblage and geochemical zones (PAZs and GZs), a dendrogram showing geochemical zonation produced by CONISS, and the LOI-2 curve. A bar with an asterisk indicates the interval plotted in Fig. 7.

Table 3
Summary of geochemical data, profile CNY1, Cooney Lough.

GZs	Depths[a]	Age range[a]	Main features	Interpretation	PAZs
9	318–300	935–770	Increase in Fe, S, Zn and alkalies in subzone 9a; Al high in subzone 9c	LOI suggests decrease in mineral input. Elevated Fe, S and Zn point to reducing conditions in catchment and increased soil acidification	7
8	370–320	1625–935	Al and REEs generally low. Fe high in subzone 8a. Elevated Ca in subzones 8a, 8c and 8d	Fluctuations in LOI hint at varying levels of erosion. Highest erosion in subzones 8a, 8c and 8e	5c (370 and 368 cm), 5d, 5f, 6a and 6b
7	378–372	1840–1625	Large peak in P; also peak in Fe; Al low; small decrease in LOI	Peak in P difficult to explain; probably connected with within-lake changes, including increase in productivity	5b and 5c (374 and 372 cm)
6	407–380	2935–1840	Rather high values for alkalies, Al and Ca in subzone 6a. Distinct decrease in subzone 6b	Initially erosional levels similar to subzone 5a. Distinct decrease in subzone 6b	4c (excl. 408 cm), 4d and 5a
5	430–408	3765–2935	Major changes including low LOI and elevated alkalies and Ti (5a), followed by inc. in Fe and S (5b). Average values in 5c	Greatly elevated erosion in subzones 5a and 5b. Return to rather steady-state conditions in 5c	3 (430 cm only), 4a, 4b and 4c (408 cm only)
4	448–432	4565–3765	Al and Ca elevated; also alkalies, Fe and REEs in subzone 4a; in 4b decrease in most elements	Increased erosion followed by decline to the lowest up to this point; pointers to increased erosion at the top of zone	2d (excl. bottom), 3 (excl. 430 cm)
3	468–450	5600–4565	Alkalies, Fe, Al and Ti steady in subzone 3a and decrease in subzone 3b	Low levels of erosion, especially in subzone 3c	2bβ, 2c and bottom of 2d (to 450 cm)
2	478–470	6035–5600	Alkalies and Fe generally decreasing	Increasing soil stability as expected given the stable woodland cover with little evidence of woodland perturbation	2a (478 cm only) and 2bα
1	500–479	7760–6035	Alkalies, Fe and Fe/Mn high (esp. in subzones 1a and 1c; also high values for Al and REEs)	High alkalis suggest erosion of unweathered soils(subzone 1a). Overall levels of erosion probably modest (cf. high LOI until the end of zone 4). High Fe, Fe/Mn, Al and REEs in subzone 1c suggest increased erosion of unweathered soils and an increase in podsolization. Peaks in Zn, Ca and P at top of 1d suggests inc. erosion and lake productivity	1a, 1b, 1c and 2a (to 479 cm)

[a] Depths refer to the pollen spectra (depths in cm from top of sediment column); age ranges in cal yr BC, rounded to the nearest 5 yr

values which suggest that the peak is not due to experimental error. There are also large peaks at 416 and 408 cm (GZ 5c) and smaller peaks elsewhere (e.g. 485 cm, 342 cm and 316 cm). Phosphorus may be regarded as an indicator of lake productivity but the tendency of P to be released from sediments under reducing conditions and its interaction with Fe and also Mn reduces its value as an indicator of lake productivity (the complexities associated with interpreting P records are discussed at length by Engstrom and Wright, 1984). The large P peak in GZ 7 (Mn values are also elevated) occurs towards the end of a period of reduced farming (PAZ 5b). It is assumed that this, and the other peaks in P, are largely reflecting changes in the limnic environment rather than soil erosion, as pollen evidence for strong human impact is lacking. Erosion, the result of a climate anomaly, is also a possibility.

Peaks in Ba invariably coincide with peaks in Sr. The former element has higher values overall (average 46 mg kg^{-1} versus 32 mg kg^{-1} for Sr). Both curves seem to be reflecting soil erosion but within-lake processes may also be important (peaks in Ca, Ba and Sr generally correspond).

