



# Neolithic land-use dynamics in northwest Ireland: multi-proxy evidence from Lough Arrow, County Sligo

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## Abstract

A high-resolution multi-proxy study of lake sediments from Loughbrick Bay in Lough Arrow, County Sligo, Ireland provides a detailed record of Neolithic vegetation history and land-use change. The high concentration of megalithic monuments around Lough Arrow suggests that the region was a centre of settlement and ritual activity during the Irish Neolithic. The pollen record indicates that human activities, including farming, intensified ca. 100 years after the mid-Holocene elm decline, which is dated to 3820 BC. Pastoral and arable farming formed part of the Neolithic subsistence economy, in particular during the first half of the Neolithic. Although levels of human impact were low during most of the later Neolithic, allowing woodland recovery, short periods of arable farming recurred during that time. Human pressure on the landscape increased again at the end of the Neolithic and during the Chalcolithic period. Interruption of farming and settlement activities often coincided with wetter climate. Comparison of this study with records from nearby lakes shows that the type of farming varied at a local scale. While pastoral farming was widespread, cereal cultivation was spatially and temporally restricted. The pollen evidence suggests that wheat was the predominant crop during the earlier Neolithic, whereas barley became more important during the later Neolithic.

**Keywords** Ireland · Neolithic · Pollen analysis · Non-pollen palynomorphs · Lake sediment geochemistry · Land-use change · Climate variability

## Introduction

County Sligo in northwestern Ireland (Fig. 1) is renowned for its abundance of archaeological sites dating to the Neolithic period (4000–2500 BC; Table 1). The Neolithic

represents an important period of societal, cultural, and technological development in Irish prehistory. It is characterised by the shift from a mobile to a more sedentary lifestyle, the introduction of agriculture, adoption of new technologies, and emergence of megalithic architecture (Waddell 2000). Important archaeological sites located in County Sligo include the causewayed enclosure at Magheraboy, which is regarded as the earliest Neolithic causewayed enclosure in Ireland and Britain (Danaher 2007, 2019), and two of Ireland's four major passage tomb complexes, namely Carrowmore on the Cúil Irra peninsula and Carrowkeel-Keshcorran on summits of the Bricklieve Mountains (Fig. 1). The large number of Neolithic monuments in County Sligo is indicative of widespread settlement (Danaher 2007) and highlights the significance of the region as a ritual centre in Neolithic Ireland.

Given the rich archaeological inventory of the region, previous palynological research in County Sligo largely focussed on the reconstruction of vegetation dynamics and anthropogenic activities in proximity to megalithic and other prehistoric monuments (Fig. 1). Investigations

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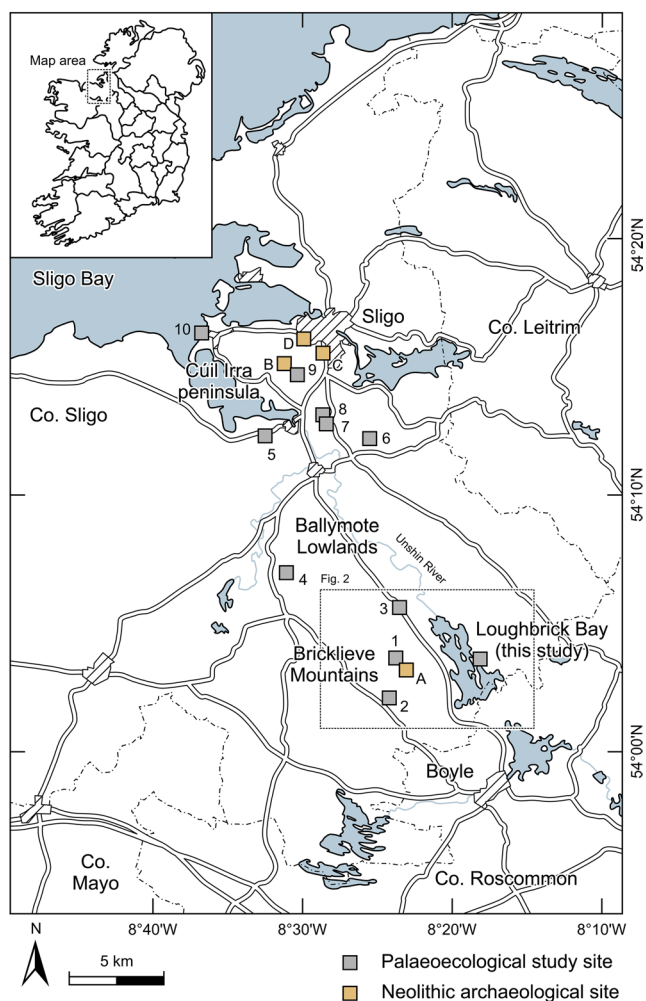
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**Fig. 1** Map of County Sligo, Ireland showing the location of the study area, selected Neolithic archaeological sites (A–D), and locations of previously published pollen and chironomid records (1–10). A Carrowkeel-Keshcorran megalithic complex; B Carrowmore megalithic complex; C Causewayed enclosure at Magheraboy; D Excavated sites at Ballydoogan. 1. Treanscrabbagh Bog (Mitchell 1951; McAulay and Watts 1961; Göransson 1984, 2002) and Lough Availle (Stolze 2012; Stolze et al. 2013a); 2. Templevanny Lough (Stolze et al. 2013b; Taylor et al. 2017a); 3. Loughmeenaghan (Stolze et al. 2012); 4. Rathdooney Beg (Mount 1999); 5. Cooney Lough (O’Connell et al. 2014; Taylor et al. 2017b); 6. Lough Dargan (Ghilardi and O’Connell 2013a, b; Taylor et al. 2013); 7. Ballygawley Lough (Göransson 1984, 2002); 8. Union Wood Lake (Dodson and Bradshaw 1987); 9. Cloverhill Lough (Göransson 1984, 2002); 10. Strandhill (Göransson 1984, 2002)

concentrated at sites south of the Cúil Irra peninsula in the northern part of the county (Göransson 1984, 2002; Dodson and Bradshaw 1987; Ghilardi and O’Connell 2013a, b; O’Connell et al. 2014) and in and around the Bricklieve Mountains in the southeast (Mitchell 1951; McAulay and Watts 1961; Göransson 1984, 2002; Mount 1999; Stolze et al. 2012, 2013a, b; Stolze 2012, 2019).

**Table 1** Subdivision of the Irish Neolithic following McClatchie et al. (2016)

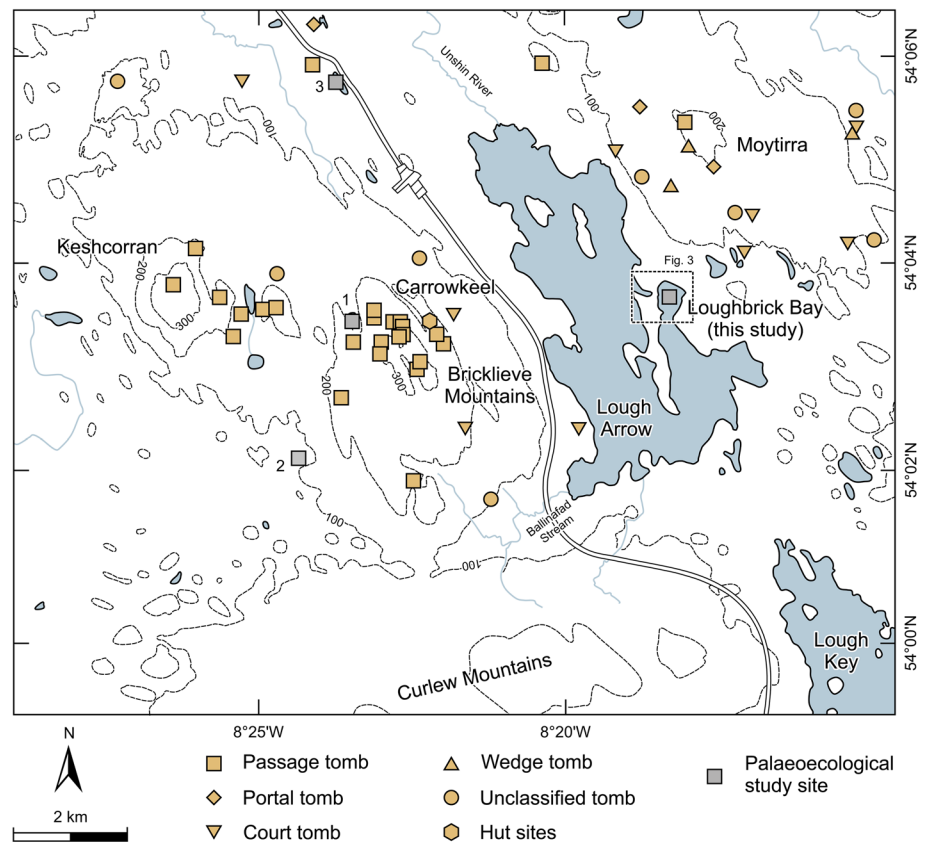
Period	Subdivision	Age range (cal year bc)
Early Neolithic	Early Neolithic I	4000–3750
	Early Neolithic II	3750–3600
Middle Neolithic	Middle Neolithic I	3600–3400
	Middle Neolithic II	3400–3000
Late Neolithic		3000–2500

Combined chironomid and stable isotope studies yielded further information on levels of Neolithic farming impact in both areas (Taylor et al. 2013, 2017a, b).

