

**A Multi-Proxy Holocene Palaeoenvironmental Record of
Climate Change and Prehistoric Human Activity from Lough
Cullin, southeast Ireland**

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Keywords:	Palaeoecology, Pollen Analysis, Chronology, Archaeology, Ireland, Human Impact, Climate
Abstract:	A multiproxy (pollen, microcharcoal, loss-on-ignition, magnetic susceptibility and geochemistry) sequence from Lough Cullin, southeast Ireland, supported by a high-resolution radiocarbon chronology, modelled using Bayesian approaches, provides a record of environmental change for much of the Holocene. Following the establishment of mixed deciduous woodland, climatic deterioration was likely responsible for pronounced vegetation change and erosion, 7615-6500 cal. BC to 6245-5575 cal. BC, evidence for the '8.2 Kyr' BP climate event. The so-called 'elm decline' is dated to 4220-3980 cal. BC and whilst there are possible indications of an anthropogenic cause, clear evidence of woodland clearance with cereal pollen is recorded at 3900-3700 cal. BC, 3790-3580 cal. BC and 3760-3650 cal. BC, during a period of clearance and farming of 320-450 years duration. A reduction in farming/settlement and woodland regeneration during the Middle Neolithic parallels the archaeological record, with low levels of activity during the Late Neolithic/Chalcolithic after 2960-2525 cal. BC, prior to increases during the Bronze Age then woodland clearance and agriculture between 1500-1410 and 1275-1000 cal. BC, corresponding with the archaeological evidence. A subsequent 'step-wise' reduction in human activity follows,

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	<p>from the latter date to 815-685 cal. BC, and a brief but pronounced cessation at 690-535 cal. BC. Renewed woodland clearance and agriculture commenced until 415-250 cal. BC. From the latter date until cal. AD 390-540, the Late Iron Age/Early Medieval period, a phase of woodland recovery is attested, followed by renewed landscape disturbance and arable agriculture in particular, continuing to the close of the record at cal. AD 780-1035.</p>

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3 54 ***Abstract.***
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5 55 A multiproxy (pollen, microcharcoal, loss-on-ignition, magnetic susceptibility and
6 56 geochemistry) sequence from Lough Cullin, southeast Ireland, supported by a high-resolution
7 57 radiocarbon chronology, modelled using Bayesian approaches, provides a record of
8 58 environmental change for much of the Holocene. Following the establishment of mixed
9 59 deciduous woodland, climatic deterioration was likely responsible for pronounced vegetation
10 60 change and erosion, 7615-6500 *cal. BC* to 6245-5575 *cal. BC*, evidence for the '8.2 Kyr' BP
11 61 climate event. The so-called 'elm decline' is dated to 4220-3980 *cal. BC* and whilst there are
12 62 possible indications of an anthropogenic cause, clear evidence of woodland clearance with
13 63 cereal pollen is recorded at 3900-3700 *cal. BC*, 3790-3580 *cal. BC* and 3760-3650 *cal. BC*,
14 64 during a period of clearance and farming of 320-450 *years* duration. A reduction in
15 65 farming/settlement and woodland regeneration during the Middle Neolithic parallels the
16 66 archaeological record, with low levels of activity during the Late Neolithic/Chalcolithic after
17 67 2960-2525 *cal. BC*, prior to increases during the Bronze Age then woodland clearance and
18 68 agriculture between 1500-1410 and 1275-1000 *cal. BC*, corresponding with the archaeological
19 69 evidence. A subsequent 'step-wise' reduction in human activity follows, from the latter date to
20 70 815-685 *cal. BC*, and a brief but pronounced cessation at 690-535 *cal. BC*. Renewed woodland
21 71 clearance and agriculture commenced until 415-250 *cal. BC*. From the latter date until *cal. AD*
22 72 390-540, the Late Iron Age/Early Medieval period, a phase of woodland recovery is attested,
23 73 followed by renewed landscape disturbance and arable agriculture in particular, continuing to
24 74 the close of the record at *cal. AD* 780-1035.
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43 76 **Keywords: Palaeoecology, Pollen Analysis, Chronology, Archaeology, Ireland.**
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45 77 **1. Introduction**
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47 78 Understanding the character and chronology of Holocene vegetation development and the
48 79 respective roles of climatic and anthropogenic impact on patterns and process of landscape
49 80 change is a key focus of palaeoecological research. There is a long history of such research in
50 81 Ireland, where the wide distribution of peatland and lake deposits provides the required
51 82 sampling sites, and investigations continue to provide new insights into environmental change.
52 83 Various questions concern the timing and character of human activity, climatic change and its
53 84 relationship to archaeology, continue to be a subject of ongoing debate (see Kelly and
54 85 O'Carragain 2021 for a summary). A particular methodological issue concerns the production
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3 86 of tightly constrained chronologies that are now available for the archaeological record
4 87 (Cooney *et al.* 2011; McClatchie *et al.* 2014; McLaughlin *et al.* 2016) and the utility of formal
5 88 modelling procedures to generate robust estimates of the tempo of environmental changes such
6 89 as those around the mid-Holocene 'elm decline' (e.g. Whitehouse *et al.* 2014; Kearney and
7 90 Gearey, 2020) and the Bronze Age to Iron Age transition (e.g. Gearey *et al.*, 2021). Whilst it
8 91 has long been largely common practice to use 'single point' estimates to describe
9 92 palaeoenvironmental chronologies, largely for reasons of perceived clarity of data presentation,
10 93 we utilise posterior density estimates, as these reflect the inherent probabilistic uncertainty
11 94 associated with radiocarbon dates. It is now usual in much archaeological research to present
12 95 chronological information in this way (Whittle *et al.* 2011). In order to allow meaningful,
13 96 robust comparisons between archaeological and palaeoenvironmental datasets, it is essential
14 97 we standardise chronological 'currencies' and hence develop a 'best practice' approach.

15 98 Recent detailed palaeoenvironmental studies have focussed on the west and north of the island
16 99 (e.g. Chique *et al.* 2017; Spencer *et al.* 2020; Stolze and Monecke 2020) but there has been
17 100 relatively little research in the southeast (see Eogan *et al.* 2015). In this paper, we describe and
18 101 discuss the results of a multi-proxy palaeoenvironmental analysis of a 7.75m core from Lough
19 102 Cullin, Co. Kilkenny, southeast Ireland, which is supported by a high-resolution radiocarbon
20 103 chronology. Compilation of archaeological evidence from the close vicinity of the sampling
21 104 site provides an independent record of the relative intensity of human activity through time.

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29 106 **2. Background**

30 107 Lough Cullin (52° 19' N, -7° 06' W). is a small lake (c.5 hectares) located in the catchment of
31 108 the river Suir, in the south of County Kilkenny, southeast Ireland. The lake is situated in a low-
32 109 lying landscape (11m OD), has a maximum depth of 3.4m and is fed by a series of small streams
33 110 from the north (with a stream flowing through a channel incised into the Lower Palaeozoic and
34 111 Devonian rocks at Catsrock), east and south. The outflow is via a small stream to the south-
35 112 west. The lake is nestled in the centre of a syncline, with the underlying geology of the lake
36 113 itself being well-bedded pale grey lower Dinantian limestones of the Ballysteen Formation
37 114 (Tietzsch-Tyler and Sleeman 1994, the Hook Head formation of Keeley 1983). The slope
38 115 increases significantly 2.5 km to the east and north of the lake basin, as the geology changes
39 116 from limestone to Devonian sandstones. The recession of the lake due to nineteenth century
40 117 drainage can be seen on the various editions of Ordnance Survey maps produced during the
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3 118 nineteenth and early twentieth centuries. John O'Donovan, who was one of the civilians
4 119 employed by the Ordnance Survey of Ireland in the 1830s and compiled the name books for
5 120 the Ordnance Survey, remarked: 'I remember this lake when it was of considerable extent. It
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7 121 is now nearly drained, and the bog nearly all cut out' (OSI, n.d.). There is also sedimentological
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9 122 evidence the lake was once larger, with lacustrine sediments filling an area of 2 km² around
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11 123 the lake. The presence of a glaciofluvial sand and gravel deposit to the north of the lake
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13 124 between it and the channel at Catsrock, suggests the lake may, partly at least, owe its origin to
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15 125 glacial meltwater.
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127 **3. Methods and Materials**

128 **3.1. Core sampling and lithostratigraphy.**

129 In June 2012, a 7.75 metre sediment core was extracted from the deepest part of the lake using
130 a Livingstone piston corer from a platform secured in the centre of the lake. The core was
131 extracted and wrapped on site, and later transferred to the lab where it was cut in half along its
132 length. One half was used for geochemical analysis, and both halves were subsampled at 1 cm
133 intervals down to 6.33 metres (the top of the clays).
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135 **3.2. Palynological analysis**

136 Sub-samples of 1 cm³ were prepared for pollen analyses following standard techniques
137 including KOH digestion, HF treatment and acetylation (Moore *et al.*, 1991). Pollen
138 concentrations were established by adding a known concentration of *Lycopodium clavatum*
139 spore (batch number 177745) to the samples before treatment (Stockmarr 1971). Pollen counts
140 were made using a Leica DM 1000 LED microscope at x400, x800 and x1000 magnification
141 under oil immersion for critical examination of pollen sculpture and measurement of pollen
142 grains. A minimum pollen sum of 400 Total Land Pollen (TLP) grains, excluding spores and
143 aquatics, was employed. Pollen grains were identified mainly using the key from Moore *et al.*
144 (1991) and Bennett (1995), with reference to Fægri *et al.* (1989). Pollen and spore identification
145 was made to the lowest taxonomic level possible using the available references and following
146 the nomenclature of Stace (1997), with suggestions from Bennett *et al.* (1994). The
147 programmes TILIA and TILIA - GRAPH (Grimm 2013) were used to construct spreadsheets
148 and pollen diagrams. Local pollen assemblage zones (LPAZ) were defined based on visible
149 changes in the pollen record.
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150 **3.3. Loss on Ignition (LoI)**

151 Sediment samples (*c.* 5 cm³) were taken at 2 cm intervals to calculate loss-on-ignition (LoI %).
152 The samples were dried for 24 hours at 105 °C and subsequently transferred to porcelain
153 crucibles and ashed for 4 hours at 550 °C (after Bengtsson and Enell, 1986; Heiri *et al.*, 2001).

154 **3.4. Geochemical analysis**

155 Geochemical analysis was carried out through non-destructive X-ray fluorescence (XRF) core
156 scanning of the split cores using a Cox Analytical Systems ITRAX XRF Core Scanner located
157 in the School of Geography, University College Dublin. 28 trace elements were selected for
158 analysis (Mg, Al, Si, P, S, Cl, Ar, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ge, As, Br, Rb, Sr, Y,
159 Zr, Ba, Nd, Pb, U), of which 10 key elements (Fe, Si, Ti, Ca, K, Sr, Rb, Mn, Cu, and Br) and
160 the ratio of inc:coh were chosen for interpretation. Cores were scanned at 600 µm step intervals
161 with a count time of 15 seconds, using a Mo tube operating at 30 kV and 30 mA.

162 The elemental data obtained are counts only, and so should be considered as semi-quantitative
163 in nature (Croudace *et al.* 2006; Weltje and Tjallingii 2008). The data was normalized using
164 kilo counts per second (kcps) to account for the variation in XRF intensities (Jouve *et al.* 2013;
165 Turner *et al.* 2015; Gregory *et al.* 2019). Relative elemental concentrations within a core can
166 provide valuable information on the sedimentology and palaeoclimatic history of an area
167 (Guyard *et al.* 2007), particularly when coupled with data from other methodologies.