As regards to the rare earth elements (REEs), values for U, and Zr, Y and La (these have comparable concentrations), and Sc are combined (elements are listed in decreasing order of importance). There is a good correspondence with the alkalis. This suggests that the REEs, which are usually regarded as conservative elements indicative of mineral inputs (e.g. Tanaka et al., 2007), reflect soil erosion. In the case of La and Sc, concentrations were below the reliable detectable levels, i.e. <0.04 and <0.02 mg kg^{-1}, respectively, in approximately half of the samples (mainly above 428 cm). For the other elements, about one third of the samples (mainly in GZ 6b, 7, and 8b, d and c) are below-reliable-detection limits (<0.02 mg kg^{-1}). These low concentrations may be connected with the increased sedimentation rate (the rate increases at a slow but more or less constant rate between GZ 7 and 8b).

Discussion

Most proxies for past environmental change have their particular strengths and weaknesses including the proxies employed here, namely pollen and elemental analyses. The pollen data reflect the vegetation, in this instance, mainly in the general vicinity of the lake as the lake is rather small. The vegetation in turn is assumed to be in equilibrium with the edaphic and climatic conditions, and the degree and type of human impact. Determining to what extent these and other factors such as competition between species that have similar ecological amplitudes influence vegetation at any particular time is usually of prime interest but difficult to achieve. The evidence provided by other proxies, such as elemental analysis, can be particularly helpful in this context but here too the record is often complex as the geochemical data usually reflect processes taking place in both the catchment and the lake itself. While it is usually assumed that the former is of greater importance, changes in pH, redox, lake levels and stratification of the water column (in Ireland stratification occurs mainly in deeper lakes, i.e. >6 m deep, and is then usually confined to summer months; Allott, 1986) can have important bearing on the within-lake behaviour of elements such as Fe, Mn, P, S and Mo (e.g. Mackereth, 1966; Schaller et al., 1997; Boyle, 2001).

In discussing the pollen and geochemical records presented here, it is convenient to use the broad divisions, early Holocene (ca. 7760–3700 BC; GZs 1–4; PAZs 1–3) and mid to later Holocene (ca. 3700–770 BC; GZs 5–9; PAZs 4–7). These divisions correspond more or less to the Mesolithic (the earliest evidence for a Mesolithic presence in Ireland is ca. 8000 BC; Woodman, 2009) while the latter spans approximately the Neolithic and Bronze Age (cultural periods shown in Fig. 6; for overview see Waddell, 2010).

Environmental change during the early Holocene (ca. 7760–3700 BC)

During this interval, it is assumed that human impact was minimal. Population levels are presumed to be low and the largely fishing/gathering-based economy had little impact on the natural environment (but cf. Warren et al., 2013). Disturbances by Mesolithic peoples were probably largely confined to the immediate vicinity of settlements. Furthermore, the main archaeological evidence for a Mesolithic presence in Sligo relates to the southern part of the county (Condit and Gibbons, 1991; Kilfeather, 2010), though investigations by Burenhult (1984) and also Woodman and Milner (2013)