This study provides new evidence for Neolithic farming activities and woodland dynamics from Loughbrick Bay in Lough Arrow in southeast County Sligo (Fig. 2). The Carrowkeel-Keshcorran passage tomb complex and other megalithic structures form a large aggregation of monuments located mainly in the uplands to the east and west of Lough Arrow (Hensey et al. 2014). The presence of these monuments suggests intense Neolithic settlement and ritual activities in the Lough Arrow region. A palynological investigation of a blanket peat core from the summit plateau of the Bricklieve Mountains indicated that the uplands were likely an open karst landscape during the Neolithic (Stolze 2019). While the uplands were used for the construction of the megalithic monuments visible from a distance, multi-proxy studies of lake sediments from Loughmeenaghan (Stolze et al. 2012) and Templevanny Lough (Stolze et al. 2013b) provide evidence for human impact, including farming, in the lowlands adjacent to the Bricklieve Mountains. The palynological data suggest that farming economies may have varied locally. While there is evidence for cereal growing at Loughmeenaghan in the lowlands to the north of the Bricklieve Mountains, pastoral farming seems to have been the main land-use practice at Templevanny Lough to the west of this upland area (Fig. 2).

This high-resolution pollen and geochemical study of a sediment core from Loughbrick Bay located in the eastern part of Lough Arrow forms part of the research effort investigating possible local variations in Neolithic human impact and land-use patterns within the archaeologically important region around Lough Arrow. Loughbrick Bay was chosen for this study due to its central location within the landscape and its sheltered nature. The Loughbrick Bay multi-proxy record provides critical new insights into changing Neolithic farming practices in the lowland to the east of the Bricklieve Mountains.

**Fig. 2** Detailed map of the Lough Arrow region showing passage tombs and megalithic monuments of other Neolithic traditions. The Bricklieve Mountains and the Moytirra uplands are important landscape foci around the lake. The coring site at Loughbrick Bay and locations of published palaeoecological records are indicated. 1. Treanscrabbagh Bog (Mitchell 1951; McAulay and Watts 1961; Göransson 1984, 2002) and Lough Availe (Stolze 2012; Stolze et al. 2013a); 2. Templevanny Lough (Stolze et al. 2013b; Taylor et al. 2017a); 3. Loughmeenaghan (Stolze et al. 2012)



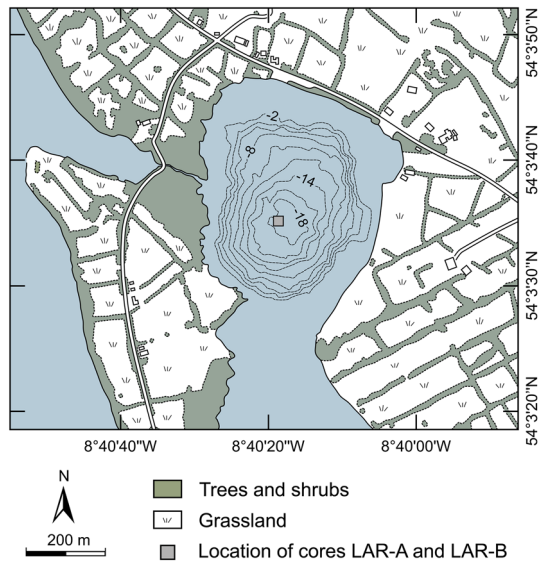
## Study site

Lough Arrow is a large 1,247 ha lake (Free et al. 2006) located in the Ballymote Lowlands (Fig. 1). The lake lies at 54 m above sea level (a.s.l.) and has a maximum water depth of 39 m. Lough Arrow was shaped during the Late Midlandian (ca. 27000–10500 BC; Knight et al. 2004). The glaciers that carved the region flowed out from an ice sheet situated over the midlands of Ireland in a northwesterly direction (Monecke 2019). The direction of the ice flow is illustrated by the northwest to southeast orientation of the lake. Deposition of sediments transported by the ice mass resulted in the formation of drumlins that impound the lake (MacDermot et al. 1996). The bedrock geology in the immediate vicinity of the lake consists of Carboniferous limestone, with Devonian and Carboniferous sandstone occurring to the south in the Curlew Mountains (Monecke 2019). The lake is bordered by the Bricklieve Mountains located ~2.5 km to the west and the Moytirra uplands ~1.5 km to the east (Fig. 2). The two upland areas rise to heights of ~300 m and 200 m a.s.l., respectively. The Curlew Mountains with elevations of up to 250 m a.s.l. lie to the southwest.

Lough Arrow is fed by springs, a few small streams, and the Ballinafad Stream in the southwest. The lake drains through the Unshin River to the northwest (Fig. 2). The shores of the lake are formed of drift or peat (Wynne 1887).

Gravel- and cobble-sized rocks washed out of the drift occur on the lake bottom or along exposed shorelines. Submerged peat and tree stumps were observed in the shallow waters in the west and southwest of Lough Arrow and in Loughbrick Bay (Wynne 1887). Land use data from 1990 indicate that 59% of the lake's catchment area of 65.76 km<sup>2</sup> was used as pasture and 29% was assigned to other agricultural land. Forestry accounted for 4% and bogs for 8% of the area (Free et al. 2006).

Loughbrick Bay, a sheltered, medium-sized (20 ha) bay located on the eastern side of Lough Arrow was chosen for coring (Fig. 3). The bay is connected with the open water body of the lake through a small channel on the western side and a wide passage to the south, where a sill at 1.5–2 m below today's lake level separates the basin from the main lake. In the 19th century, Loughbrick Bay was "almost a small separate lake, partly surrounded, and nearly divided from Lough Arrow, by bog banks. Through a gap in these banks a boat could just pass; but the banks have since been almost entirely washed away" (Wynne 1887, p. 501). The immediate surroundings of Loughbrick Bay consist of farmland with hedgerows and scattered dwellings. *Schoenoplectus lacustris* and *Phragmites australis* occur on the lakeshore. *Nuphar lutea* is present in the shallow waters along the lake edge. Plant nomenclature follows Webb et al. (1996).



**Fig. 3** Map of Loughbrick Bay and its surroundings on the east side of Lough Arrow. Bathymetry (in metres), location of duplicate cores, and vegetation and land use are indicated

## Methods

### Coring

Following a bathymetric survey of Lough Arrow and inspection of surface sediments collected along several transects, two 10-m long parallel cores, LAR-A and LAR-B, were obtained in April 2010 from the deepest part of Loughbrick Bay (17.8 m; 54° 3′ 35.04″ N, 8° 18′ 18.60″ W; Fig. 3). LAR-B was retrieved approximately 3–5 m southeast of LAR-A. A rod-operated Usinger piston corer with 2-m-core barrels was used (Mingram et al. 2007). The cores were transferred to Kiel University, Germany, for analyses and stored in a cold room at 4 °C.

### Pollen analysis

Prior to sampling, the sediment interval deposited during the Neolithic period was identified in both parallel cores LAR-A and LAR-B using the smear-slide method described in Stolze (2015). This quick determination of the pollen content also ensured that the interval of interest was contained within a core segment obtained in a single drive. Thus, issues arising from use of multiple core segments were avoided. Core LAR-B was identified as being the more suitable core. High-resolution sampling was carried out on this core between 500.5 and 590.5 cm at 1 cm resolution. The sediments in this interval consisted of black brown, fine detritus mud. Samples of 1.5 cm<sup>3</sup> were taken from 1 cm thick sediment slices and processed following standard techniques (Faegri and Iversen 1989), including sieving using a 125 µm sieve and

HF treatment. *Lycopodium clavatum* spores (batch 177745;  $n = 18,584 \pm 1,853$  per tablet) were added to each sample prior to chemical treatment to allow calculation of pollen concentrations and pollen accumulation rates (Stockmarr 1971).