168 Along with the geochemical data, the ITRAX scanner returns a profile of the magnetic
169 susceptibility (MS) measurement of the core at 4 mm resolution. MS is the amount of
170 magnetisation acquired by the sediments of the core due to the application of a weak magnetic
171 field. MS is related to the amount of dia- para- and ferrimagnetic minerals within the core
172 (Støren *et al.* 2016), and changes in MS can be indicative of sediment flux and erosion in lake
173 catchments (Evans and Slaymaker 2004).

175 **3.5. Chronology**

176 **3.5.1. Radiocarbon Dating**

177 Thirty-three samples (52 measurements in total) were dated by Accelerator Mass Spectrometry
178 at the Scottish Universities Environmental Research Centre (SUERC-), Queen's University
179 Belfast (UBA-) and Beta Analytic (Beta-). All measurements were obtained from organic
180 sediment samples except for *UBA-22422*, which was obtained from a branch fragment of *Salix*

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3 181 sp. (willow). Where possible, duplicate measurements on the humin (the acid and alkali-
4 182 insoluble) and humic (alkali-soluble, acid insoluble) fractions (Cook *et al.* 1998, 21) were
5 183 obtained to test the reliability of sediment derived radiocarbon determinations (cf. Brock *et al.*
6 184 2011) and the statistical consistency (Ward and Wilson 1978) of each paired date assessed
7 185 using the OxCal (Bronk Ramsey 2009a) programme.

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12 186 The resulting radiocarbon determinations are presented as conventional radiocarbon ages
13 187 (Stuiver and Polach 1977) quoted in accordance with the international standard established by
14 188 the Trondheim Convention (Stuiver and Kra 1986). The calibrations have been calculated using
15 189 the published datasets, IntCal20, (Reimer *et al.* 2020) and the computer program OxCal v4.3
16 190 (Bronk Ramsey 2009a) and are cited with the end points rounded outward to 10 years. The
17 191 calibrated date ranges have been calculated using the maximum intercept method (Stuiver and
18 192 Reimer 1986) and the graphical distribution of the calibrated result derived from the probability
19 193 method (Stuiver and Reimer 1993). All radiocarbon dates are cited at 95.4% confidence, unless
20 194 stated otherwise.

21 195 22 23 24 25 26 27 28 29 30 196 **3.5.2. Bayesian Modelling.**

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33 197 In order to refine the chronology of palynological features and extend the chronological
34 198 framework to changes which fall between dated horizons, a Bayesian approach was employed
35 199 to the modelling of the radiocarbon dates (Buck *et al.* 1992). The Bayesian approach has been
36 200 widely discussed in the literature (e.g. Blaauw and Christensen 2005; Blaauw *et al.* 2007a;
37 201 Blaauw *et al.* 2007b; Bronk Ramsey 2008). The approach taken here uses the software OxCal
38 202 v4.3 program (Bronk Ramsey 2009a), and the *P_Sequence* function (Bronk Ramsey 2008) was
39 203 chosen to allow for a Poisson process, or a potentially random rate, of sediment formation. The
40 204 prior information for the deposition rate was defined as $\log_{10}(k/k_0)$ where $k_0 = 1$. This
41 205 allows k to take any value from 0.01–100. This value used was estimated from the radiocarbon
42 206 dates following the approach outlined in Blockley *et al.* (2007; 2008)

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45 207 The command *Outlier()* was used in OxCal (Bronk Ramsey 2009b) to identify any
46 208 measurements that were statistically defined as outliers at a 0.05 probability (1 in 20 chance).
47 209 The model has been constrained using *Boundaries*, the depths of which have been defined
48 210 based on stratigraphic changes (see below). The ranges quoted in italics are *posterior density*
49 211 *estimates*, derived from this Bayesian modelling of the radiocarbon chronology (Bayliss *et al.*
50 212 2007) and are cited at 95.4% probability, unless stated otherwise.

213 4. Results.

214 4.1. Stratigraphy.

215 The core lithology was (from top to bottom) light grey, organic-rich sediment (0 - 1.75 m);
216 dark brown gyttja (1.75 m - 6.26 m), with a layer of sandier gyttja between 5.55 m and 5.74 m.
217 The gyttja lies above 6 cm of sand (6.26 m - 6.32 m). At the base of the sequence was 1.65
218 metres of laminated grey-brown silty clay, with an angular pebble within the sediment at 7
219 metres.

221 4.2. Palynological analysis.

222 A total of forty-nine different taxa, including spores, were recorded across the Lough Cullin
223 pollen profile. The data is presented in Table 1 and the percentage pollen diagram LC (Figure
224 2) and pollen concentration diagram (Figure 3) have been divided in 13 local pollen assemblage
225 zones (LPAZ). LPAZ boundaries are given as *posterior density estimates* derived from the age-
226 depth model shown in Figure 5. In addition, a curve for ‘anthropogenic indicator’ (*sensu* Behre
227 1981) taxa has been calculated (comprising *Cerealia*-type, *Artemisia*-type, Asteraceae undif.,
228 Caryophyllaceae, *Plantago lanceolata*, *Plantago major/media*, *Rumex*, *Trifolium*-type, and
229 *Urtica dioica*).

231 4.3. Loss on Ignition (LoI), Magnetic Susceptibility (MS) and Geochemistry

232 The results of loss on ignition are presented in Table 1 and, with the results of geochemistry
233 and magnetic susceptibility analyses, shown in Figure 4. Zonation for LoI data follows the
234 LPAZ used in the pollen diagram. LoI results are relatively stable throughout the sequence,
235 with some generally minor fluctuations. However, there is a marked decrease in LoI values at
236 5.09 m, with a significant and more sudden decrease at 4.90 m, possibly indicating accelerated
237 minerogenic sedimentation into the lake. LoI begins to increase at 3.14 m to a peak at 2.15 m,
238 from where it decreases to the top of the core.

239 The geochemical data, given the high resolution, is ‘noisy’ and must be interpreted with some
240 caution. These data do not always track the changes in LoI, but there are observable patterns
241 which may be hypothesised as reflecting weathering and erosion of different areas of the
242 catchment: in particular, increased values for Calcium (Ca) may derive predominantly from the
243 limestone bedrock areas (see above, Section 2), with Iron (Fe) from the sandstone areas. The

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3 244 latter element does not consistently track the MS curve, possibly because of the dissolution of
4 245 magnetic minerals.

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9 247 **4.4. Chronology**

11 248 **4.4.1. Radiocarbon dating and Bayesian modelling.**

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14 249 The measurement on the humic fraction GU43402 from 2.61m failed, therefore the humin
15 250 measurement (SUERC-72571) from this depth was used in the model. Four pairs of
16 251 measurements from 2.65m (SUERC-70823 and SUERC-70824), 2.71m (SUERC-70825 and
17 252 SUERC-70826), 3.26m (SUERC-76326 and SUERC-76666) and 5.34m (SUERC-70843 and
18 253 SUERC-70844) are not statistically consistent (see Table 2). In all instances the humic fraction
19 254 is younger than the humin fraction; this is likely caused by the downwards penetration of humic
20 255 acids from above, therefore the humin fractions (SUERC-70824, SUERC-70826, SUERC-
21 256 76666 and SUERC-70844) have been used in the modelling process for these depths.
22 257 Measurement UBA-22422, a fragment of *Salix* (willow) twig, was identified as a possible
23 258 outlier and has been excluded from the model; this determination was considerably older than
24 259 those below it, suggesting that reworked material had been incorporated into the profile.

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33 260 An age-depth model (Bronk Ramsey 2008) for the profile was constructed to provide a
34 261 chronology for the sequence. The *P_Sequence* model (Figure 5) has good agreement
35 262 ($A_{\text{model}}=99$) and has been used to provide estimates for the boundaries between the local pollen
36 263 assemblage zones (Table 1). Except for UBA-22422 (the *Salix* twig) the model shows good
37 264 agreement, suggesting the sequence is intact below 2.19m.

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42 265 The pollen sequence can be estimated to cover a period of 8830-9560 years (95.4% probability,
43 266 distribution not shown), probably 9060-9330 years (68.2% probability, distribution not
44 267 shown). Estimates derived from the age-depth model suggest an average deposition rate of 4-
45 268 5 cm/100yr (distribution not shown) between the upper and basal radiocarbon measurements;
46 269 it can be estimated that 21-23 years (distribution not shown) are represented in every
47 270 centimetre.

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53 271 The effectiveness of the model can be seen by considering the radiocarbon determination UBA-
54 272 22423: this provided a calibrated (unmodelled) date of 750-400 cal. BC. The output on the
55 273 model (Figure 5) constrained this to 595-445 cal. BC (Figure 5), a significant reduction in the
56 274 bandwidth, from 350 to 150 years. This reduction was partly achieved through obtaining two
57 275 determinations that fell on the 'steep' part of the radiocarbon calibration curve (SUERC-70824

276 and Beta-426775) thus helping to constrain the determinations between them, in particular
277 those on the 'Hallstatt plateau'.

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279 **5. Interpretation**

280 LC-1: 6.25-6.03m, 9050-8090 cal. BC to 7615-6500 cal. BC

281 The pollen diagram covers much of the Holocene from 9030-8065 cal. BC to cal. AD 780-
282 1035, the Early Mesolithic to the Medieval period. *Quercus* (oak) and *Ulmus* (elm) are well
283 established from the base of the sequence and constitute the main tall canopy trees in the
284 landscape around Lough Cullin. *Corylus avellana*-type (probably largely hazel) is abundant,
285 comprising a major component of the vegetation, probably as an under-storey shrub, while
286 *Betula* (birch) and *Salix* (willow) had minor presences in the landscape. Low values for non-
287 arboreal pollen (NAP), <5%, suggest the woodland had a rather closed structure. The presence
288 of *Hedera helix* (ivy) and *Polypodium vulgare* (common polypody) probably indicate the
289 presence of epiphytes (Molloy and O'Connell 1991).

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291 LC-2: 6.03-5.88m, 7615-6500 cal. BC to 6245-5575 cal. BC

292 Zone LC-2 is marked by a decrease in hazel (c.50% to 30%) and oak (c.30% to 20%) and
293 corresponding increases in *Pinus sylvestris* (Scots' pine) (c.4% to 20%) and birch (c.4% to
294 15%) between 5.97 to 5.93m. Hazel falls to its lowest value for the zone at 5.89m,
295 corresponding to a peak in birch; whilst oak reaches its lowest percentage at 5.93m, at which
296 point pine demonstrates a clear peak, attaining its highest values for the entire sequence before
297 falling again. There are also reductions in elm and ivy apparent across these levels. Total NAP
298 values do not show any fluctuations, suggesting the vegetation changes involved the woodland
299 canopy taxa. Total pollen concentrations display a marked reduction across these levels, from
300 232×10^3 to 155×10^3 grains cm^{-3} , which may reflect fluctuations in relative pollen productivity.