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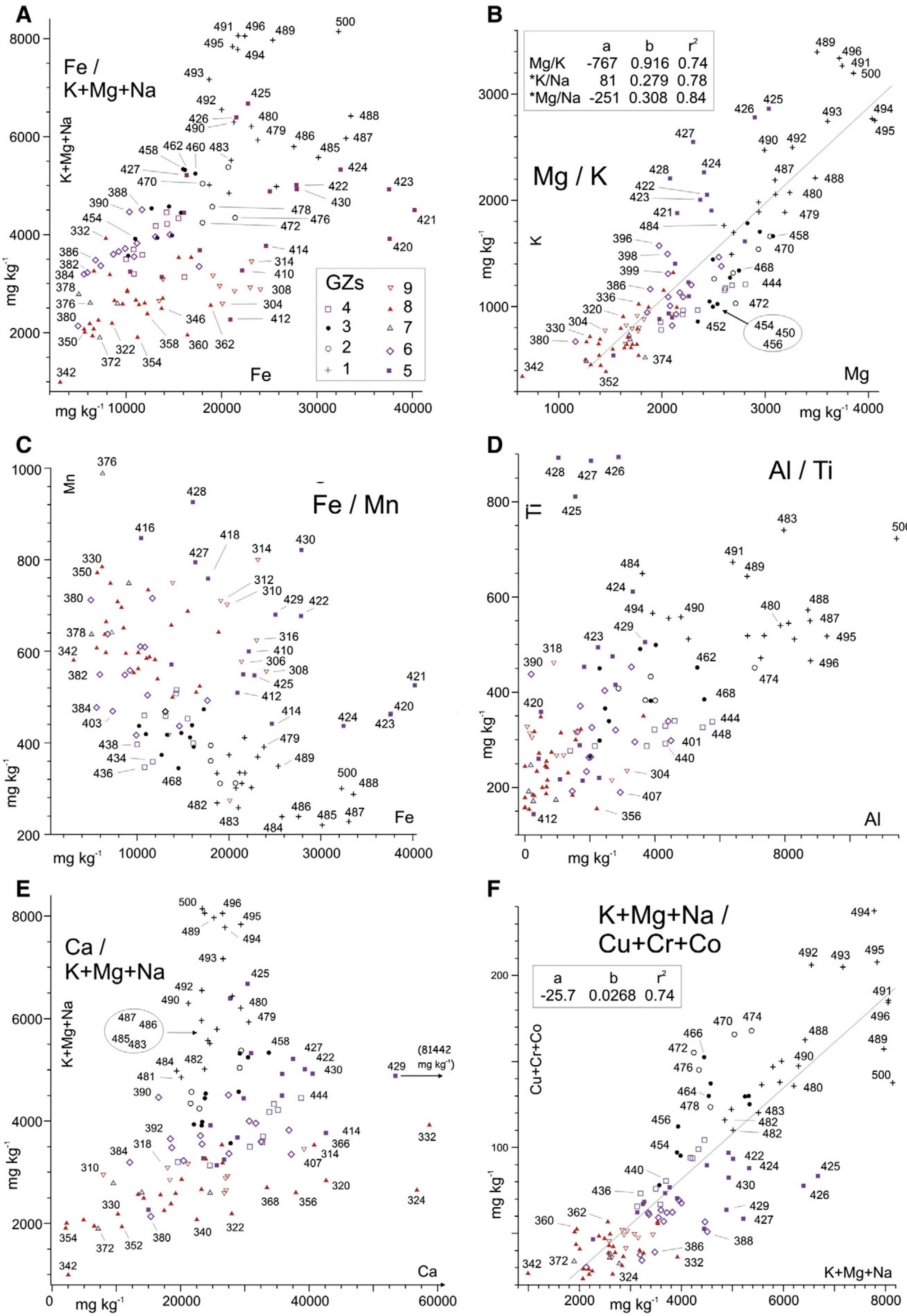

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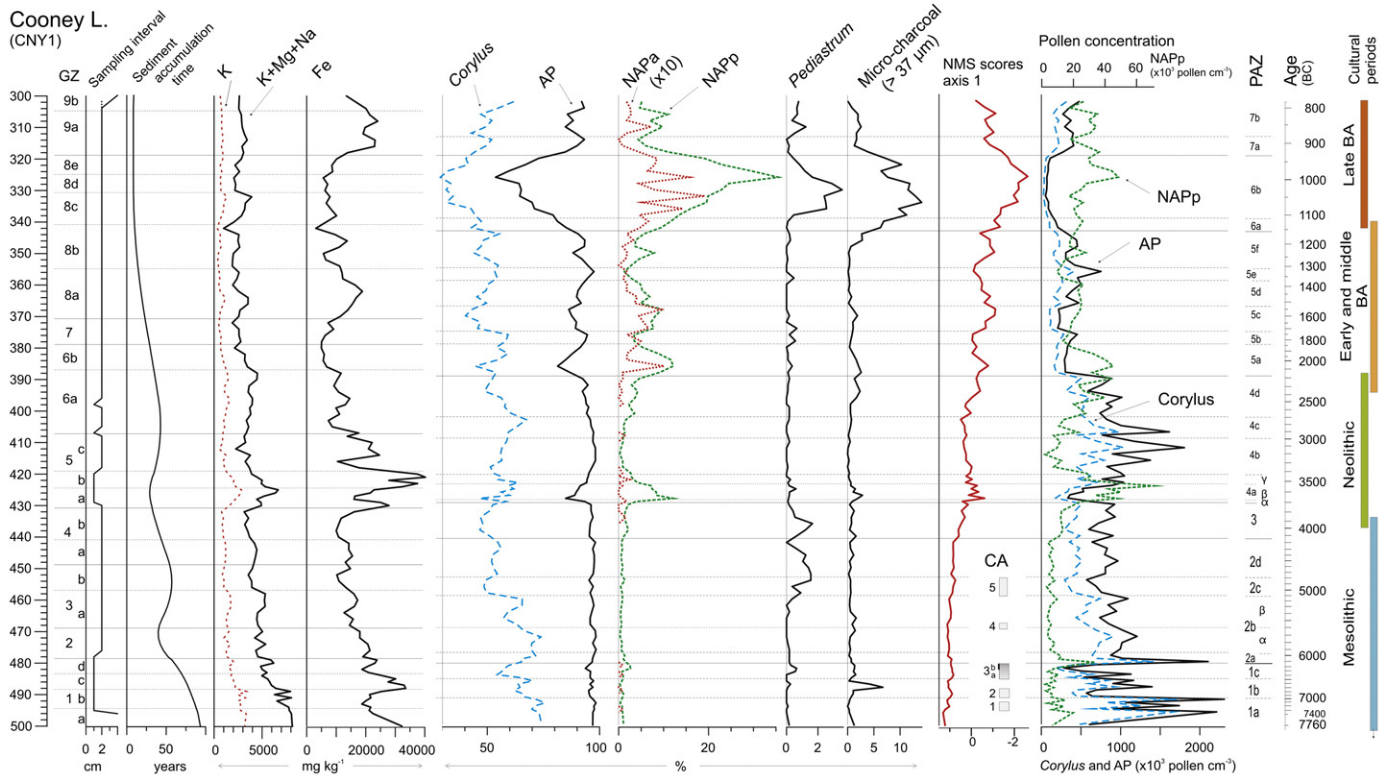