The pollen samples, mounted in glycerine, were counted at  $\times 400$  magnification. Critical pollen and spores were examined using oil immersion at  $\times 600$  magnification under phase contrast illumination. Pollen and spore identification and nomenclature followed primarily Moore et al. (1991). Identification and naming of *Acer*, *Silene* type, *Sorbus* group, *Tilia cordata* type, and *Trifolium repens* type followed Beug (2004). Cereal type pollen grains were determined using the morphological criteria in Beug (2004). *Aethusa cynapium* type was identified following Punt (1984). Nomenclature and other details relating to non-pollen palynomorphs (NPPs) are given in ESM Table 1. At least 1,000 terrestrial pollen grains and pteridophyte spores were counted in each sample. Pollen clumps were counted as discrete single entities and not the grains forming the clump. Pollen and non-pollen palynomorph percentages were calculated relative to a terrestrial pollen and pteridophyte spore sum.

Pollen diagrams were constructed using the program Tilia Version 2.1.1 (Grimm 1991, 2004). Determination of the pollen zones was carried out by stratigraphically constrained cluster analysis using the software PAST version 3.25 (Hammer et al. 2001), applying the paired group algorithm. Only data of pollen and spore types exceeding a threshold of 5% of the pollen sum were used in this calculation (Birks 1986). Prior to analysis, the raw data were normalised to the sum of the included pollen and spore types. The robustness of the established groupings was tested by applying different similarity indices. The statistical significance of the pollen zones was determined by applying the broken-stick model in the software psimpoll (Bennett 1996).

### Chemical analyses

Loss-on-ignition analysis was performed on 1 cm<sup>3</sup> sediment obtained from the same depths as the pollen samples. The wet samples were dried overnight at 105 °C. The organic and inorganic carbon contents were determined by combusting the samples at 550 °C for 4 h (LOI<sub>550</sub>), followed by combustion at 950 °C for 2 h (LOI<sub>950</sub>), respectively (Heiri et al. 2001). The remaining non-combustible ash is derived from biogenic silica, biochemically precipitated oxides and sulphides, authigenic carbonate, or mineral matter present in the samples. Stratigraphically constrained cluster analysis was performed on the loss-on-ignition data, using the software PAST version 3.25 (Hammer et al. 2001).

The elemental composition of the sediment core was determined semi-quantitatively by X-ray fluorescence, using an Avaatech core scanner with a point sensor at Kiel

University. Signal intensities of selected elements were determined at a 0.5 cm resolution. Measurement conditions for Al, Ca, Fe, K, P, and Si were set to 0.4 mA, 10 kV, and a count time of 30 s.

## Radiocarbon dating

Eleven samples were chosen for radiocarbon dating (Table 2). Slices of 1-cm thickness were taken from the core, soaked in 10% HCl to remove the carbonate fraction, and wet sieved through a 500 µm sieve. Remains of terrestrial plants were submitted to the <sup>14</sup>C Chrono Centre at Queen's University Belfast for radiocarbon dating by accelerator mass spectrometry. Prior to analysis, the samples were pre-treated with acid.

Calibration and chronological analysis of the <sup>14</sup>C measurements were carried out using the program OxCal 4.3 (Bronk Ramsey 2009) applying the IntCal13 curve (Reimer et al. 2013). Prior to age-depth modelling, outliers were determined using the outlier analysis method in OxCal 4.3. Bayesian age-depth modelling was subsequently performed using a Poisson deposition model. To account for changes in the sedimentation rate, a variable number of events per unit length (*k*) was applied (Bronk Ramsey 2008; Bronk Ramsey

and Lee 2013). The modelled calendar ages are expressed as the mean of the posterior probability distributions and rounded to the nearest 10 years. The sediment accumulation rate was derived from the depositional model.

## Results

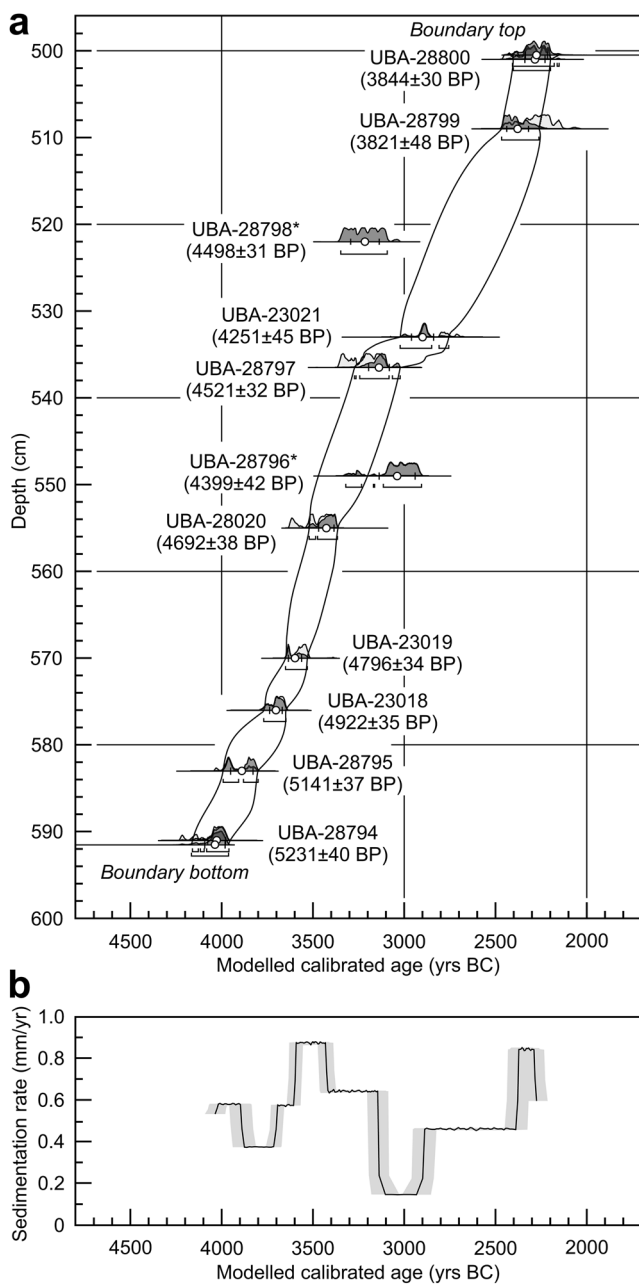
### Radiocarbon dating

Nine of the eleven radiocarbon dates yielded reliable ages (Table 2). The <sup>14</sup>C measurements of samples UBA-28796 and UBA-28798 were detected as outliers, with UBA-28796 being too young and UBA-28798 being too old. Material for sample UBA-28798, which was taken from close to an inwash layer, may have contained eroded terrestrial plant material that gave an older age. Bayesian age-depth modelling produced an OxCal *P*-Sequence with a model agreement index of 92%, suggesting a high level of agreement between the model and the data. Age-depth modelling indicates that the studied sediment interval from 590.5 to 500.5 cm was deposited between 4020 and 2280 BC (Fig. 4), which broadly corresponds to the Irish Neolithic

**Table 2** Radiocarbon dates from Loughbrick Bay, County Sligo, Ireland

Sample no. (UBA-)	Depth (cm)	Material dated	δ <sup>13</sup> C (‰)	<sup>14</sup> C age (BP ± 1σ)	Cal age (years BC)	Mean cal age (years BC ± 1σ)
28800	502–500	Leaf fragments (11), bud scales (2), bud scale fragment, plant fragments (8), charred plant fragments (2)	– 26.4	3,844 ± 30	2457–2204	2310 ± 70
28799	510–508	<i>Betula</i> nutlet, leaf fragments (47), bud scales (2), charred plant remains (2), stems (3)	– 29.8	3,821 ± 48	2459–2141	2280 ± 90
28798*	523–521	Leaf fragments (9), bud scales (2), bud scale fragment, bract base, Cyperaceae nut	– 28.0	4,498 ± 31	3347–3096	3220 ± 80
23021	534–532	Bud scale and leaf remains (4)	– 26.4	4,251 ± 45	3008–2675	2840 ± 70
28797	537–536	Cyperaceae nut, wood fragment, bract fragment	– 29.8	4,521 ± 32	3357–3101	3220 ± 80
28796*	550–548	<i>B. pubescens</i> nutlets (3) and bract	– 25.1	4,399 ± 42	3322–2907	3040 ± 100
23020	556–554	Bud scale, leaf remains (3), Cyperaceae nut	– 25.6	4,692 ± 38	3630–3369	3470 ± 70
23019	571–569	Leaf remains, <i>B. pubescens</i> bract, <i>Salix</i> bud scales, bud scale	– 34.1	4,796 ± 34	3650–3521	3570 ± 40
23018	577–575	<i>Betula pubescens</i> nutlet, <i>Salix</i> bud scale, cf. moss stems, bud scale, leaf stem base, leaf fragments (2)	– 30.2	4,922 ± 35	3771–3646	3700 ± 40
28795	584–582	Leaf fragments (22), <i>Alnus</i> bud scales (2), bud scale	– 28.5	5,141 ± 37	4040–3803	3930 ± 70
28794	592–590	Nutlets of <i>Betula</i> (1), <i>Alnus</i> (1), <i>B. pubescens</i> (1), and <i>B. cf. humilis</i> (2), cf. <i>Alnus</i> fragment, leaf fragment, bud scales (2)	– 28.2	5,231 ± 40	4228–3963	4050 ± 70