301 In terms of geochemistry, this zone sees the highest values for Ti, Ca and Mn for the entire
302 diagram, tracking increasing values for MS, although LoI percentages remain fairly steady
303 (c.30%). This pattern may indicate a change in the source of inorganic material eroded from
304 the catchment, with weathering of the soils on the limestone (Ca) as well as the sandstone
305 bedrock (Fe) implied. These fluctuations are closely associated with the changes in woodland
306 composition outlined above. Taken collectively, the data may well indicate the impact of

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3 307 climatic deterioration, with destabilised soils across the catchment associated with pronounced
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5 308 declines in thermophilous arboreal taxa (oak, hazel, elm and ivy), and related expansion in
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7 309 trees/shrubs (pine and birch) tolerant of colder conditions.

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9 310 Towards the top of LC-2, *Alnus glutinosa* (alder) percentages begin to rise, implying the
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11 311 establishment of this tree, probably as alder carr at the lake edge. The date for the establishment
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13 312 of alder (5.89m, 6350-5910 cal. BC, the 'rational limit', *sensu* Smith and Pilcher 1978) appears
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15 313 to be slightly earlier than elsewhere across Ireland. This spread and expansion of alder post-
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17 314 7000 BP appears to have been erratic in space and time (Bennett and Birks 1990): for example,
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19 315 alder became established after 5490-5010 cal. BC (6315±110, *D-115*) at Belle Lake (Craig
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21 316 1978), after 5480-5070 cal. BC (6330±80, *Beta-65095*) at Clara Bog (Connolly 1999; Crushell
22
23 317 *et al.* 2008), whilst at Lough Kinale (Ballywillin Crannog core) this tree expanded after 5720-
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25 318 5560 cal. BC (6720±40, *Beta-173320*; Brown *et al.* 2005; Selby *et al.* 2005).

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27 320 LC-3: 5.88-5.19m, 6245-5575 cal. BC to 4320-4020 cal. BC

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29 321 By the close of LC-2, oak and hazel recovered as the dominant woodland taxa. Arboreal taxa
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31 322 remain very well represented in LC-3 (minimum 95%) with few other marked changes.
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33 323 However, *Ilex aquifolium* (holly) is recorded from midway through the zone (5.30m): this shrub
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35 324 tends to become established in more open conditions (Molloy and O'Connell 1987), but there
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37 325 is no evidence of significant changes to the woodland structure that might suggest disturbance
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39 326 similar to the previous zone. Indicators of open environments such as *Plantago lanceolata*
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41 327 (ribwort plantain), are present only sporadically prior to the establishment of holly, but cease
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43 328 during the initial expansion of the latter. The low levels of NAP (<5%) suggest open
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45 329 environments were limited, although the extent of openness will have been greater than implied
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47 330 by the percentages.

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49 331 The LoI values do not show any marked changes, falling slightly towards the top of the zone.
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51 332 The geochemical data show reductions for Ca and Mn, although there are increases in Mn
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53 333 midway through the zone. Fluctuating values for Fe with pronounced decreases at the top and
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55 334 base of the zone are apparent. These fluctuations are slightly enigmatic but might imply some
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57 335 destabilisation of the local soils, albeit not on a similar scale to LC-2.

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3 338 LC-4a: 5.90-5.01m, 4320-4020 cal. BC to 4050-3960 cal. BC
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5 339 Zone LC-4a is defined by a pronounced reduction in elm from 4220-3980 cal. BC,
6 340 accompanied by a temporary fall in hazel, although other arboreal taxa remain steady. NAP
7 341 increases (c.10%), primarily Poaceae (grass), but with sporadic grains of other herbs including
8 342 ribwort plantain, Asteraceae (daisies) and Caryophyllaceae (pink family). There are decreases
9 343 in LoI percentages across the zone coincident with increasing anthropogenic indicators,
10 344 indicating increased mineral inwash into the lake and/or changes in accumulation rates
11 345 associated with the reduction in woodland and expansion of open environments. This is
12 346 supported by the rather abrupt fluctuations in Ti, Fe and Ca, indicating weathering and erosion
13 347 in the lake catchment, again potentially involving soils on both the limestone and sandstone
14 348 geologies.
15

16 349

17 350 LC-4b: 5.01-4.82m, 4050-3960 cal. BC to 3860-3650 cal. BC and LC4c: 4.82-4.71m, 3860-
18 351 3650 cal. BC to 3685-3530 cal. BC
19

20 352 Further reductions in arboreal pollen (AP), c. 80%, specifically oak and hazel are recorded
21 353 from 4040-3910 cal. BC, with rises in NAP (c. 20%) and a greater diversity of ruderal
22 354 herbaceous taxa including ribwort plantain, Ranunculaceae (buttercups), *Rumex* (docks),
23 355 daisies, *Artemisia*-type (mugwort) and *Urtica dioica* (nettles). This indicates the expansion of
24 356 open, pastoral environments, at the expense of deciduous woodland, especially oak but with
25 357 hazel affected to a lesser degree. The identification of *Cerealia*-type (cereal) grains at: 3890-
26 358 3700 cal. BC, 3790-3580 cal. BC and 3760-3560 cal. BC demonstrate arable farming in the
27 359 pollen catchment. The LoI percentages show an abrupt drop to their lowest values for the entire
28 360 sequence (4.90m) corresponding to a peak in total anthropogenic indicators, followed by an
29 361 equally abrupt recovery, indicating inwash of minerogenic material. There are no clear
30 362 corresponding changes in the geochemistry, other than some fluctuations in Ti, nor does the
31 363 MS show any response.
32

33 364 This phase lasted until 3860-3650 cal. BC, at which point AP began to recover (LC-4c).
34 365 However, although there are reductions in NAP across this subzone, anthropogenic indicators
35 366 including ribwort plantain and cereal-type are still recorded. The impression is of clearance of
36 367 woodland and some destabilisation of soils during LC-4b, followed by a less intense period of
37 368 human activity with some recovery of trees and shrubs in LC-4c. The initial phase lasted for
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3 369 70-320 years, and the subsequent phase 10-270 years, with the pollen data implying both
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5 370 pastoral and arable land-use.
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9 372 LC-5: 4.71-4.35m, 3685-3530 cal. BC to 3355-3120 cal. BC and LC-6; 4.38-4.08m, 3355-3120
10
11 373 cal. BC to 2960-2525 cal. BC
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13 374 The overall AP values increase, especially elm, and the ribwort plantain curve is interrupted,
14
15 375 reflecting woodland recovery. Elm populations regenerated, although not to their previous
16
17 376 extent, while *Fraxinus* (ash) played an increased role in the arboreal vegetation dynamics,
18
19 377 presumably expanding into the gaps created in the woodland in LC-4. This recovery of elm
20
21 378 and associated woodland regeneration was sustained until 3310-3090 cal. BC, when a second
22
23 379 reduction in elm is apparent, primarily concomitant with increased representation of alder, a
24
25 380 slight increase in ash and marginally increased levels of NAP, primarily in wet-loving taxa
26
27 381 such as Cyperaceae (sedges) and *Filipendula* (meadowsweet). This suggests the expansion of
28
29 382 wetland environments, probably in the form of alder carr at the lake's edge, perhaps as
30
31 383 processes of hydrosere succession created favourable habitats. The muted response in NAP
32
33 384 aside from the wetland taxa, raises questions concerning the cause and process of the decline
34
35 385 in elm (see below). LoI values are stable (c.36%) across LC-5 and LC-6 but decline towards
36
37 386 the top of the latter zone (c.30%). Some fluctuations in Fe are recorded, possibly indicating
38
39 387 changes in the source of the minerogenic input into the lake.
40

41 389 LC-7a: 4.08-3.90m, 2960-2525 cal. BC to 2620-2240 cal. BC
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43 390 A small but pronounced reduction in AP and re-establishment of a continuous curve for ribwort
44
45 391 plantain and other light demanding ruderal/grassland taxa (including buttercups, daisies,
46
47 392 mugwort, Lactuceae (dandelions etc.) are apparent from 2960-2525 cal. BC, indicating an
48
49 393 expansion of open, meadow environments. The woodland regeneration phase in the previous
50
51 394 zones (LC-5 and 6) lasted between 660-1120 years. The appearance of cereal-type pollen at
52
53 395 2860-2420 cal. BC suggests arable farming around Lough Cullin. After the latter date, NAP
54
55 396 continues to increase at the expense of primarily hazel and oak. Charcoal shows a slight
56
57 397 increase and loss on ignition values are generally stable (c.30-34%); MS values increase
58
59 398 coincident with a spike in Fe at c.4m, the highest values for anthropogenic indicators for this
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400 399 zone. These data collectively indicate catchment scale disturbance, related to the evidence for
woodland reduction and the expansion of open environments.

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3 401 LC-7b: 3.90-3.56m, 2620-2240 to 1880-1740 cal. BC and LC-7c: 3.56-3.34m, 1880-1740 to
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5 402 1500-1410 cal. BC
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7 403 Zone LC-7b is primarily defined on the basis of steadily increasing NAP, primarily grasses,
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9 404 with continuing low values of other herbs, suggesting open areas persisted but were of limited
10
11 405 extent. Low values of microcharcoal are recorded, indicating restricted burning during this
12
13 406 zone. This picture changes at the transition from LC-7b to LC-7c, around the Middle Bronze
14
15 407 Age (1880-1740 cal. BC), with increases in ribwort plantain and the appearance of other
16
17 408 anthropogenic indicators including dandelions and docks towards the close of the zone,
18
19 409 reflecting an expansion in open, pastoral environments. However, percentages of arboreal
20
21 410 pollen remain relatively steady, although there are fluctuations in hazel values. Charcoal values
22
23 411 do not increase. The overall impression is of some expansion in open grassland environments,
24
25 412 but only small decreases in woodland cover. The LoI values are largely stable, rising slightly
26
27 413 across 7b (from c. 30 to 40%) before falling slightly across 7c. There are no clear changes in
28
29 414 the MS or geochemical data other than a rise in Ca, possibly indicating disturbance on the
30
31 415 limestone areas.
32

33 416
34 417 LC-8: 3.34-3.14m, 1500-1410 to 1275-1000 cal. BC

35 418 The opening of LC-8 marks the beginning of a period of intensive human impact on the
36
37 419 environment, the most pronounced recorded for the entire sequence. This seems to follow a
38
39 420 brief period of reduced impact at the opening of the zone with reduced total anthropogenic
40
41 421 indicators and increases in hazel, followed by a very pronounced increase in NAP (c. 45%),
42
43 422 especially grasses, and associated decline in AP demonstrating a significant opening up of the
44
45 423 woodland cover. The rising values for ribwort plantain (peaking c.7%) alongside grasses and
46
47 424 to a lesser extent sedges, demonstrate the expansion of open, pastoral environments to form the
48
49 425 greater proportion of the landscape around the lake. The occurrence of a single grain of cereal-
50
51 426 type pollen at 3.20m (1380-1220 cal. BC) indicates arable farming. There are also reductions
52
53 427 in alder, suggesting the alder carr on the wetter soils, probably close to the lake edges, were
54
55 428 affected by clearance at this time.

56 429 However, a relatively restricted range of herbs is recorded: Chenopodiaceae (fat fen family),
57
58 430 buttercups and *Succisa* (devil's bit scabious) appear alongside the peak of ribwort plantain, all
59
60 431 of which are typical of open grassland/meadow environments. The concomitant increase in
432 *Pteridium aquilinum* (bracken) across this zone is further evidence for the opening up of

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3 433 the landscape on drier soils, whilst a spike in charcoal demonstrates increased burning. The
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5 434 LoI percentages fall, generally tracking the increase in NAP, whilst in the geochemical data,
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7 435 Fe also shows pronounced peaks at the opening and close of the zone, coincident with small
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9 436 rises in Mn and Ti, and increases in the MS curves.