Figure 6. Summary diagram drawn to a depth scale. Sampling interval (1 cm represents continuous sampling; uppermost pollen sample is at 302 cm (indicated by broken line); in the case of elemental analysis the uppermost sample is at 300 cm; there was no sample taken at 302 cm), sediment accumulation time, K, alkalis (K + Mg + Na) and Fe curves, percentage pollen curves (*Corylus*, AP, NAPp and NAPa (this curve is exaggerated × 10); the x-scale used for NAPa and NAPp is × 2 that used for *Corylus* and AP); *Pediastrum* and micro-charcoal curves; NMS scores (derived from percentage curve data), axis 1; pollen concentration curves (note: x-axis scale for NAPp is exaggerated × 20). Climate anomalies (CAs; as in Ghilardi and O'Connell, 2013a) and cultural periods (after Waddell, 2010) are indicated. GZ and PAZ boundaries are indicated on the left and right-hand sides, respectively, of the diagram.

provided evidence for a late Mesolithic presence on Cúil Irra and its environs.

The pollen data suggest more or less full and relatively stable woodland cover during this interval in the vicinity of Cooney L., at least with respect to the tall canopy trees. The main changes in pollen representation (tree/shrub populations follow probably broadly similar patterns) are as follows: *Corylus* (hazel) declines in PAZ 1c, a strong recovery follows (PAZ 2a, b) and from the base of PAZ 2c values generally decline; *Quercus* (oak) shows a strong decline in the upper part of PAZ 1c, i.e. during the main climate anomaly (CA 3b) which is regarded as corresponding to the 8.2 ka event (Rohling and Pälike, 2005; Hede et al., 2010; Ghilardi and O'Connell, 2013a); *Ulmus* (elm) attains highest percentage values in PAZs 2d and 3, and *Alnus* (alder), which is consistently represented from mid PAZ 2a (ca. 6100 BC) to the top of PAZ 2c, exceeds ca. 1% only from the base of PAZ 2d (ca. 4740 BC). The pattern in the pollen concentration values (Fig. 6) points to substantial changes in pollen productivity, especially in the interval PAZ 1a–2a. It is suggested by Ghilardi and O'Connell (2013a) that these changes were connected with climate fluctuations (CAs 1–3).

There is broad correspondence between the pollen and the physical/geochemical data in this part of the profile. In GZ 1, which corresponds with PAZ 1 and the lower part of PAZ 2a, erosional indicators (cf. Al, Ti and alkalis) are at their highest for the profile. PAZs 1c and 2a reflect the main phases of instability as regards to vegetation. The pollen changes are suggestive of lower temperatures and less precipitation followed by strong recovery. The geochemistry suggests that overall levels of erosion declined during CA 3 and especially during CA 3b when the climate anomaly was most intense (cf. alkalis; also LOI). The substantial increase in Fe (also Mo) recorded in GZ 1c (6740–6360 BC; 8690–8310 cal yr BP), at the same time as the alkalis were decreasing, may be due to positive redox conditions at the sediment/water interface, brought about by lower lake levels. Interestingly, increased Fe and Mo concentrations preceded CA 3 and ended as the climate anomaly reaches its maximum, i.e. CA 3b which spans the interval 6430–6150 BC (8380–8100 cal yr BP). PAZ 2a is regarded as reflecting positive reaction of the vegetation to recovery in climatic conditions (probably temperature and precipitation) after CA 3. The small peak in the erosional indicators at the top of GZ 1d may arise from increased erosional input brought about by increased precipitation after the 8.2 ka climate downturn.

There is a precise correspondence between the boundaries GZ 2/3 and PAZ 2bα/β (ca. 5600 BC). Fe and REEs trend towards lower levels but the alkalis remain steady. The pollen shows a distinct shift towards lower *Corylus* and higher *Ulmus* values. These changes support the idea of increased stability in both soils and vegetation in the catchment at this time.