Calibrated age ranges are reported at the 95.4% confidence interval. <sup>14</sup>C measurements detected as outliers using the outlier analysis method in OxCal 4.3 are marked with an asterisk (\*)



**Fig. 4** Deposition model and sediment accumulation rates for core LAR-B from Loughbrick Bay. **a** Bayesian age-depth model showing probability distributions for each calibrated date (light grey) and the posterior probability distributions taking the model into account (dark grey). Samples considered as outliers are marked with an asterisk. **b** Sedimentation rates determined by Bayesian age-depth modelling. (Color figure online)

(4000–2500 BC; McClatchie et al. 2016) and Chalcolithic periods (2500–2000 BC; O’Brien 2012).

The sediment accumulation rate, averaging ~0.6 mm/year, varies throughout the core. High sedimentation rates of ~0.875 mm/year and ~0.844 mm/year occur between 569.5 and 555.5 cm (3590–3430 BC) and between 507.5 and

501.5 cm (2360–2290 BC), respectively, whereas low rates of 0.375 mm/year and 0.17 mm/year are recorded between 582.5 and 576.5 cm (3880–3720 BC) and between 536.5 and 533.5 cm (3140–2930 BC; Fig. 4), respectively.

### Pollen and non-pollen palynomorphs

The pollen and non-pollen palynomorph data are presented in Figs. 5, 6, and 7. Three pollen zones and five subzones are identified. Information on the occurrence of cereal type pollen together with details on their ages, the number of counted cereal type pollen grains in each sample, and cultural periods are given in Table 3.

#### Zone LAR-1 (591–579 cm; 4030–3780 BC)

Arboreal pollen (AP) dominates the basal pollen zone (94–97%), with *Corylus*, *Ulmus*, *Quercus*, and *Alnus* being the main contributors. Clumps of these AP types are documented throughout the zone. *Pinus* subgenus *Pinus* pollen is present at ~3%; a clump of immature grains and a stoma are also recorded. Single occurrences of *Tilia* pollen are noted. *Ulmus* percentages (~20%) and concentrations decline at 580.5 cm (3820 BC). This is accompanied by a reduction of *Pinus* subg. *Pinus*, increase in *Alnus* values, and the presence of *Sambucus nigra* type. *Pteridium aquilinum* spores are present. Trace amounts of *Plantago lanceolata* type occur at 586.5 cm (3950 BC) and at 580.5–579.5 cm (3820–3800 BC).

A diverse aquatic pollen assemblage is recorded, including *Cladium mariscus*, *Myriophyllum* undiff., *Potamogeton* subg. *Coleogeton*, *Nymphaea alba* type, and *Stratiotes aloides*. Green algal taxa (*Botryococcus*, *Pediastrum boryanum* var. cf. *boryanum*, and *Tetraedron* cf. *minimum*) and suberized basal cells of *Nymphaeaceae* mucilaginous hairs (HdV-127) are present.

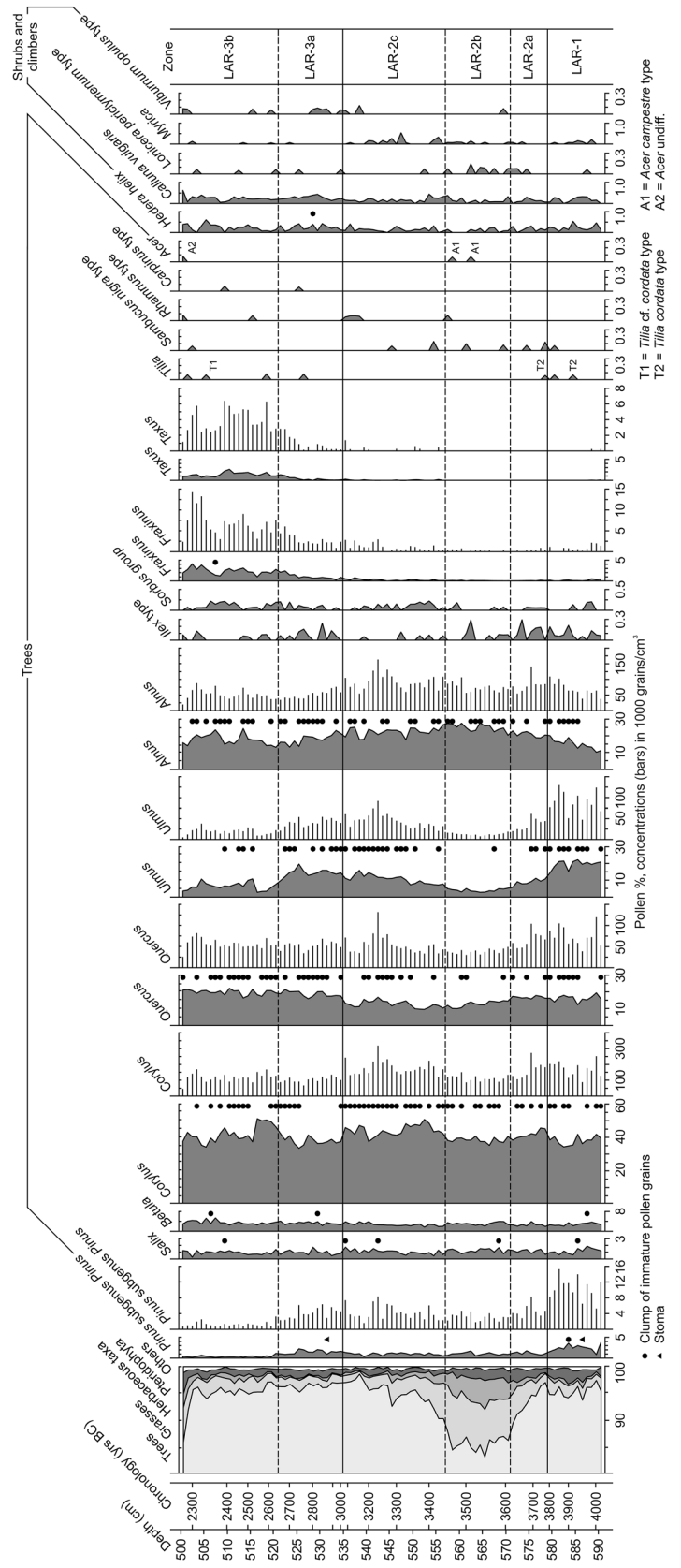
#### Zone LAR-2 (579–535 cm; 3780–3040 BC)