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11 437 The combined data seem to indicate a short episode of reduced human activity and the recovery
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13 438 of shrubs, prior to intensive clearance and farming leading to soil disturbance across the
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15 439 catchment. Overall, the period between *1500-1410* and *1275-1000 cal. BC* was one of
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17 440 woodland reduction. Most parts of the landscape were affected, from the fertile dryland soils
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19 441 through to the 'marginal' wetland contexts. There is evidence for farming, predominantly of a
20
21 442 pastoral character, and since cultivation is significantly underrepresented palynologically,
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23 443 arable plots were also present locally.

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25 444
26 445 LC-9: 3.14-2.925m, *1275-1000 cal. BC* to *815-685 cal. BC* and LC-10: 2.925-2.82m, *815-685*
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28 446 *cal. BC* to *690-535 cal. BC*

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30 447 The previous period of woodland clearance and farming was followed by the recovery of
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32 448 woodland taxa (50-60%), especially hazel, oak and alder, accompanied by reductions in grasses
33
34 449 and ribwort plantain (LC-9). However, increased diversity in herbs is recorded, specifically the
35
36 450 anthropogenic indicators fat hen family, nettles and dandelions. Micro-charcoal values also
37
38 451 increase, whilst a single cereal grain coincides with the peak in ribwort plantain at *1020-915*
39
40 452 *cal. BC* indicating the presence of arable and pastoral habitats.

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42 453 However, the subsequent zone, LC-10, is notable for a marked fall in ribwort plantain and
43
44 454 recovery of AP, especially hazel and oak, but with elm values also forming a low but consistent
45
46 455 curve for much of the zone. Elm tends to thrive on fertile, better- drained soils that are often
47
48 456 suitable for arable agriculture (as observed in the previous zones), implying that trees and
49
50 457 shrubs re-colonised much of the landscape. The almost complete absence of microcharcoal also
51
52 458 contributes to the impression of little anthropogenic activity, until the close of the zone. There
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54 459 is a small but sustained increase in LoI across the zone, with Fe values reduced relative to the
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56 460 previous zone, suggesting some stabilisation of the catchment soils related to the recovery of
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58 461 the woodland.

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3 464 LC-11: 2.82-2.64m, 690-535 cal. BC to 415-250 cal. BC and LC-12: 2.64-2.36m, 415-250 cal.
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5 465 BC to 390-540 cal. AD
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7 466 The landscape changed again at the opening of LC-11, with a fairly abrupt increase in ribwort
8
9 467 plantain defining the zone transition, suggesting opening of the landscape. The response from
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11 468 other herbs, grasses included, is slightly muted, although levels of dandelions rise towards the
12
13 469 close of the zone and there are occasional records of other grains such as mugwort, fat hen
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15 470 family, meadowsweet and buttercups. There is a steady reduction in hazel across the zone and
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17 471 oak also displays a fall, following a peak at the opening of the zone, contributing to falling AP
18
19 472 from *c.*90% to 70% across the zone. Total anthropogenic indicators reach their highest
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21 473 percentage at the top of LC-11, at which point cereal-type pollen is recorded at 430-360 cal.
22
23 474 BC. However, microcharcoal values show only modest increases. The record therefore
24
25 475 indicates a resurgence in human activity, which led initially to an expansion in grassland and
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27 476 pasture and the clearance of areas of woodland, with evidence for arable cultivation towards
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29 477 the end of the zone.

30 478 Almost immediately following the peak in pastoral and arable farming, there is evidence for
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32 479 what can only be described, on the basis of the pollen record, as the apparent possibly complete
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34 480 cessation of human activity. This is manifested through an abrupt drop in ribwort plantain at
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36 481 the opening of LC-12, and the disappearance of this species for the entire zone. Grasses also
37
38 482 display a slight reduction, whilst few other herbs are recorded. Microcharcoal values are
39
40 483 minimal and absent from the middle section of the zone, closely paralleling the behaviour of
41
42 484 total anthropogenic indicators. AP percentages increase, mainly hazel and oak, but with some
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44 485 recovery in elm and birch. Overall, from around 415-250 cal. BC to 390-540 cal. AD, woodland
45
46 486 dominated the landscape around Lough Cullin.
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49 488 LC-13: 2.36-2.15m, cal. AD 390-540 to cal. AD 780-1035

50 489 The final zone, LC-13, opens with the relatively abrupt resumption of the ribwort plantain
51
52 490 curve, a steady rise in grasses and reductions in hazel and subsequently oak. Elm effectively
53
54 491 disappears from the record and microcharcoal values also increase. Other herbs reappear
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56 492 including docks, mugworts and daisies etc., all of which form continuous curves. Total
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58 493 anthropogenic indicators demonstrate a marked increase whilst cereal-type pollen is recorded
59
60 494 in almost all levels, indicating a significant expansion and persistence of arable cultivation in
495 the pollen source area. Despite this, the maintenance of AP (*c.*80%) until the close of the

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3 496 diagram, suggests sizable areas of woodland remained locally. The diagram closes at *cal. AD*
4 497 *780-1035* with an indication of renewed falls in arboreal taxa suggesting further anthropogenic
5 498 pressure on the woodland. There is a hint that by this time, clearance of woodland was starting
6 499 to impact all parts of the landscape again, with alder falling to its lowest values since LPAZ
7 500 LC-2. The LoI values increase across the zone, with the rising values for Fe that began in LC-
8 501 12 also continuing.

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503 **6. Discussion**

504 *Overview*

505 The Lough Cullin sequence provides a record of vegetation change from the Early Mesolithic
506 (*9050-8090 cal. BC*) through to the Medieval period (*cal. AD 780-1035*), a period of *10020-*
507 *9025 years*. A series of phases of expansions and contractions of AP and NAP are apparent:
508 with one exception (see below), these appear to reflect human disturbance, characterized by
509 increases in taxa indicative of open, pastoral environments and disturbed soils (especially
510 ribwort plantain, grasses, docks, dandelions and occasional grains of cereal pollen suggesting
511 arable agriculture) and falls in values of tree/shrub pollen showing contraction in
512 wood/scrubland.

513 It should be noted total tree and shrub pollen percentages rarely drop below 75% of total land
514 pollen for the entire record, implying that although herbaceous taxa are probably
515 underrepresented palynologically (Caseldine and Fyfe 2006), wood/scrub cover remained of
516 greater extent than open ground, even during episodes of human impact and woodland
517 clearance (see below). Episodes of intensified human activity seem to have impacted most on
518 the populations of hazel and oak, with elm affected at some points, especially at the start of the
519 Neolithic (*4040-3900 cal. BC*). The behaviour of *Fraxinus* (ash) suggests this fast growing and
520 light demanding tree was favoured by the opening up of the woodland canopy during episodes
521 of increased human activity (Caseldine and Hatton 1996).

522 The values for microcharcoal, an indicator of the frequency of burning in the landscape around
523 the site (probably mainly from domestic fires, but potentially from natural burns), closely track
524 these phases, with increased values associated with rises in pollen taxa indicating human
525 activity. Microcharcoal falls noticeably during episodes of woodland recovery. The
526 fluctuations in the LoI, MS and geochemical data provide additional information concerning
527 the patterns of inwash and provenance of inorganic material into the Lough during the episodes

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3 528 of landscape disturbance. On the basis of these data, the most pronounced episodes of
4 529 weathering at the catchment scale by far occurred during LC2, 4a, 7a and 7c, with the first
5 530 presenting the clearest signal for the entire record.
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11 532 *The 8.2ka Event: Climatic forcing and vegetation change (LC-2)*
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13 533 The earlier Holocene landscape was dominated by deciduous woodland, consisting
14 534 predominantly of hazel, oak and elm, with some birch and willow probably growing on the
15 535 damper soils. Scots' pine was probably growing locally, despite the possibility of long-distance
16 536 transport of this species' pollen (Pilcher *et al.* 1995, cf. Lageard *et al.* 1999). This limited
17 537 representation is comparable with records from the east and midlands (e.g. Caseldine and
18 538 Hatton 1996; Selby *et al.* 2005), although Scots' pine had become established locally at Kelly's
19 539 Lough, Co. Wicklow (Leira *et al.* 2007) by 7450-7070 cal. BC (8220±50 BP, β -173463).
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25 540 The abrupt reduction in hazel and oak in LC-2 indicates significant changes in this woodland
26 541 composition, also reflected by a pronounced fall in pollen concentrations. Hazel pollen
27 542 production can be adversely affected by climatic shifts such as air frosts, drought or excessive
28 543 precipitation levels (Tallantire 2002), while oak is also sensitive to early spring and autumn
29 544 frosts (Giesecke *et al.* 2008). On the other hand, pine and birch are tolerant of low summer
30 545 temperatures and can be rapid colonisers, given suitable conditions (Atkinson 1992;
31 546 Richardson and Rundel 1998; Paus 2010). The expansion of pine and birch alongside the small
32 547 increases in NAP, and the fluctuations in the geochemical, LoI and MS data, can be interpreted
33 548 as the impact of climatic deterioration, possibly a shift to a more continental climate, with
34 549 colder winters but also lower summer temperatures and a considerably lower annual thermal
35 550 sum (cf. Huntley 2012).
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43 551 The date range at Lough Cullin (7120-6230 cal. BC to 6350-5910 cal. BC) correlates with
44 552 climate anomalies in the Greenland ice-core records (Rasmussen *et al.* 2007; Thomas *et al.*
45 553 2007) between 8.5 and 7.9 kyr BP (Rohling and Pälike 2005). This climatic deterioration might
46 554 have resulted from changes in the strength of the Atlantic meridional overturning circulation
47 555 (cf. Alley *et al.* 1997; Alley and Ágústsdóttir 2005; Ellison *et al.* 2006; Hede *et al.* 2010),
48 556 leading to colder and drier conditions in the North Atlantic region (Alley *et al.* 1997; Barber *et*
49 557 *al.* 1999; Alley and Ágústsdóttir 2005; Wiersma and Renssen 2006). The clear
50 558 palaeoenvironmental signature at Lough Cullin provides persuasive evidence for the impact of
51 559 this climatic 'event' on the eastern as well as western seaboard of Ireland, with the chronology
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3 560 of the increase in Scots' pine overlapping with dendrochronological evidence for expansion in
4 561 this tree after 6250 BC (Torbenson *et al.*, 2015).

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7 562 Similar reductions in thermophilus taxa coincident with increases in cool-tolerant trees are
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9 563 exhibited in other Irish pollen records: Cooney Lough, County Sligo showed a marked
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11 564 reduction in pollen from hazel and oak, synchronous with expansion of pine and birch (Ghilardi
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13 565 and O'Connell 2012). Fluctuations in the frequency of juniper at An Loch Mór, Inis Oírr
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15 566 (Molloy and O'Connell 2004) and increased representations of pine at the expense of hazel are
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17 567 recorded during a period of erosion at Lough Maumeen, Connemara (Huang 2002).