GZ 3b suggests particularly stable edaphic conditions. This subzone broadly corresponds to PAZ 2c (CA 5) where there is a distinct shift towards lower *Corylus* values, and the lower part of PAZ 2d where

Figure 5. Biplots of geochemical results. All samples (114) are plotted, geochemical zonation is indicated, and selected samples (depths) are labelled where space is available. In the case of the alkalis, the Mg/K relationship and the parameters for the linear relationship y = a ∗ x + b are shown. K/Na and Mg/Na relationships also show a strong linear relationship (parameters indicated in B; plots not shown). The linear relationship between the alkalis and Cu + Cr + Co is also indicated.

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Alnus consistently exceeds 1% for the first time. *Pediastrum* shows a modest expansion that is unexpected, given the postulated soil stability. Soil stability may be the result of less precipitation. Dry conditions can be expected to favour pine which has wide ecological tolerances compared with most deciduous trees (Ellenberg, 1996).

GZ 4 points to somewhat increased erosion (cf. especially Al and REEs) but, overall, any changes were probably modest (highest sustained LOI values for the profile). The subdivision GZ 4a/4b corresponds with the PAZ 2d/3 boundary where *Alnus* expands which points to local presence of alder. At this time, the geochemical indicators suggest decreased erosion so it is unlikely that increased precipitation was involved as might be expected, given that alder is hygrophilous.

Environmental change in the mid to later Holocene (ca. 3700–770 BC)

The date 4000 BC is crucial in that it is now generally accepted that this date is at, or close to, the beginning of the Neolithic in Britain and Ireland (Collard et al., 2010; Whittle et al., 2011; Stevens and Fuller, 2012). Furthermore, a general consensus is now emerging that the first substantial Neolithic impact in Ireland registers at about 3700 BC (Cooney et al., 2011; McClatchie et al., 2012; Smyth, 2013; Whitehouse et al., 2013). Recent AMS ^{14}C dates from two Carrowmore passage tombs also suggest that the Carrowmore tombs were first used no earlier than about this time (Hensey and Bergh, 2013). In the CNY1 profile, the GZ 4/5 boundary is dated to 3765 BC while the PAZ 3/4 boundary is dated to 3715 BC (it is 1 cm higher in the profile). These boundaries are now considered in detail as they reflect substantial change that is potentially connected with the start of Neolithic farming.

To enable the changes in geochemistry and pollen — both change in quick succession — to be followed more closely, the main curves for the relevant interval centred on the early and mid Neolithic are plotted in Figure 7. A distinct change in the pollen data is initiated at the base of PAZ 3 (cf. NMS scores, Figs. 2 and 5) which is dated to 4155 BC. AP remains very high (96%) and NAP, consisting mainly of Poaceae and *Plantago lanceolata*, shows only slight expansion. NAPp averages only 1.6%. NAPp includes all NAP regarded as indicative of grassland as distinct from disturbed biotopes; the latter is referred to as NAPa and includes cereal-type pollen. NAPa makes only a minor contribution in PAZ 3 (average: 0.03%) and also in the following PAZs (mainly <1%). The *Plantago lanceolata* curve begins at the uppermost pollen spectrum of PAZ 3 (3730 BC), but it achieves only 0.9% which is very modest in the context of Irish pollen diagrams (cf. O'Connell and Molloy, 2001). At 430 cm the trend of decreasing *Ulmus* values is already well established (between adjacent samples 432 cm and 430 cm, *Ulmus* falls from 19.2% to 14.4%). The Elm Decline, i.e. PAZ 3/4 boundary, is placed 1 cm higher, i.e. between 430 cm and 429 cm.

The base of GZ 4b coincides with the base of PAZ 3 (ca. 4155 BC). The geochemistry suggests low levels of erosion until near the top of GZ 4b when erosional indicators begin to rise (GZ 4b/5 boundary is between samples 432/430 cm, i.e. at ca. 3765 BC). So it is assumed that stable conditions prevailed in the vicinity of the lake until that time, immediately after which the geochemistry indicates increased soil erosion and the pollen suggests initial opening-up of the woodland cover and modest expansion of open habitat (cf. *Plantago lanceolata*). That the disturbances recorded immediately before the Elm Decline were due to the onset of Neolithic farming is also quite plausible.