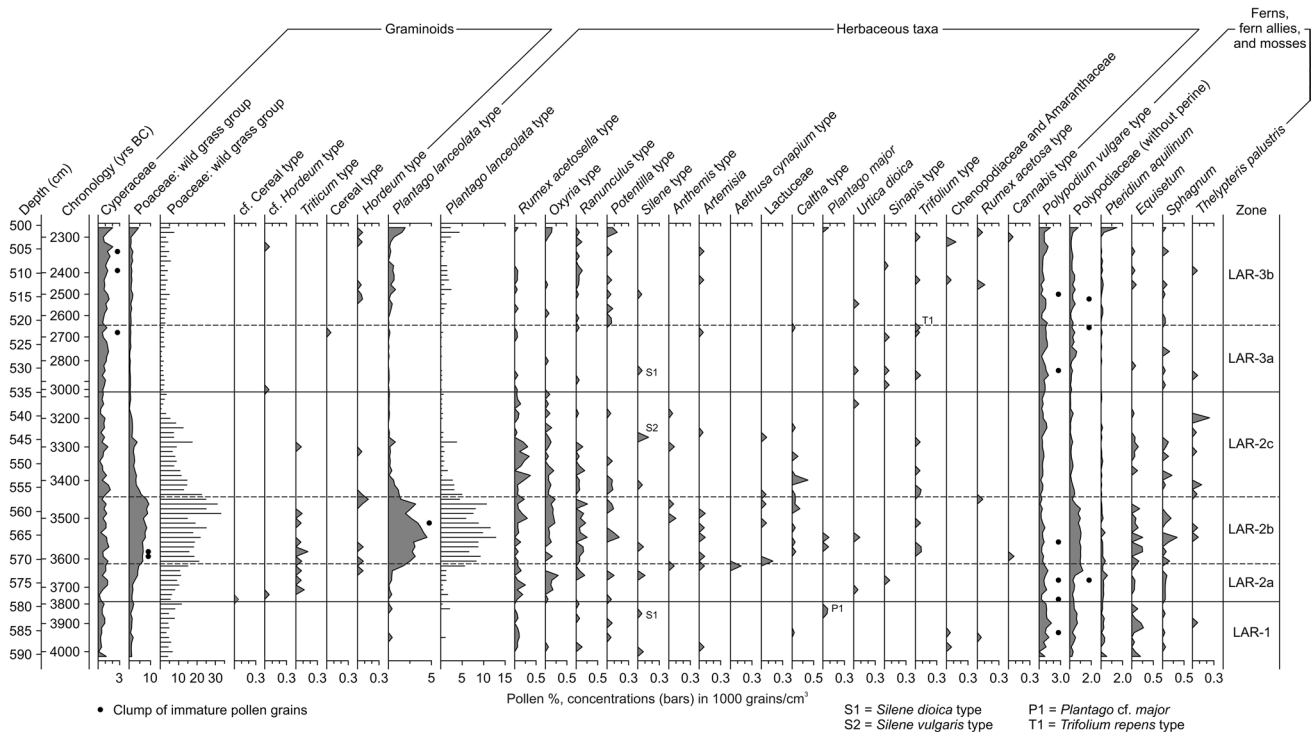
This zone is characterised by reduced AP and elevated non-arboreal pollen (NAP) values as well as indicators of farming. Three subzones are distinguished reflecting different stages of anthropogenic activity.

##### Subzone LAR-2a (579–571 cm; 3780–3620 BC)

AP declines from 97 to 91% in this subzone, which is mainly related to decreasing *Ulmus* values. NAP, largely defined by Poaceae: wild grass group, increases from 576.5 cm (3720 BC) onwards. *P. lanceolata* type begins to form a continuous curve at 577.5 cm (3740 BC). Other pastoral indicators such as *Ranunculus* type and *Rumex acetosella* type and indicators of waste or ruderal places (*Artemisia*, *Urtica dioica*,

**Fig. 5** Pollen diagram of the main arboreal, shrub, and climber pollen types from Loughbrick Bay. Concentrations (bars) are given for selected pollen types. Records of clumps of immature pollen grains are indicated





**Fig. 6** Pollen diagram of the main non-arboreal pollen and spore types from Loughbrick Bay. Concentrations (bars) are given for selected pollen types. Records of clumps of immature pollen grains are indicated

and *Aethusa cynapium* type) are present. Cereal type pollen is recorded intermittently throughout this subzone, starting at 576.5 cm (3720 BC). A possible cereal type and a possible *Hordeum* type pollen grain are recorded at 578.5 and 577.5 cm (3770 and 3740 BC), respectively. Due to their comparably poor preservation, a precise determination was not possible. *Pteridium aquilinum* spores are more abundant than in LAR-1.

Unlike LAR-1, only two aquatic pollen types are documented, including *Potamogeton* subg. *Potamogeton* type, which enters the record and becomes frequent from 573.5 cm (3660 BC) onwards. Green algal remains and Nymphaeaceae basal hair cells (HdV-127) are abundant above 576.5 cm (3720 BC). *Diporothea webbiae* spores increase from 577.5 cm onwards (3740 BC).

#### Subzone LAR-2b (571–557 cm; 3620–3450 BC)

AP decreases to ~85% (average). *Quercus* and *Ulmus* are mainly responsible for this reduction, the latter declining to ~3% at 564.5 cm (3540 BC). NAP, primarily consisting of Poaceae: wild grass group and *P. lanceolata* type, is most abundant in this subzone. *P. lanceolata* type rises to 4.5% at 565.5 cm (3550 BC), followed by a decline and a concomitant rise in Poaceae: wild grass group percentages and concentrations. Other grassland indicators, including

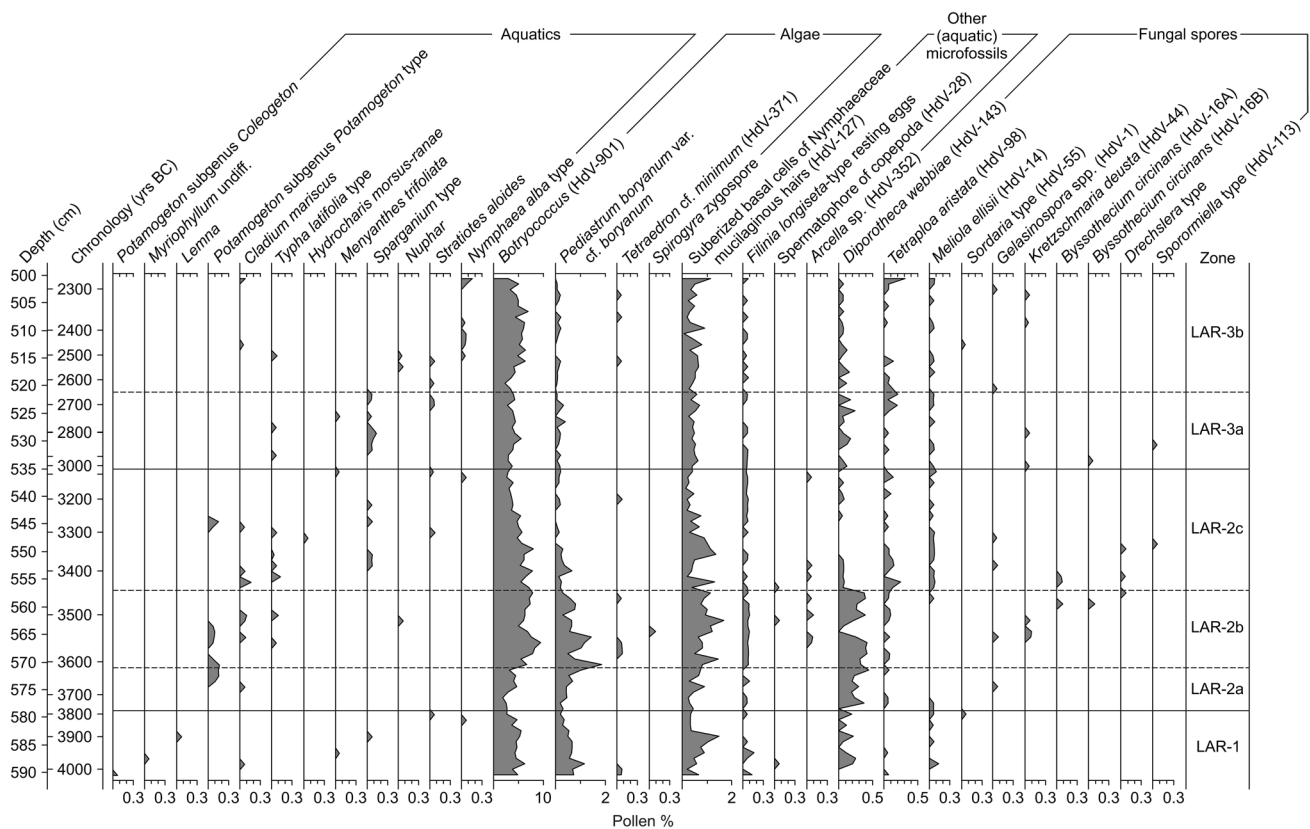
*Anthemis* type, *Caltha* type, Lactuceae, *Plantago major*, *Ranunculus* type, and *Trifolium* type are present. Indicators of waste places and nutrient-rich conditions such as *S. nigra* type, *Artemisia*, and *U. dioica* are recorded. *Triticum* type and *Hordeum* type occur in this subzone.

Pollen of *C. mariscus* and *Potamogeton* subg. *Potamogeton* type are recorded. *Typha latifolia* type and *Nuphar* enter the record. Green algae (*Botryococcus*, *Pediastrum boryanum*, *Tetraedron* cf. *minimum*) and Nymphaeaceae basal hair cells (HdV-127) are most abundant in this subzone. *Arcella* is recorded for the first time. *Drechslera* type spores are recorded in the uppermost sample at 557.5 cm (3460 BC). *Spirogyra* zygospores and spores of the wood-decaying fungi *Kretzschmeria deusta* and *Bysothecium circinans* are documented in the middle part of LAR-2b.