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20 569 *The 'Elm Decline': Neolithic woodland clearance and agriculture*

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22 570 Mesolithic impacts on the environment have been identified in pollen records from the UK and
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24 571 Ireland (e.g. Smith 1970; Simmons and Innes 1996; Innes *et al.* 2003; Warren *et al.* 2014;
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26 572 Warren 2020), but there is little evidence for such 'disturbance events' in the Lough Cullin
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28 573 record, although the archaeological record indicates Mesolithic activity (Gleeson and Breen
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30 574 2006a; 2006b; Wren 2006a; 2006b; Russell 2010). A continuous ribwort plantain curve and
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32 575 increased values for NAP (especially ruderal taxa) are evident from the Early Neolithic around
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34 576 4040-3900 *cal. BC*, and some 10-260 years after the initial decline in elm at 4220-3980 *cal.*
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36 577 *BC*. This may indicate the 'elm decline' was unrelated to human activity, although rising values
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38 578 for grass and trace values for anthropogenic indicators are coeval with reductions in this tree.
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40 579 However, this might equally reflect open environments resulting from the mortality of elm
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42 580 trees due to disease (Casedline and Fyfe 2006). The fluctuations in the geochemical data, LoI
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44 581 and MS are distinct, if not as pronounced as in LC-2, indicating the decline in elm was coeval
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46 582 with disturbance to local soils and inwash of minerogenic matter into the Lough. Other Irish
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48 583 records (O'Connell and Molloy 2001; Ghilardi and O'Connell 2013; Molloy *et al.* 2014;
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50 584 Kearney and Gearey 2020; McClatchie and Potito 2020), also indicate a 'gap' between the
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52 585 'Elm Decline' and clear palynological evidence for human disturbance. Overall, this may refute
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54 586 an anthropogenic cause for the reduction in elm, although the chronological disparity could
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56 587 also reflect increased stimulation of arboreal pollen production resulting from openings to the
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58 588 woodland canopy (cf. Aaby 1986).

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60 589 The Early Neolithic (LC-4a) is marked by the continuous presence of ribwort plantain from
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58 590 4040-3900 *cal. BC* until 3720-3540 *cal. BC*, a duration of 220-450 years. During this period,
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60 591 there was a substantial opening up of the woodland and expansion in open habitats, presumably

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3 592 relatively close to the lake, although this is considerably earlier than the estimated date (3720-
4 593 3680 cal. BC) for the Neolithic 'house horizon' and the first cereal cultivation in Ireland
5 594 (McSparron 2008; Cooney *et al.* 2011; McClatchie *et al.* 2014; Whitehouse *et al.* 2014;
6 595 McLaughlin *et al.* 2016). Overall, the impact of Early Neolithic agriculture in Irish pollen
7 596 records is rather variable (Connolly 1999; Crushell *et al.* 2008; O'Carroll 2012), perhaps
8 597 reflecting the fact that Early Neolithic agriculture was spatially heterogeneous (Whitehouse *et*
9 598 *al.* 2014) with varying levels of intensity, and the relative proximity of activity to sampling
10 599 sites would further attenuate the signal.

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17 600 Cereal-type pollen is recorded at 3900-3700 cal. BC, an estimated 50-290 years after the start
18 601 of clearance and again from 3790-3580 cal. BC. Palynological evidence from Newrath, south
19 602 of Lough Cullin (Timpany 2009) also strongly suggests Neolithic arable agriculture at this
20 603 time. The most reliable evidence is the presence of charred cereal grain in Neolithic
21 604 archaeological contexts (e.g Hughes 2006; Monteith 2009; 2011; McKinstry 2010). The
22 605 chronological model estimates farming continued for 220-450 years, implying Early Neolithic
23 606 farmers did not engage in shifting cultivation *contra* Iversen's (1941) *Landnam* model, but
24 607 rather longer-term, fixed-plot agriculture (Whitehouse *et al.* 2014; McClatchie and Potito,
25 608 2020).

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33 609 This phase of agriculture was followed by woodland regeneration and a decline in
34 610 anthropogenic indicators from 3720-3540 cal. BC. A similar pattern of re-afforestation is
35 611 implied during the Middle Neolithic in other parts of Ireland (e.g. Ghilardi and O'Connell 2013;
36 612 Molloy *et al.* 2014; Chique *et al.* 2017; Stolze and Monecke 2020). It has been suggested the
37 613 Middle Neolithic saw a reduction in human activity overall (Whitehouse *et al.* 2014), rather
38 614 than a shift in location, as reflected by the archaeological record: the number of confirmed
39 615 Middle Neolithic archaeological sites in the region is substantially lower than in the preceding
40 616 Early Neolithic, also in keeping with the archaeological evidence from across Ireland. This has
41 617 also been linked to climatic change, dubbed the '5.2 ka event' (Roland *et al.* 2015), although
42 618 the precise nature and timing of this remains unclear (Plunkett *et al.*, 2020).

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51 619 Evidence for sustained human activity is subsequently absent until 2960-2525 cal. BC, a period
52 620 of woodland regeneration of estimated 660-1120 years, followed by a renewal of arable and
53 621 pastoral activity. The reappearance of agricultural activity during the Late Neolithic is indicated
54 622 in other pollen records (Molloy and O'Connell 2004; Molloy *et al.* 2014; Stolze and Monecke
55 623 2020) whilst the archaeological record also suggests a limited Late Neolithic presence in south-
56 624 east Ireland (Tierney 2005; Wren 2006b; Monteith 2011).

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3 625 The reduction in Scots pine from 2620-2240 cal BC, probably coincides with the beginnings of
4 626 the ‘Pine Decline’ in the region. The decline of Scots pine has been well documented across
5 627 much of Ireland, northern Scotland and England (e.g. Bennett 1984; Bridge *et al.* 1990; Gear and
6 628 Huntley 1991; Pilcher *et al.* 1995; Lageard *et al.* 1999; Mighall *et al.* 2004), although recent
7 629 studies have suggested the persistence of the taxa in certain regions (McGeever and Mitchell
8 630 2016; Sassoon *et al.* 2021). Numerous competing hypotheses have been proposed for the cause
9 631 of this reduction, from climate (Bradshaw and Browne 1987; Mighall *et al.* 2004) to
10 632 anthropogenic activity (Tipping *et al.* 2008), however Lough Cullin provides no conclusive
11 633 evidence for the cause of this at the site.
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21 635 *Human activity from The Bronze Age to Early Medieval Period.*

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23 636 Relatively low levels of human activity are indicated during the Late Neolithic (LC-7a) through
24 637 to the Chalcolithic/Early Bronze Age (LC-7b), followed by resurgence into the Middle Bronze
25 638 Age (LC-7c), peaking in the Middle to Late Bronze Age (from 1500-1410 cal. BC to 1275-
26 639 1000 cal. BC). Excursions in the geochemical data, especially Ca during LC-7c, followed by
27 640 increases in Fe and associated peaks in MS towards the top of LC-8, support the picture that
28 641 the Middle Bronze Age saw significant scrub/woodland clearance, farming and associated
29 642 destabilisation of soils. Following this, human activity then seems to have decreased in two
30 643 ‘steps’: an initial reduction, which may be described as a contraction, during the Late Bronze
31 644 Age from 1275-1000 cal. BC to 815-685 cal. BC (LC-9) followed by a pronounced ‘collapse’
32 645 from 815-685 cal. BC until 690-535 cal. BC (LC-10), the Bronze Age to Iron Age transition.
33 646 Human impact on the landscape seems to have almost completely ceased, quite abruptly in this
34 647 latter period.
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45 648 This pattern is paralleled by the changes in archaeological site distributions across this entire
46 649 period (cf. Armit *et al.* 2013.; Becker *et al.* 2017); extensive landscape utilisation until the
47 650 beginning of the Hallstatt plateau, followed by a marked contraction. This characteristic pattern
48 651 can also be traced in the archaeology in the southeast (Eogan *et al.* 2015). Comparison with
49 652 data from recently published Irish pollen records indicates a broadly coherent pattern during
50 653 the Early to Middle Bronze Age of consistent and increasing woodland clearance and
51 654 agriculture, followed by fluctuating human activity during the Late Bronze Age (Chique *et al.*
52 655 2017; Spencer *et al.* 2020; Stolze & Monecke, T. 2020). tt (2009) has previously drawn
53 656 attention to a similar pattern, suggesting a link between increased archaeological visibility
54 657 during the Late Bronze Age and palynological evidence for intensified pastoral activity, and
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3 658 indicating that the end of this period may have been characterised by consolidation of
4 659 settlement and agriculture.

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9 661 *Climate change and human activity during Later Prehistory*

11 662 It has long been suggested there is an apparent coincidence between the ‘end’ of the Bronze
12 663 Age (ca. 1150-800/600 cal. BC) and evidence for climatic deterioration (wetter/colder
13 664 conditions) across northwest Europe; the period known as the ‘Sub-Boreal to Sub-Atlantic
14 665 transition’ or the ‘2.8 Ka event’ (see Gearey *et al.*, 2020 for a recent review). Some scholars
15 666 have suggested a direct causal link, with the onset of wetter/colder conditions, impacting
16 667 directly on Bronze Age settlement and agriculture. However, Armit *et al.* (2014) have
17 668 presented combined palaeodemographic (Armit *et al.* 2013) and hydroclimatic data (peatland
18 669 Bog Surface Wetness/BSW records; Swindles *et al.* 2013) from Ireland, arguing a ‘peak’ in
19 670 human activity *c.*1050 to 900 BC, was followed by a reduction to *c.*800 BC and a rapid
20 671 ‘collapse’ to *c.*750 BC. The combined BSW data indicate climatic deterioration *c.*750-550 BC,
21 672 which may suggest that this ‘event’ can be causally ‘disconnected’ from the ‘end’ of the Bronze
22 673 Age, at least as indicated by the proxy demographic data.

23 674 There are few comparative palaeotemperature datasets for this period; although a recent
24 675 chironomid-based reconstruction (expressed as mean July air temperature, referred to as
25 676 Chironomid-inferred temperatures: C-ITs) is available from Lough Meenachrinna, Co.
26 677 Donegal (Taylor *et al.* 2018). These data indicate C-ITs of 11.5°C during the Early Bronze Age
27 678 (*c.*1390 BC), rising into the Middle Bronze Age (*c.*1310-1100 BC) to peak at 13.5 °C (*c.*1260
28 679 BC), then falling to *c.*12 °C at the beginning of the Late Bronze Age (*c.*1150-960 BC). Slight
29 680 increases in C-ITs to 12.8 °C are recorded from the end of the Bronze Age into the Iron Age
30 681 (*c.*920-620 BC), later dropping to 11.4 °C (*c.*660-480 BC). The range of palaeotemperature
31 682 fluctuations in this record are relatively small and their potential significance for human activity
32 683 hard to assess (K. Taylor, pers.comm.)

33 684 However, ‘events’ in the Lough Cullin pollen record can be described as chronologically
34 685 ‘imbricated’ with the palaeoclimatic ‘events’: a clear peak in human activity during the Middle
35 686 Bronze Age, followed by contraction or consolidation during the Late Bronze Age and a
36 687 pronounced fall into the Iron Age. The initial reduction (LC-9) also overlaps with the beginning
37 688 of the palaeodemographic drop (Armit *et al.* 2014) and the subsequent ‘collapse’ (LC-10) with
38 689 the postulated climatic deterioration in the BSW records (see also Plunkett *et al.*, 2020 who

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3 690 point to a gap in germination in the bog oak record between 751-713 BC and 709-668 BC).
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5 691 Correlations are hampered by the variable chronological precision of the different records; even
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7 692 with the improved chronological precision of the Cullin record, the ranges for the palynological
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9 693 'events' are still 'smeared' over several centuries. Nevertheless, the chronological
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11 694 correspondence between the postulated climatic downturn (*c.*750 BC) in the BSW records and
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13 695 the contraction of human activity during the Bronze Age-Iron Age transition (690-535 *cal. BC*)
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15 696 at Lough Cullin can be noted; at the very least leaving open the possibility of a link between
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17 697 the two. Further analysis is also hampered by a general lack of detailed knowledge of the
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19 698 precise nature or severity of climatic changes, and an associated lack of clarity concerning
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21 699 pattern and process of social-cultural changes from Bronze to Iron Age (see Gearey *et al.*, 2020;
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23 700 Coyle-McClung and Plunkett, 2020 for further discussion).