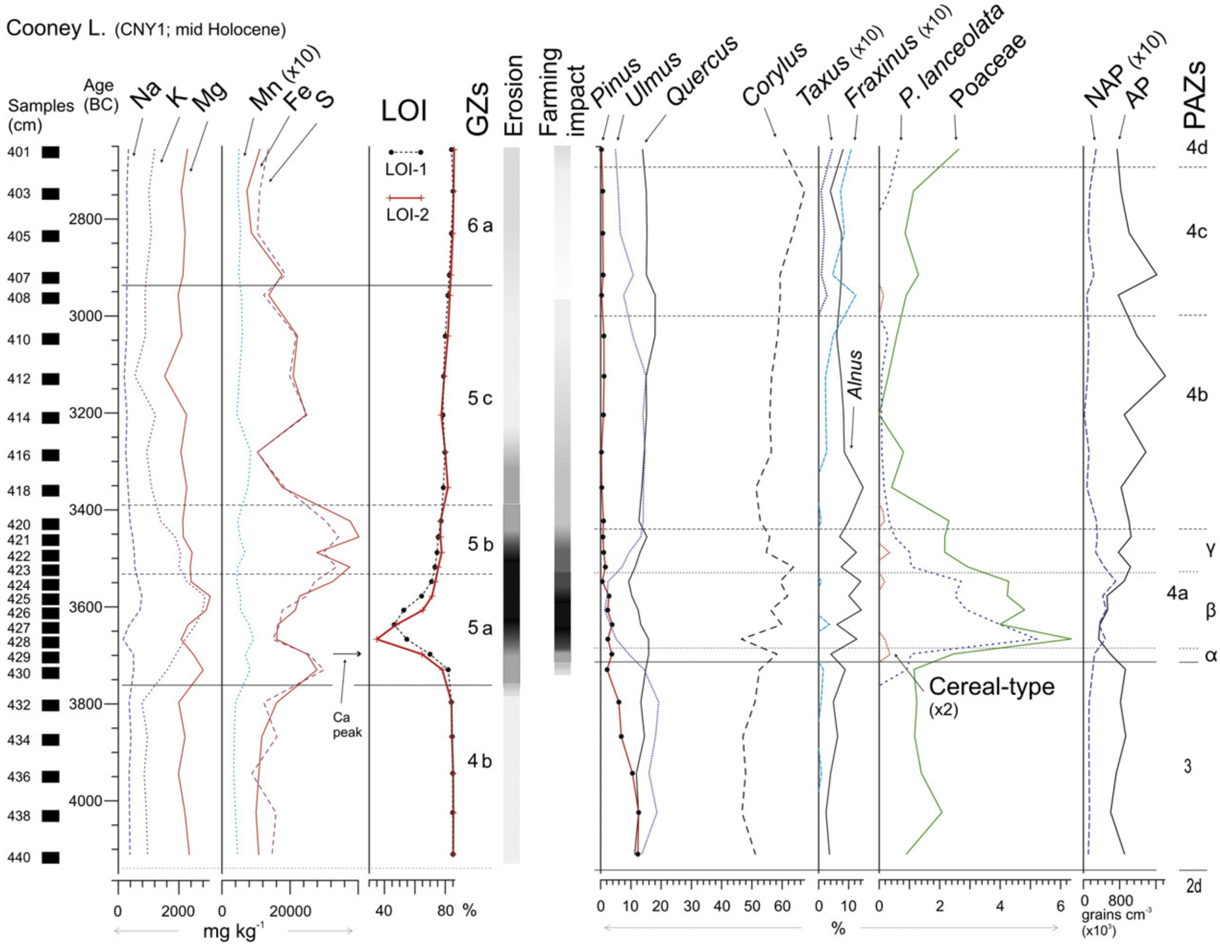

Figure 7. Plot, to a time scale, of selected curves (geochemical, and percentage and concentration pollen; note: selected curves are magnified with respect to the x-axis scale) from mid part of profile CNY1, Cooney L., i.e. from base of PAZ 3 (4110 BC; 440 cm) to bottom of PAZ 4d (2655 BC; 401 cm). Levels of soil erosion and farming impact as reflected by the geochemical and pollen records, respectively, are indicated schematically (darker indicates higher magnitude).