#### Subzone LAR-2c (557–535 cm; 3450–3040 BC)

This subzone opens with a rise of AP from 90 to 96%, the high value is attained at 550.5 cm (3360 BC). *Corylus* and *Ulmus* mainly contribute to this increase. *Alnus* and *Quercus* are also important constituents. AP shows another marked increase at 539.5 cm (3190 BC) and attains 99% at 538.5 cm (3170 BC). *Fraxinus* pollen rises markedly at 543.5 cm (3240 BC). Pastoral pollen indicators initially decline and remain





**Fig. 7** Percentage diagram of selected aquatic pollen and non-pollen palynomorph types from Loughbrack Bay

at lower values between 550.5 and 545.5 cm (3360–3280 BC). A brief rebound of mainly Poaceae: wild grass group and *P. lanceolata* type centres on 545.5 cm (3280 BC). *Hordeum* type and *Triticum* type occur in this interval.

An increase of the number of aquatic pollen types is observed. *Hydrocharis morsus-ranae*, *Menyanthes trifoliata*, *N. alba* type, *Sparganium* type and *Stratiotes aloides* are part of the pollen assemblage. Green algal remains of *Botryococcus* and *Pediastrum boryanum*, initially high, drop in abundance above 549.5 cm (3340 BC). Nymphaeaceae basal hair cells (HdV-127) show low values between 554.5 and 551.5 cm (3420–3370 BC). *Drechslera* type spores are documented between 554.5 and 549.5 cm (3420–3340 BC).

### Zone LAR-3 (535–500 cm; 3040–2270 BC)

This zone is marked by generally high AP values, averaging 96%. Two subzones are distinguished. Pastoral and arable farming indicators recur in the upper subzone.

#### Subzone LAR-3a (535–521 cm; 3040–2640 BC)

*Quercus* pollen is more abundant than in LAR-2c, while *Corylus* percentages and concentrations are lower. *Ulmus*

pollen recovers to about 20%, but declines at 524.5 cm (2720 BC), which is accompanied by a rise in *Fraxinus* and *Taxus* values. NAP is very low and indicators of anthropogenic activity are scarce.

#### Subzone LAR-3b (521–500 cm; 2640–2270 BC)

*Ulmus* percentages continue to decline and attain ~3% at 516.5 cm (2540 BC). The decrease is accompanied by a rise in *Corylus* values. *Taxus* and *Fraxinus* values are higher than in LAR-3a. Clumps of *Fraxinus* pollen are noted. *Pinus* subg. *Pinus* percentages decline to <1% at 519.5 cm (2610 BC). NAP, dominated by Poaceae: wild grass group and *P. lanceolata* type, is generally higher than in LAR-3a and rises notably at 501.5 cm (2290 BC). Low values of *P. lanceolata* type are noted between 507.5 and 504.5 cm (2360–2330 BC). *Hordeum* type is recorded at 515.5 cm (2520 BC). Indicators of grassland (e.g. *Trifolium* type and *Ranunculus* type) and waste places (*Artemisia* and Chenopodiaceae and Amaranthaceae) are recorded. *Pteridium aquilinum* spores are more abundant than in LAR-3a.

**Table 3** Cereal pollen type occurrences in core LAR-B from Loughbrick Bay, County Sligo (TTPS total terrestrial pollen and spore)

Cereal pollen type	Depth (cm)	Age (bc)	Cereal pollen type count	TTPS sum	Cultural period
<i>Hordeum</i> type	501.5	2290	1	1,290	Chalcolithic
<i>Hordeum</i> type	503.5	2320	1	1,521	Chalcolithic
cf. <i>Hordeum</i> type	504.5	2330	1	1,519	Chalcolithic
<i>Hordeum</i> type	512.5	2460	1	1,935	Chalcolithic
<i>Hordeum</i> type	514.5	2500	1	1,872	Late Neolithic
<i>Hordeum</i> type	515.5	2520	1	1,434	Late Neolithic
Cereal type	522.5	2670	1	1,724	Late Neolithic
cf. <i>Hordeum</i> type	534.5	3000	1	1,664	Late Neolithic
<i>Triticum</i> type	546.5	3300	1	1,321	Middle Neolithic II
<i>Hordeum</i> type	547.5	3310	1	1,688	Middle Neolithic II
<i>Hordeum</i> type	556.5	3440	1	1,543	Middle Neolithic I
<i>Hordeum</i> type	557.5	3460	2	1,329	Middle Neolithic I
<i>Hordeum</i> type	558.5	3470	1	1,520	Middle Neolithic I
<i>Triticum</i> type	560.5	3490	1	1,161	Middle Neolithic I
<i>Triticum</i> type	562.5	3510	1	1,371	Middle Neolithic I
<i>Triticum</i> type	566.5	3560	1	1,438	Middle Neolithic I
<i>Hordeum</i> type	567.5	3570	1	1,264	Middle Neolithic I
<i>Triticum</i> type	568.5	3580	2	1,197	Middle Neolithic I
<i>Triticum</i> type, <i>Hordeum</i> type	570.5	3610	1, 1	1,233	Early Neolithic II
<i>Triticum</i> type, <i>Hordeum</i> type	572.5	3640	1, 1	1,305	Early Neolithic II
<i>Triticum</i> type	574.5	3680	1	1,367	Early Neolithic II
<i>Triticum</i> type	576.5	3720	2	1,716	Early Neolithic II
cf. <i>Hordeum</i> type	577.5	3740	1	1,608	Early Neolithic II
cf. Cereal type	578.5	3770	1	1,643	Early Neolithic I

### Loss on ignition and X-ray fluorescence

Constrained cluster analysis performed on the loss-on-ignition data yielded statistically significant zone boundaries at 571 cm (3620 BC) and 554 cm (3410 BC). While the lower boundary occurs at the same depth as the boundary between pollen zones LAR-2a and LAR-2b, the boundary at 554 cm is located 3 cm higher than the boundary between LAR-2b and LAR-2c. Due to the similar stratigraphic positions of the zone boundaries, the established pollen zones were applied to the geochemical data to facilitate comparison of both data sets (Fig. 8).

The inorganic carbon curve obtained by loss-on-ignition analysis at 950 °C (LOI<sub>950</sub>) largely reflects the calcium carbonate fraction in the sediments as suggested by the same trend of the LOI<sub>950</sub> data and Ca counts determined by XRF analysis. The weight loss of the samples at 950 °C is primarily related to CO<sub>2</sub> released during decomposition of calcium carbonate in the sediments. The non-combustible fraction and the Si count data agree with the trend of elements derived from terrestrial sources (Al and K). This indicates

that the autochthonous component such as biogenic silica or biochemically precipitated oxides is low or negligible.

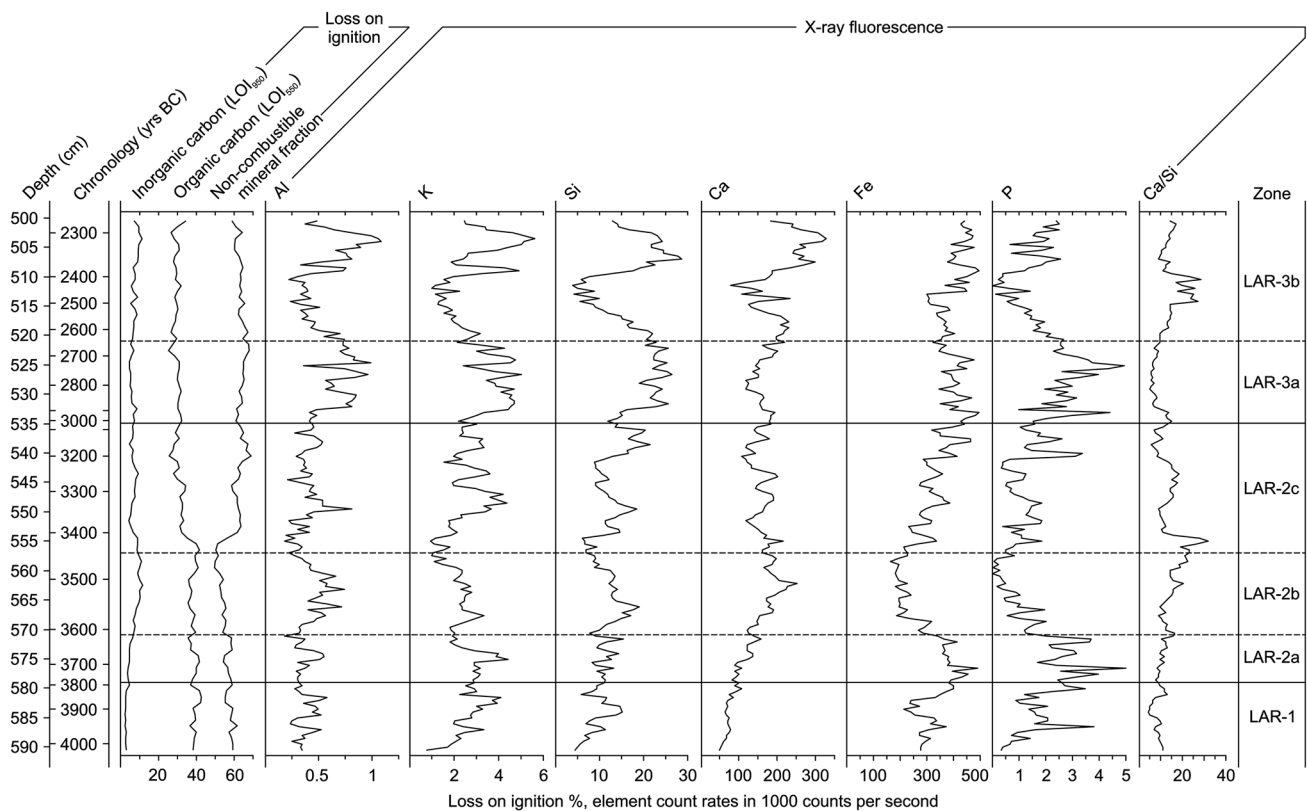
#### Zone LAR-1 (591–579 cm; 4030–3780 BC)