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25 701 Whatever the cause/s of the decline in anthropogenic activity during the transitional period
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27 702 between Bronze and Iron Ages, two 'steps' can be defined: a rapid recovery following the
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29 703 previous 'collapse' and marked expansion in woodland clearance and farming very soon
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31 704 afterwards, between 690-535 *cal. BC* and 415-250 *cal. BC* (LC-11). This was followed by
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33 705 another phase of woodland recovery from the latter date until 390-540 *cal. AD* (LC-12). A
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35 706 marked period of woodland regeneration is a feature of many Irish pollen records during later
36
37 707 prehistory, sometimes referred to as the 'Late Iron Age Lull' (Mitchell and Ryan 1997)
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39 708 although the reduction in activity dates to the Developed Iron Age at Lough Cullin. The timing
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41 709 of woodland regeneration and reduced human activity generally varies between records, from
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43 710 the final centuries BC to the early centuries AD (Chique *et al.* 2017). In some locations, human
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45 711 activity continued, albeit at fairly low levels, across the Late Iron Age (Figure 6). There are
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47 712 indications of drier/warmer conditions in Ireland from *c.*300 BC-400 AD (Coyle-McClung and
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49 713 Plunkett, 2020), corresponding broadly with the woodland regeneration phase (LC-11) in the
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51 714 Cullin record.

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53 715 At Lough Cullin, human activity seems to have ceased almost completely until *cal. AD* 390-
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55 716 540, when there was a relatively abrupt resumption of the ribwort plantain curve, a steady rise
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57 717 in grass and reductions in hazel and oak (LC-13). Anthropogenic indicators demonstrate a
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59 718 marked increase and cereal pollen is recorded in almost all the samples across the zone,
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719 indicating a significant expansion of arable cultivation locally. In comparison to the sporadic
720 record of cereal pollen from the rest of the sequence, the Early Medieval period saw the most
721 extensive period of arable cultivation in the Lough pollen catchment. A steady rise in Fe and
722 Ca towards the close of the zone, a peak in MS track rising NAP; the increasing LoI values is

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3 723 contrary to the evidence for increased mineral input, but may reflect increased eutrophication
4 724 of the lake due to the input of organic material from intensified arable and pastoral farming;
5 725 the record terminates at *cal. AD 780-1035* with increasing anthropogenic indicators and NAP
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8 726 and associated reductions in AP.
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12 13 728 **7. Conclusions**

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15 729 The Lough Cullin sequence provides a nuanced and detailed multi-proxy (pollen, loss-on-
16 730 ignition, geochemistry and magnetic susceptibility) reconstruction of Holocene environmental
17 731 and landscape change from *9050-8090 cal. BC* to *780-1035 cal. AD*, the Mesolithic to the Early
18 732 Medieval Period; the provision of a high resolution radiocarbon chronology has allowed a
19 733 comparatively high level of chronological precision for the later prehistoric period in particular,
20 734 using Bayesian approaches permitting formal, robust estimates of the timing and duration of
21 735 particular events, avoiding potentially misleading precision resulting from other approaches to
22 736 age-depth modelling of palaeoenvironmental records. The data provide clear evidence for the
23 737 impact of the ‘8.2 Kyr’ BP climate event on the environment of the southeastern seaboard of
24 738 Ireland. Certainly, on the basis of the geochemistry and magnetic susceptibility datasets, the
25 739 ‘signature’ of the 8.2 ‘event’ is very pronounced, which is interpreted as reflecting the impact
26 740 of this colder/drier period across the entire catchment. Later alleged prehistoric climatic
27 741 ‘events’ are largely obscured or overlain by human impact, reflecting woodland clearance,
28 742 settlement and agriculture which began during the Early Neolithic, slackened during the Middle
29 743 Neolithic before intensifying in the Middle-Late Bronze Age. The compilation of
30 744 archaeological data has allowed a qualitative comparison of the palaeoenvironmental record
31 745 with the spatially delimited evidence of human activity and taking account of the uncertainties
32 746 associated with the interpretation of both records, broad correspondence in terms of implied
33 747 intensities of human activity are indicated. A steady ‘demise’ of human activity during the Late
34 748 Bronze Age-Iron Age is apparent, although there is no clear evidence to illuminate the cause/s
35 749 of this, there is chronological correspondence with alleged national climatic deterioration
36 750 around the mid-8th century BC. There is also unambiguous evidence for a reduction in human
37 751 activity during the Iron Age until the Early Medieval period, providing further indication of
38 752 the spatial and chronological variability of settlement and agriculture in Ireland across these
39 753 periods. Despite ongoing archaeological and palaeoenvironmental investigation of the later
40 754 prehistoric period in particular, uncertainties concerning data interpretation and variations in
41 755 the chronological resolution, precision and robustness of different proxy climate records,

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3 756 hamper the formulation of mechanistic models linking environmental and cultural processes.
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5 757 The development of new methods and the generation of further, high resolution
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7 758 palaeoenvironmental records are one key to future progress, but this must include further
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9 759 research into archaeological data on regionally specific scales.
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For Peer Review

LPAZ/Top Depth (m)	Posterior density estimate (95.4% probability)	Posterior density estimate (68.2% probability)	Cultural period	Main pollen features	LoI
LC13 2.15	780-1035 cal. AD	810-940 cal. AD	Early Medieval	Reductions in AP (c.55%) across zone, especially <i>Corylus</i> (c.20%), <i>Quercus</i> (c.10%) and <i>Alnus</i> (c.10%) towards top of zone. Increase in NAP (c.45%), especially Poaceae (c.20%), Cyperaceae (c.15%), <i>P. lanceolata</i> (c.4%) and <i>Rumex</i> (2%). <i>Cerealia</i> -type recorded across zone. Rise in <i>Pteridium</i> (c.10% TLP+S), Charcoal increases to peak midway through zone.	OM increasing c.40% at base to c.47% at top LPAZ. Average c.43%
LC12 2.36	390-540 cal. AD	395-470 cal. AD	Late Iron Age	Pronounced increase in AP (c.95%), especially <i>Corylus</i> (c.50%) and <i>Quercus</i> (c.30%), other arboreal taxa remaining steady. Falls in NAP predominantly Poaceae and Cyperaceae, <i>P. lanceolata</i> low and sporadic. Increase in charcoal towards top of zone.	OM increasing from c.36% to c.41% at top LPAZ. Average c.39%
LC11 2.64	415-250 cal. BC	405-355 cal. BC	Iron Age	Steady reduction in AP across zone (c.70%), primarily <i>Corylus</i> and following an initial increase, <i>Quercus</i> . NAP increase, Poaceae rises (c.15%), also <i>P. lanceolata</i> (c.8%), Lactuceae (2%) and sporadic <i>Filipendula</i> . <i>Cerealia</i> -type recorded 2.65m. Charcoal low.	OM ranges c.34% at base to c.29% across LPAZ. Average c.31%
LC10 2.82	690-535 cal. BC	630-555 cal. BC	Iron Age transition	Increase in AP (c.90%), mainly <i>Corylus</i> (c.45%), other arboreal taxa remaining steady. Reductions in NAP, primarily Poaceae, <i>P. lanceolata</i> consistently present, at certain points higher values than the former. Charcoal low and sporadic.	OM increasing from c.33 to 37% across LPAZ. Average c.34%
LC9 2.925	815-685 cal. BC	795-740 cal. BC	Late Bronze Age	Both AP (between 70-85%) and NAP (30-15%) fluctuate cross the zone; former mainly due to changes in <i>Corylus</i> but <i>Quercus</i> also involved and the latter Poaceae; <i>P. lanceolata</i> remaining steady. Two <i>Cerealia</i> -type grains recorded at 3.08m, <i>Pteridium</i> peaks at c.15% and charcoal also shows increase above (3.04m).	OM ranges c.28% at base to c.35% at top of LPAZ. Average c.30%
LC8 3.14	1275-1000 cal. BC	1225-1080 cal. BC	Middle Bronze Age	Pronounced fall in AP (c.55%), especially <i>Corylus</i> (c.15%) and <i>Quercus</i> (c.10%) towards close of zone. Sharp increase in Poaceae and <i>P. lanceolata</i> , reaching highest values for diagram (c.28% and 7% respectively) also Cyperaceae (7%) and <i>Succisa</i> -type (2%), low values for Chenopodiaceae and <i>Filipendula</i> . Increase in <i>Pteridium aquilinum</i> (11% TLP+S) and Pteropsida monolete (indet.) (9% TLP+S) towards close of zone. Charcoal values very low.	OM increases from c.34% to c.37% at 3.20m, decreasing to c.29% by top of LPAZ. Average c.32%
LC7c 3.34	1500-1470 cal. BC (28.1%) 1465-1410 cal. BC (67.3%)	1495-1480 cal. BC (17.5%) 1455-1420 cal. BC (50.7%) 1875-1840 cal. BC (30.0%)		AP remaining steady (c.80%), <i>Corylus</i> increasing (c.45%) towards top of zone. NAP increases initially (c.20%), mainly Poaceae and <i>P. lanceolata</i> , followed by reduction in former (c.10%). Charcoal increases slightly to peak at top of zone.	OM ranges c.34 to c.36% across LPAZ. Average c.35%
LC7b 3.56	1880-1740 cal. BC	1820-1800 cal. BC (14.1%) 1780-1750 cal. BC (24.2%)	Chalcolithic & Early Bronze Age	NAP remaining steady (15%); the latter mainly represented by Poaceae, low values for <i>P. lanceolata</i> . Charcoal remains low.	OM ranges from c.30% at base to c.40% at top LPAZ. Average c.33%