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By 3715 BC, there are strong indications of farming — predominantly pastoral but also arable — in the catchment (GZ 5a and PAZ 4aα and 4aβ). Initially, soils that were largely unweathered were eroded (429 cm; 3700 BC; note increase in alkalis, especially K) in the context of woodland clearances and limited arable farming. There were probably also limnic changes, including increased lake productivity that may be largely responsible for the spike in Ca values (see Results). The substantial soil erosion led to increased sediment accumulation (Fig. 6) and probably also changes in lake trophic status similar to that at L. Dargan, 7.6 km to the east, where chironomid and also $\delta^{15}N$ data indicate a distinct shift to more eutrophic conditions as a result of early Neolithic farming (Taylor et al., 2013). The main Landnam phase, i.e. woodland clearances in the context of farming (clearances were probably quite limited, especially if the elm population was decimated by disease as most likely was the case; micro-charcoal values also remain low), had a duration of ca. 150 yr, or 275 yr if the period with low farming impact represented by PAZ 4aα and 4aγ is included. The geochemical data suggest substantial erosion but the pollen data indicate rather modest impact. This difference suggests that clearances were probably spatially circumscribed, i.e. largely within the catchment so that there was relatively little impact in the wider region about the lake. This fits in with the low density of megaliths in this part of north Sligo. At L. Dargan, on the other hand, where there is a small cluster of megaliths, substantial early Neolithic impact, i.e. Landnam, is recorded in the interval 3760–3390 BC, i.e. it starts at about the same time as at Cooney L. but is of much longer duration and greater intensity (Ghilardi and O'Connell, 2013b, 2013c; Taylor et al., 2013).

The high Fe concentrations (also elevated Fe/Mn ratio) that characterise GZ 5b may be connected with development of reducing conditions in the soils of the catchment as human disturbance diminished and woodland regenerated (PAZ 4b). In this part of the profile, there is strong positive correlation between S and Fe (also Zn, and Mo to some extent). Co-precipitation of Fe and S (as iron sulphide) may have been facilitated by the development of anoxic conditions at the lake bottom and top of the sediment column (cf. Engstrom and Wright, 1984), as a result, for example, of lake-water stratification. A combination of land-use change, as indicated by the pollen, and climate change that affected runoff and also within-lake conditions, cannot, however, be excluded.

In PAZ 4c the interruption of the *Plantago lanceolata* curve (but Poaceae representation increases somewhat) suggests little or no farming. The geochemistry suggests that erosion continued to be rather important, at least until the end of GZ 6a (2105 BC). More or less all geochemical indicators suggest reduced erosion during GZ 6b (2105–1840 BC; Fig. 4). This is unexpected as the pollen indicates a strong renewal of farming activity at ca. 2175 BC (PAZ 5a; early Bronze Age). At L. Dargan, too, a distinct increase in farming impact begins at ca. 2125 BC. In Ireland generally, pollen records suggest a distinct increase in activity coinciding with the beginning of the Bronze Age and so the records from Cooney L. and L. Dargan serve to emphasise the increase in farming activity that took place at the beginning of the Bronze Age, especially in western Ireland (see Conclusions).

The relationship between geochemistry and pollen data in the upper part of the profile is rather weak. Clearly defined farming phases are identified from the pollen record (PAZs 5c, d and f, and 6). In the geochemical record, on the other hand, there are no large shifts apart from a major peak in P (GZ 7) which coincides with generally lower values for erosional indicators, including LOI. The pollen record indicates reduced activity so presumably the peak in P is mediated largely by within-lake changes that are unconnected with farming impact in the catchment.

Dilution, due to increased sediment accumulation which is assumed to be the result of higher lake productivity connected with increased inwash, is probably responsible for the poor responses shown by the geochemical data in the upper part of the profile. Geochemical features of note include the elevated Fe values (also S) immediately above the PAZ 5c/5d boundary which marks the beginning of a decline in farming in the mid Bronze Age (ca. 1500 BC) as reflected in the pollen record. There may have been a shift towards reducing conditions in the catchment soils as farming intensity declined. Most surprisingly, the major period of farming impact recorded in PAZ 6 (1155–935 BC) (pollen, micro-charcoal; also *Pediastrum* and *Glomus* chlamydospores which suggest soil inwash; cf. van Geel et al., 1989; van Geel et al., 2003) is only weakly reflected in the geochemical record. Erosional indicators show a small increase, largely confined to GZ 8c which corresponds to the lower part of PAZ 6b where the intensity of both pastoral and arable farming increases substantially. Fe concentration increases in GZ 9a, presumably due to a decrease in the redox potential of the soils in the catchment as farming intensity declined as the Bronze Age drew to a close (PAZ 7a).

Conclusions

The early part of the geochemical record (the record begins shortly after 7800 BC) supports the idea that, though the pollen and hence vegetation changes were relatively small and the landscape was fully wooded, moderate and changing levels of soil erosion persisted. The 8.2 ka event, which is well expressed in the pollen record, does not find clear expression in the geochemical record. The geochemistry, and especially the alkalis, suggests decreasing erosion for a considerable period (close on four centuries) prior to the 8.2 ka event, probably due to reduced precipitation and runoff. Climate recovery, that appears to have involved an over-correction of short duration (cf. Ghilardi and O'Connell, 2013a), is postulated to have led to the increase in geochemical erosion indicators probably as a result of increased precipitation.