Organic carbon (LOI<sub>550</sub>) values are high and the count rates of terrestrial elements increase. A rise in the inorganic carbon (LOI<sub>950</sub>) values and the count rates of Ca and Fe occurs from 580.5 cm (3820 BC) onwards.

#### Zone LAR-2 (579–535 cm; 3780–3040 BC)

The values of the non-combustible mineral fraction and count rates of terrigenous elements such as K show a rise in subzone LAR-2a at 574.5 cm (3680 BC). In LAR-2b, the Al, K, and Si count rates show a decline at 559.5 cm (3480 BC). Inorganic carbon (LOI<sub>950</sub>) and Ca count rates continue to rise and remain elevated above 562.5 cm (3510 BC). Fe and P count rates are low.

A notable change in the data is recorded in subzone LAR-2c at 554.5 cm (3420 BC) as expressed by a steep decline



**Fig. 8** Loss-on-ignition and selected X-ray fluorescence data from Loughbrick Bay

of the organic and inorganic carbon data and an increase of the non-combustible mineral fraction and count rates of terrestrial elements (Al, K, and Si) which peak at 548.5 cm (3330 BC).

### Zone LAR-3 (535–500 cm; 3040–2270 BC)

The count rates of the terrestrial elements Al, K, and Si vary markedly in the upper part of the zone, with elevated values occurring between 532.5 and 522.5 cm (2890–2670 BC) and at 503.5 cm (2320 BC).

## Discussion

### Vegetation dynamics and human impact during the Neolithic

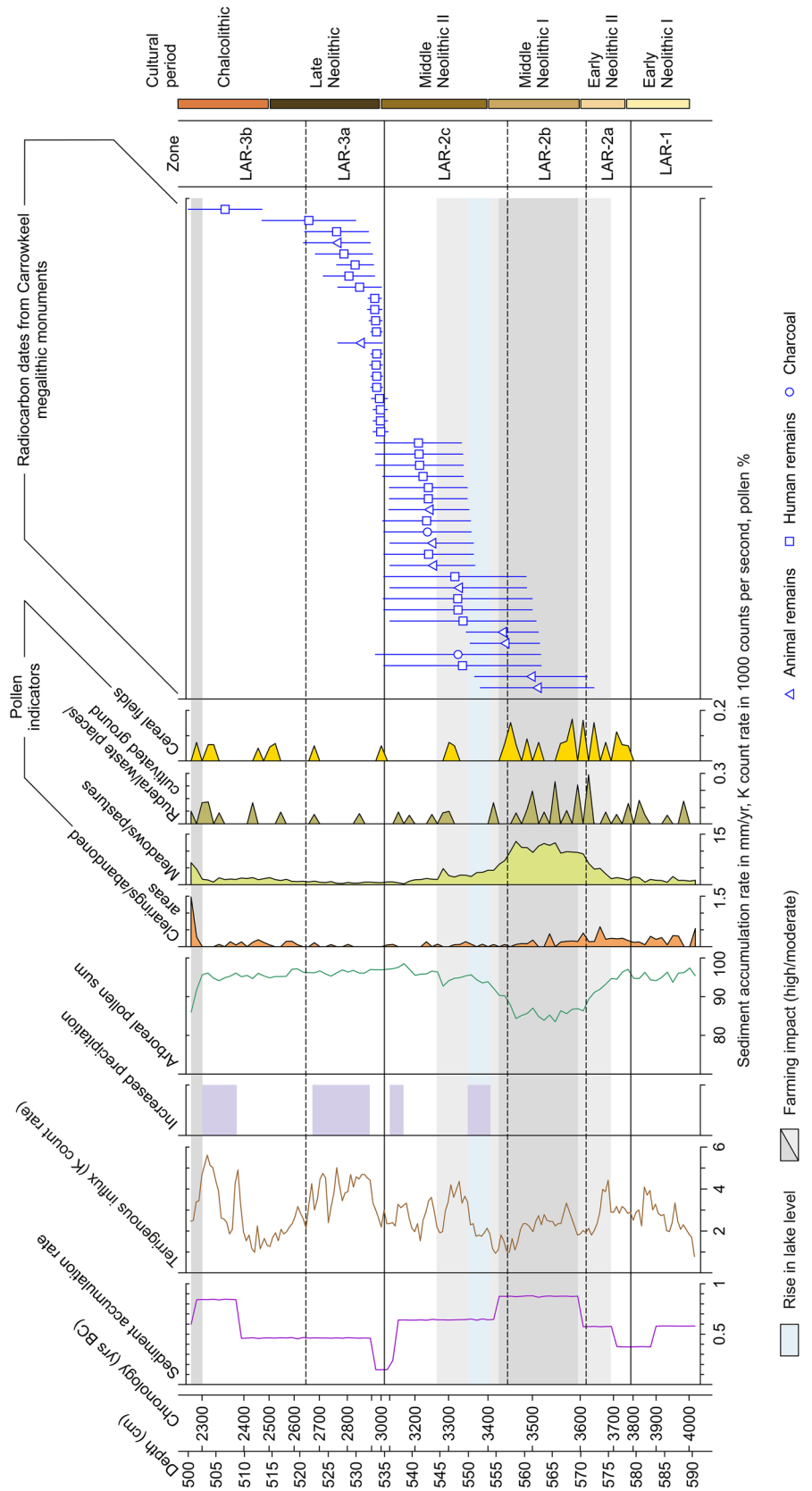
Based on the size of Loughbrick Bay, the pollen record reflects vegetational changes within a radius of ~600–800 m (cf. Sugita 1994). Age-depth modelling indicates that the pollen zones largely correspond, within the limitations of radiocarbon dating, to the chronological division of the Irish

Neolithic (Table 1; Fig. 9). This division is based on the integration of archaeobotanical, archaeological, and radiometric evidence from Ireland (McClatchie et al. 2016). The lower pollen zone boundaries appear to predate the onset of the respective Neolithic subperiod by 20–50 years, which is within the uncertainties associated with radiocarbon dating. However, the pollen zone boundary LAR-3a/b precedes the transition to the subsequent cultural period, the Chalcolithic, by 160 years, suggesting that this difference can possibly not be explained by dating uncertainties.