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5	LC7a	2620-2240 cal. BC	2505-2320 cal. BC	Late Neolithic	<i>Ulmus</i> remains low, <i>Corylus</i> values fall mid-way to c.25%. Other trees at similar values to previous zone. Increased NAP (c.15%), a second continuous <i>P. lanceolata</i> curve (c.3%) from start of zone, Poaceae also increases, Asteraceae, Apiaceae, <i>Filipendula</i> and Ranunculaceae present. Single grain <i>Cerealia</i> -type (4.02m) alongside <i>Artemisia</i> -type. Pteropsida (monolete) indet. increases to 8% TLP+S. Charcoal values show very slight increase.	OM ranges c.33 to c.35% across LPAZ. Average c.33%
6	3.90					
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10	LC6	2960-2525 cal. BC	2845-2630 cal. BC	Middle Neolithic II	Steady reduction in <i>Ulmus</i> (c.2-3%), <i>Alnus</i> increases (c.25%) and <i>Salix</i> also present in slightly greater values (c.3%). NAP steady at c.7%, predominantly Cyperaceae, continuous Ranunculaceae, sporadic <i>Filipendula</i> , <i>P. lanceolata</i> , <i>Succisa</i> -type. Charcoal remains steady.	OM ranges c.35 to c.37% across LPAZ, dropping to c.30% at top. Average c.34%
11	4.08					
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14	LC5	3355-3120 cal. BC	3275-3150 cal. BC	Middle Neolithic I	AP values increase overall (c.95%), primarily <i>Corylus</i> (c.30%), <i>Quercus</i> (c.25%) and <i>Ulmus</i> (c.8%) and <i>Alnus</i> (c.20%). NAP values decline, only sporadic records of <i>P. lanceolata</i> . Slight increase in <i>Polypodium</i> (6% TLP+S). Charcoal remains steady.	OM ranges from c.35 to c.37% across LPAZ. Average c.36%
15	4.38					
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18	LC4c	3685-3530 cal. BC	3650-3555 cal. BC	Early Neolithic II	<i>Quercus</i> (c.25%) and <i>Ulmus</i> (c.4%) values recover, <i>Corylus</i> remaining c.30%. NAP values are reduced (c.5%) although a continuous but reduced curve for <i>P. lanceolata</i> (c.1% max) is exhibited, <i>Cerealia</i> -type pollen recorded (2 grains 4.77 and 1 grain 4.75m); other herbs similar to previous zone. Charcoal also remaining at similar levels.	OM ranges from c.31% at base to c.36% at the top of LPAZ. Average c.34%
19	4.71					
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23	LC4b	3860-3650 cal. BC	3815-3710 cal. BC	Early Neolithic I	<i>Quercus</i> (25 to 15%) and <i>Corylus</i> (40 to 30%) decreasing across zone; NAP increases to c.20%, predominantly Poaceae (10%), continuous presence of <i>P. lanceolata</i> (c.5%) and Ranunculaceae (c.1-2%), <i>Artemisia</i> -type, Asteraceae, <i>Rumex acetosella/acetosa</i> , <i>Filipendula</i> and <i>Urtica dioica</i> recorded at lower values. Single grain of <i>Cerealia</i> -type (4.85m). Charcoal increases at top of the zone.	OM ranges c.10% at 4.90m to c.31% at top of LPAZ. Average c.29%
24	4.82					
25						
26						
27						
28	LC4a		4040-4010 cal. BC (25.8%)		<i>Ulmus</i> values decrease at the start of zone (c.10% to c.3%) and thereafter remain very low; a temporary reduction in <i>Corylus</i> (c.25%), followed by recovery (c.40%). NAP values increase to c.10%, consisting of Poaceae (c.6%) and other herbs recorded include Asteraceae, Caryophyllaceae and <i>Plantago lanceolata</i> . Pteropsida (monolete) indet. increases to 9% TLP+S. Charcoal remains low.	OM ranges c.30 to c.25% at top of LPAZ. Average c.27%
29	5.01	4050-3960 cal. BC	4005-3975 cal. BC (42.4%)	Late Mesolithic	<i>Corylus</i> recovers (c.40%), while <i>Alnus</i> increases steadily to a peak (c.25%), <i>Quercus</i> and <i>Ulmus</i> stable (20% and 10% respectively). The initiation of low but continuous <i>Ilex</i> curve is recorded at top of zone. NAP values remaining low. Slight if sporadic increases in charcoal.	
30						
31						
32	LC3	4320-4020 cal. BC	4225-4070 cal. BC		Temporary reduction in both <i>Corylus</i> (c.30%) and <i>Quercus</i> (c.20%) corresponding with spikes in <i>Betula</i> (c.15%) and <i>Pinus</i> (c.20%), followed by recoveries in the former. <i>Alnus</i> increases abruptly at top of zone to c.15%. NAP remaining low (c.4%). Charcoal remaining very low.	OM ranges from c.29 to c.38%. Average c.34%
33	5.09					
34						
35						
36	LC2	6245-5575 cal. BC	6120-5780 cal. BC	Early Mesolithic		OM ranges c.35 to c.33%. across LPAZ. Average c.34%
37	5.84					
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7615-6500 cal. BC

7320-6745 cal. BC

Dominated by AP, high values of *Corylus* (c.50%) and *Quercus* (c.30%),
Ulmus (c.8%), *Pinus*, and *Betula* present (2-4%). A continuous but low
presence of *Hedera helix* (2%) and *Salix* (1%). NAP values very low,
traces of Poaceae, Cyperaceae and *Filipendula*. Charcoal very low.

OM ranges from c.35to
c.40% across the
LPAZ.
Average c.37%

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For Peer Review

Lab Code	Dated Material	¹⁴ C Age (BP)	Depth (m)	¹³ δC ‰
UBA-22422	Fragment of willow branch	2526±32	1.78	-20.7
SUERC-70812	Organic sediment (humic fraction)	1141±32	2.19	-29.8
SUERC-70813	Organic sediment (humic fraction)	1198±29	2.19	-30.5
Statistically consistent measurements ($T^2=1.9$; T^2 (5%)=3.8%; $v=1$). Weighted mean 1170±21				
Beta-423349	Organic sediment (humic fraction)	1420±30	2.29	-29.6
Beta-423350	Organic sediment (humic fraction)	1500±30	2.29	-29.9
Statistically consistent measurements ($T^2=3.6$; T^2 (5%)=3.8%; $v=1$). Weighted mean 1460±22				
SUERC-70814	Organic sediment (humic fraction)	1661±27	2.37	-29.6
SUERC-70815	Organic sediment (humic fraction)	1635±29	2.37	-30.4
Statistically consistent measurements ($T^2=0.4$; T^2 (5%)=3.8%; $v=1$). Weighted mean 1622±20				
Beta-426773	Organic sediment (humic fraction)	1910±30	2.45	-29.1
SUERC-70816	Organic sediment (humic fraction)	1959±29	2.49	-29.4
SUERC-70817	Organic sediment (humic fraction)	1996±29	2.49	-29.9
Statistically consistent measurements ($T^2=0.8$; T^2 (5%)=3.8%; $v=1$). Weighted mean 1978±21				
SUERC-70821	Organic sediment (humic fraction)	2003±29	2.53	-29.2
SUERC-70822	Organic sediment (humic fraction)	2074±29	2.53	-29.7
Statistically consistent measurements ($T^2=3.0$; T^2 (5%)=3.8%; $v=1$). Weighted mean 2039±21				
SUERC-72575	Organic sediment (humic fraction)	2114±29	2.55	-29.4
SUERC-72576	Organic sediment (humic fraction)	2135±29	2.55	-29.4
Statistically consistent measurements ($T^2=0.2$; T^2 (5%)=3.8%; $v=1$). Weighted mean 2125±24				
Beta-426774	Organic sediment (humic fraction)	2150±30	2.60	-29.1
SUERC-72571	Organic sediment (humic fraction)	2181±33	2.61	-29.9
GU43402	Organic sediment (humic fraction)	FAILED	2.61	-
SUERC-70823	Organic sediment (humic fraction)	2250±29	2.65	-29.4
SUERC-70824	Organic sediment (humic fraction)	2336±29	2.65	-30.1
Statistically inconsistent measurements ($T^2=4.397$; T^2 (5%)=3.8%; $v=1$).				
SUERC-70825	Organic sediment (humic fraction)	2328±29	2.71	-29.4
SUERC-70826	Organic sediment (humic fraction)	2436±26	2.71	-29.8
Statistically inconsistent measurements ($T^2=7.7$; T^2 (5%)=3.8%; $v=1$).				
UBA-22423	Organic sediment (humic fraction)	2413±31	2.77	-25.0
SUERC-70827	Organic sediment (humic fraction)	2467±29	2.81	-29.3
SUERC-70831	Organic sediment (humic fraction)	2506±29	2.81	-29.6
Statistically consistent measurements ($T^2=1.0$; T^2 (5%)=3.8%; $v=1$). Weighted mean 2489±20				
SUERC-70832	Organic sediment (humic fraction)	2446±27	2.915	-29.3
SUERC-70833	Organic sediment (humic fraction)	2514±29	2.915	-29.9
Statistically consistent measurements ($T^2=3.0$; T^2 (5%)=3.8%; $v=1$). Weighted mean 2478±20				
Beta-426775	Organic sediment (humic fraction)	2620±30	2.94	-29.1
Beta-426776	Organic sediment (humic fraction)	2750±30	3.04	-28.9
SUERC-70834	Organic sediment (humic fraction)	2794±26	3.08	-28.9
SUERC-70835	Organic sediment (humic fraction)	2821±29	3.08	-29.7
Statistically consistent measurements ($T^2=0.5$; T^2 (5%)=3.8%; $v=1$). Weighted mean 2806±20				
Beta-423351	Organic sediment (humic fraction)	3050±30	3.18	-28.8
Beta-423352	Organic sediment (humic fraction)	3020±30	3.18	-30.2
Statistically consistent measurements ($T^2=0.5$; T^2 (5%)=3.8%; $v=1$). Weighted mean 3035±22				
SUERC-76326	Organic sediment (humic fraction)	3026±24	3.26	-29.6
SUERC-76666	Organic sediment (humic fraction)	3132±32	3.26	-29.8
Statistically inconsistent measurements ($T^2=7.0$; T^2 (5%)=3.8%; $v=1$).				
SUERC-76327	Organic sediment (humic fraction),	3162±24	3.34	-29.3