The alkalis and especially K, and also Al, Ti and the REEs, are regarded as mainly reflecting mineral soil erosion while Fe and S (but not in the lowest part of the profile) are interpreted as mainly reflecting changing redox conditions, mainly in the catchment soils.

Early Neolithic impact (ca. 3715–3440 BC) is clearly expressed in the geochemical and pollen data. The former points to Neolithic farming being located within the catchment. The pollen suggests that Neolithic Landnam was relatively weak so it is concluded that the Neolithic clearances were not regional in character.

Between 3340 and 2700 BC, farming impact was low and the pollen hints at a local cessation of farming between ca. 3000 and 2700 BC. A similar lull — most likely a cessation in farming — is recorded in the nearby profile from L. Dargan (from ca. 3005–2705 BC; Ghilardi and O'Connell, 2013b, 2013c) and also in recently published profiles from the Carrowkeel/Keshcorran area in south Sligo (Stolze et al., 2012, 2013a, 2013b). The available evidence therefore points strongly to (a) a decline in farming, in those parts of Co. Sligo with detailed pollen diagrams, that had already started at ca. 3500 BC and (b) a break in farming activity for about three centuries beginning at ca. 3000 BC. As previously highlighted by O'Connell and Molloy (2001), human impact involving considerable, even if often localised, woodland clearance attributable to Neolithic farmers is concentrated in the early part of the Neolithic in western Ireland and indeed in Ireland generally. Recently available results of AMS ^{14}C dating programmes from Irish Neolithic rectangular houses (McSparron, 2008; Smyth, 2013; Whitehouse et al., 2013), megalithic tomb contexts (Schulting et al., 2012; Hensey and Bergh, 2013), cereal macrofossils (McClatchie et al., 2012; Whitehouse et al., 2013), and a comprehensive overview of the dating of the Neolithic in Britain and Ireland (Whittle et al., 2011), all serve to emphasise the high level of impact in the early part of the Irish Neolithic, i.e. starting in approximately the thirty eight century BC (before 3700 BC). What is not so clear is when and why the high levels of human impact ended. Whitehouse et al. (2013) have recently suggested, citing pollen evidence, that there was "a period of re-afforestation between ca. 3500 and 3000, which was widespread across Ireland" (this includes the initial part of what these authors refer to as a "*Plantago* Gap"). In many Irish pollen diagrams a decrease in *Plantago lanceolata* has commenced by ca.

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3500 BC but a gap, if present, starts some centuries later (at least two or more as in the Cooney L. profile and other recent detailed pollen diagrams from Sligo, e.g. Stolze et al., 2012, Ghilardi and O'Connell, 2013a, 2013b, 2013c; Stolze et al., 2013a, 2013b). There have been suggestions that the decline in farming was mainly induced by climate change (wetter and cooler; cf. Stolze et al., 2012, 2013b) but the evidence presented here and elsewhere is not entirely unambiguous in this respect (cf. Woodbridge et al., 2012; Ghilardi and O'Connell, 2013b).

At or shortly before 2100 BC, i.e. in the early Bronze Age, the pollen evidence (percentage and concentration data) suggests a distinct increase in farming, both pastoral and arable. Farming intensity oscillates, but overall continued to be much more intensive than during the Neolithic. It is assumed that this is connected with the start of the Bronze Age when farming activity increased substantially not only in north Sligo but also at several other sites in western Ireland (e.g. Molloy and O'Connell, 1995, 2004, 2012; Mitchell and Cooney, 2004; Mighall et al., 2008; Overland and O'Connell, 2008) and also in the wider British/Irish contexts. In Britain, however, the beginning of strong farming impact may relate more to the mid rather than the early Bronze Age (ca. 2100 BC versus 1500 BC) (Fyfe, 2012; Stevens and Fuller, 2012; Woodbridge et al., 2012).

At Cooney L. there is pronounced impact in the late Bronze Age (ca. 1155–935 BC), a feature also seen in the L. Dargan profile (1100–975 BC; Ghilardi and O'Connell, 2013b, 2013c) and in many other Irish pollen diagrams (e.g. Weir, 1995; Molloy, 2005; Plunkett, 2009; Molloy and O'Connell, 2012). Rather surprisingly, this late Bronze Age impact does not find strong expression in the geochemical record at Cooney L. A dilution effect may be operating, due to high sediment-accumulation rates that are probably largely attributable to human impact in the catchment.

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