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3	SUERC-76328	Organic sediment (humic fraction)	3168±24	3.34
4				-28.5
5		Statistically consistent measurements ($T^*=0.0$; $T^*(5\%)=3.8\%$; $v=1$). Weighted mean 3165±17		
6	SUERC-76329	Organic sediment (humic fraction)	3469±24	3.56
7	SUERC-76667	Organic sediment (humic fraction)	3473±32	3.56
8				-29.9
9		Statistically consistent measurements ($T^*=0.0$; $T^*(5\%)=3.8\%$; $v=1$). Weighted mean 3470±20		
10	UBA-22424	Organic sediment (humic fraction)	3800±36	3.79
11	SUERC-70836	Organic sediment (humic fraction)	4459±29	4.31
12	SUERC-70837	Organic sediment (humic fraction)	4520±27	4.31
13				-30.1
14		Statistically consistent measurements ($T^*=2.4$; $T^*(5\%)=3.8\%$; $v=1$). Weighted mean 4459±29		
15	UBA-22425	Organic sediment (humic fraction)	4710±39	4.60
16	SUERC-70841	Organic sediment (humic fraction)	4755±29	4.69
17	SUERC-70842	Organic sediment (humic fraction)	4795±26	4.69
18				-29.3
19		Statistically consistent measurements ($T^*=1.1$; $T^*(5\%)=3.8\%$; $v=1$). Weighted mean 4777±20		
20	UBA-33721	Organic sediment (humic fraction)	5080±56	4.87
21	UBA-33722	Organic sediment (humic fraction)	5076±51	4.97
22	UBA-30917	Organic sediment (humic fraction)	5210±34	5.01
23	SUERC-70843	Organic sediment (humic fraction)	5675±27	5.34
24	SUERC-70844	Organic sediment (humic fraction)	5788±26	5.34
25				-29.4
26		Statistically inconsistent measurements ($T^*=9.1$; $T^*(5\%)=3.8\%$; $v=1$).		
27	UBA-22426	Organic sediment (humic fraction)	6154±47	5.46
28	UBA-30918	Organic sediment (humic fraction)	7358±37	5.91
29	UBA-22427	Organic sediment (humic fraction)	9057±48	6.21
30				-30.0
31				*
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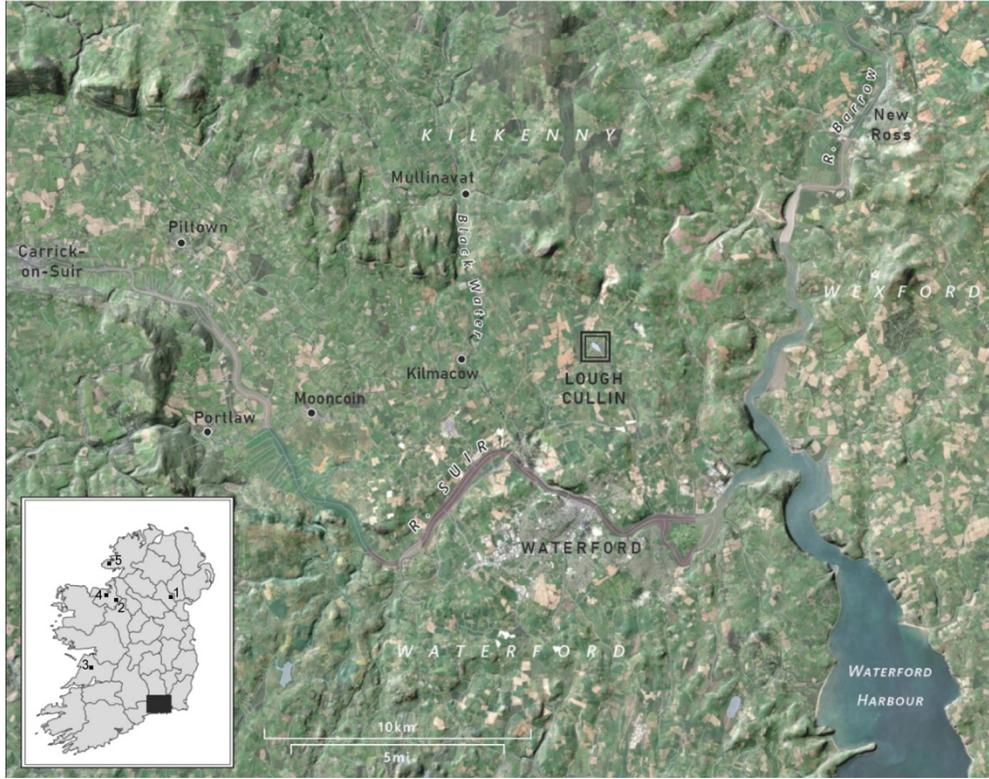


Figure 1 Location map of Lough Cullin. Inset map indicating the location of selected sites referenced in this paper. 1-Lough Muckno, 2-Lough Arrow, 3-Lough Inchiquin, 4-Lough Dargan & 5-Lough Meenachrinna.

404x316mm (118 x 118 DPI)

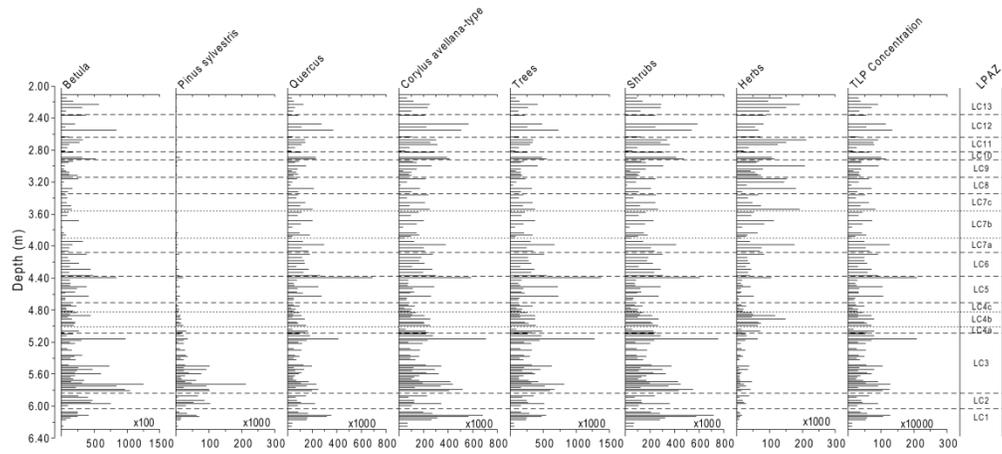


Figure 3 Selected taxa pollen concentration from Lough Cullin.

699x313mm (118 x 118 DPI)

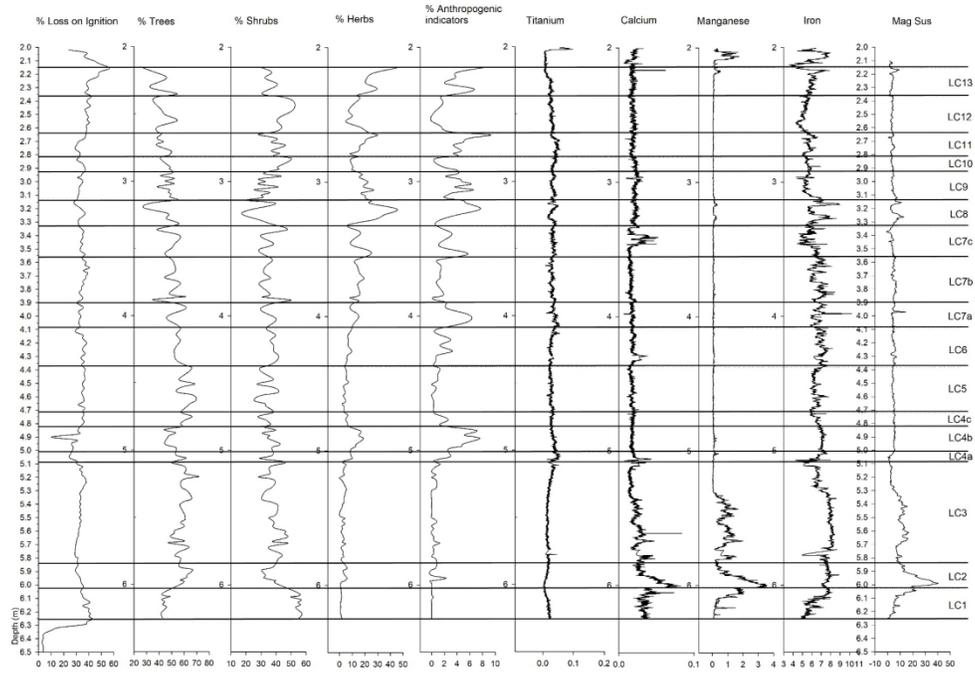


Figure 4 Loss-on-ignition (LoI), geochemistry and magnetic susceptibility (MS) diagram from Lough Cullin.

569x402mm (87 x 87 DPI)

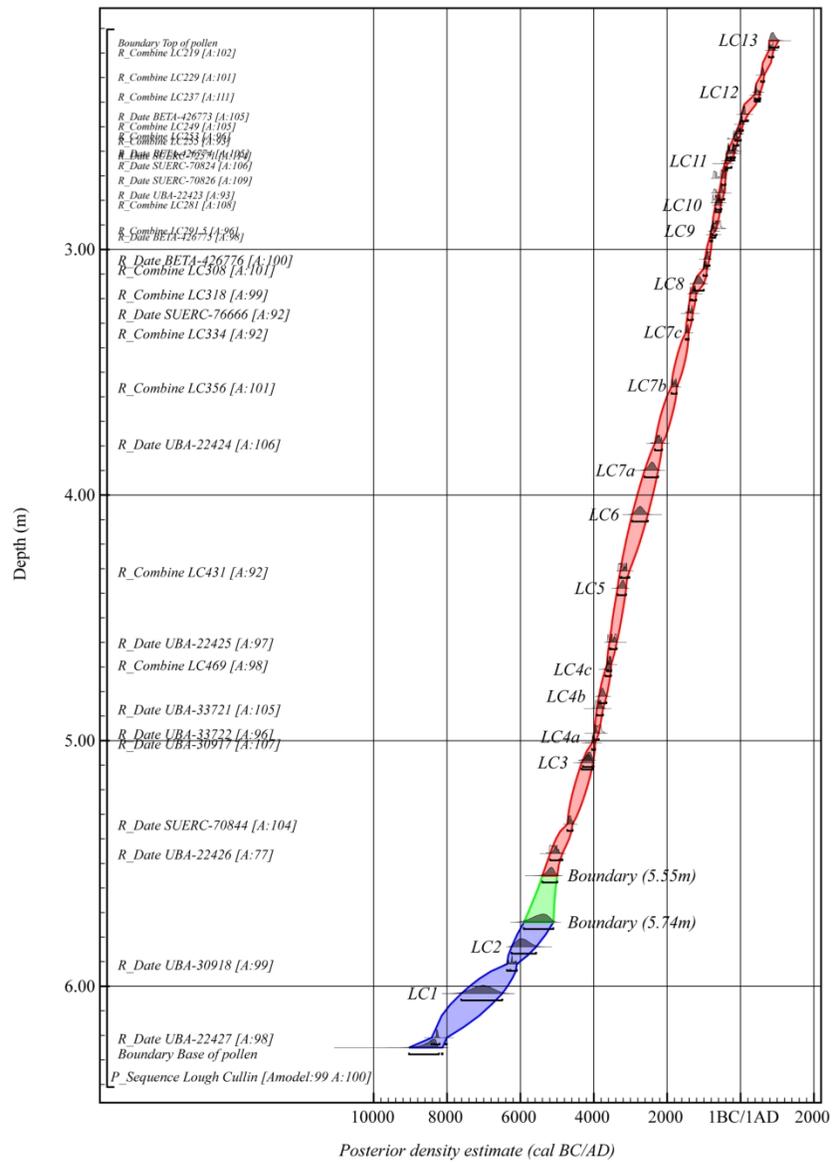


Figure 5 Bayesian age-model of the chronology of the sediment sequence at Lough Cullin (P_Sequence model (k=0.01-100) (Bronk Ramsey 2008). Coloured band showing the estimated date of sediment at the corresponding depth at 95.4% probability.

401x570mm (118 x 118 DPI)

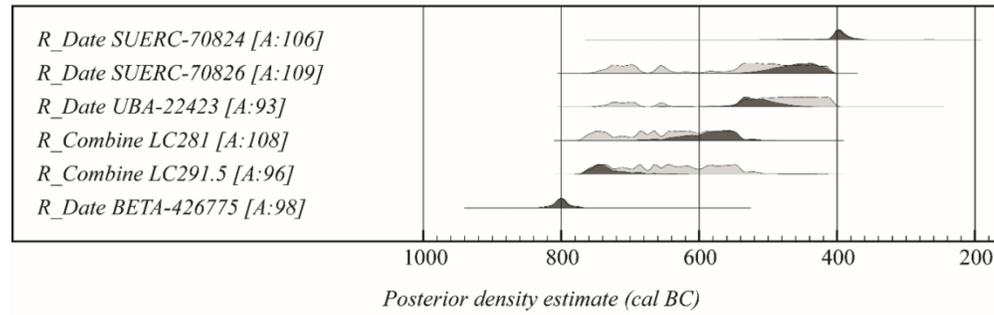


Figure 6 Unmodelled (light grey) and modelled (dark grey) dates across the 'Hallstatt' plateau. Modelled dates are derived from the Bayesian age-model shown in Figure 5.

400x127mm (87 x 87 DPI)