### Early Neolithic I (LAR-1; 4030–3780 BC)

Pollen zone LAR-1 corresponds to the Early Neolithic I (4000–3750 BC). The pollen evidence indicates that the woodland around the bay consisted mainly of *Corylus* and the tall-canopy trees *Quercus* and *Ulmus* prior to the elm decline. The high AP values are suggestive of a closed woodland cover. *Alnus* occurred on flush and poorly drained soils around the lake. Records of pollen clumps of these taxa indicate their nearby occurrence. The presence of the entomophilous pollen of *Tilia* implies that this taxon was likely present in the pollen source area. An extensive review of the palynological evidence for the Holocene occurrence of *Tilia* in Ireland suggests that this taxon has been present since the

**Fig. 9** Summary diagram showing the sediment accumulation rate as well as geochemical and pollen data from Loughbrick Bay, archaeological information from the Carrowkeel-Keshcorran megalithic complex, and Irish cultural periods. The influx of terrigenous material into the lake is indicated by the K count rate. Pollen types were grouped according to the occurrence of the corresponding plant taxa in different anthropogenic communities (Behre 1981; Webb et al. 1996; see ESM). The calibrated age ranges ( $2\sigma$  confidence interval) of human and animal remains as well as charcoal recovered from megalithic monuments at Carrowkeel are shown. Radiocarbon dates were taken from Bergh (1995), Hensey et al. (2014), and Kador et al. (2018)



Boreal period (Stolze and Monecke 2017). However, in a recent study conducted on the Aran Islands off the western coast of Ireland, O'Connell and Molloy (2019) suggested that pollen of this taxon derived from long-distance transport, arguing against the occurrence of *Tilia* in Neolithic woodland communities in Ireland.

Despite the low *Pinus* subg. *Pinus* pollen percentages of 3%, records of a clump of immature pollen grains and a stoma suggest that pine was locally present. Similarly low pollen percentages along with records of stomata were also detected at other sites in County Sligo (Ghilardi and O'Connell 2013a) and County Donegal (Fossitt 1994). The low pollen percentages may indicate unfavourable growing conditions causing lower pollen production or the presence of isolated trees in the landscape.

Disturbance indicators such as *P. lanceolata* type pollen and *Pteridium aquilinum* spores attest to openings in the woodland cover and some minor human activity around 3950 BC. Woodland disturbance at that time was also recorded at nearby Loughmeenaghan (Stolze et al. 2012). The archaeological evidence from the Cúil Irra peninsula in the north (Scarre et al. 2003; Danaher 2007, 2019; Cooney et al. 2011; Hession 2013; Burenhult 2019) and from Lough Gara in the south (Fredengren 2002) of County Sligo supports human activity in the region during the late Mesolithic and early Neolithic.

The decline in the elm population at Loughbrick Bay commenced at 3820 BC, with the lowest abundance of *Ulmus* being reached 260 years later at 3540 BC, as suggested by the decreasing pollen percentages from ~20 to 3% in LAR-1 to LAR-2b. The long duration of the elm decline possibly suggests that suitable habitat persisted around the lake. *Pinus* also experienced a reduction at the start of the elm decline, whereas the *Alnus* population increased. This may suggest a rise in the water table to or close to the surface, favouring the growth of *Alnus*. Although not abundant, *S. nigra* type, *P. lanceolata* type, and *Pteridium aquilinum* likely reflect minor human disturbance at the start of the elm decline at Loughbrick Bay. This combined evidence may suggest that a hydrological change and human impact contributed to the elm decline at Loughbrick Bay. An elm-specific disease as a controlling factor has been proposed for other sites in the region (Ghilardi and O'Connell 2013a; Stolze et al. 2013b; O'Connell et al. 2014). A recent study on the chronology of the mid-Holocene elm decline in Ireland indicates that human activity did not consistently coincide with this event (Kearney and Gearey 2020).

In the lake, a diverse aquatic plant community consisting of emergent, floating-leaf, floating, and submerged macrophytes was present. *Botryococcus*, *Pediastrum boryanum* var. cf. *boryanum*, and other green algae occurred. This algal association is indicative of large lakes with eutrophic water conditions and a submerged and littoral vegetation, and it

is typical for Pleistocene and Holocene climatic optima (Jankowská and Komárek 2000). The high organic carbon content in the lake sediments indicates high lake productivity. A change in the lake chemistry occurred at the onset of the elm decline, as indicated by an increase in inorganic carbon, Ca, and Fe. Similar changes were observed at Loughmeenaghan (Stolze et al. 2012), Templevanny Lough (Stolze et al. 2013b), and Cooney Lough (O'Connell et al. 2014). The elevated Fe count rates may reflect increased aeration of the water body as a result of the reduction in woodland cover and loss of its sheltering effect (cf. Stolze et al. 2012). As the solubility of Fe phases is controlled by the redox state of this element, the establishment of aerobic conditions in the hypolimnion can result in the precipitation of Fe.

### Early Neolithic II (LAR-2a; 3780–3620 BC)

Based on the dating evidence, pollen zone LAR-2a corresponds to the Early Neolithic II (3750–3600 BC). The local elm population continued to decline throughout this period, accounting for the main loss in woodland cover. The expansion of pastoral and arable farming as well as disturbance indicators from 3720 BC onwards suggests an increase in human activities ~100 years after the onset of the elm decline. This date is consistent with previous findings that reveal a rapid and abrupt transition to farming in Ireland at ca. 3750 BC (Whitehouse et al. 2014). Temporal delays of about 40–60 years in the increase of human impact after the elm decline were observed at other pollen sites in County Sligo (Stolze et al. 2012, 2013b; Ghilardi and O'Connell 2013a; O'Connell et al. 2014). The increased human impact on the landscape resulted in destabilization of the soil as suggested by a rise in the non-combustible mineral fraction, increased count rates of terrigenous elements, and an acceleration of sediment accumulation in Loughbrick Bay.

The *Pteridium aquilinum* spore values in LAR-2b likely indicate initial gaps in the woodland canopy and later clearance and cultivation activities in the area (cf. Marrs and Watt 2006). *P. lanceolata* formed an important part of the grassland community. Cereal cultivation may have commenced as early as 3770 BC as indicated by the presence of possible cereal type pollen but no later than 3720 BC, when the first *Triticum* type pollen is recorded (Fig. 6; Table 3). The presence of *Aethusa cynapium* type pollen is noteworthy as *A. cynapium* is a frequent component of tilled fields, gardens, and waste places (Webb et al. 1996).

Deposition of *Diporothea webbiae* spores in the sediments increased from 3740 BC onwards, coinciding with the intensification of human activities. An Early Neolithic increase of this spore type also occurred at Lough Dargan (Ghilardi and O'Connell 2013a). Its presence has been related to wet meso- to eutrophic conditions and *Thelypteris palustris* has been suggested as a possible host plant

(van Geel et al. 1986). The Loughbrick Bay record, however, does not indicate an obvious relationship between *D. webbiae* spores and *T. palustris* (Figs. 6, 7). This fungal spore type has also been associated with *Alnus* carr (Prager et al. 2006), and with disturbance and soil erosion due to prehistoric agricultural activities (Hillbrand et al. 2012).

The archaeological evidence from County Sligo corroborates the inferred intensification of human activities during the Early Neolithic II. An earthen mound was constructed at Rathdooney Beg located northwest of the Carrowkeel-Keshcorran megalithic complex (Mount 1999; Fig. 1). Earliest depositions within the monuments of the Carrowmore megalithic complex on Cúil Irra peninsula took place during this period (Bergh and Hensey 2013). Increased activity was also noted at the causewayed enclosure at Magheraboy (Danaher 2007). Sherds of Early Neolithic carinated bowl pottery recovered from a domestic waste pit at Ballydoogan on the Cúil Irra peninsula date to ca. 3700 BC (Grogan and Roche 2013). This is in concert with the Irish archaeological record showing an intensification of anthropogenic activities including the construction of rectangular houses at 3720–3620 BC and mortuary monuments (Whitehouse et al. 2014; McLaughlin et al. 2016).

In the lake, the previously diverse aquatic macrophyte flora was largely replaced by a floating-leaf community consisting of Nymphaeaceae after 3720 BC. The concomitant increase in the abundance of the green algae *Botryococcus* and *Pediastrum* suggests increased lake productivity. This coincided with the beginning of arable farming activities and elevated nutrient availability associated with soil erosion. Increased phytoplankton growth and expansion of Nymphaeaceae in the lake were also inferred from similar pollen stratigraphic levels at Loughmeenaghan (Stolze et al. 2012).

### Middle Neolithic I (LAR-2b; 3620–3450 BC)

The geochronological evidence suggests that pollen zone LAR-2b covers most of the Middle Neolithic I (3600–3400 BC). Following continuous woodland clearance in the Early Neolithic II, open spaces were maintained for ~170 years from 3620 BC onwards. Neolithic human impact was most pronounced during this period. However, the AP values of 85% imply that human impact on the landscape was only moderate when compared to later prehistoric periods (Dodson and Bradshaw 1987; Ghilardi and O'Connell 2013a; O'Connell et al. 2014).

The Loughbrick Bay pollen record indicates that pastoral and arable land as well as ruderal and waste places were comparably widespread during the Middle Neolithic I (Fig. 9). Arable farming was dominated by wheat cultivation until 3490 BC and subsequently transitioned to the cultivation of barley. Pastoral farming intensified after 3550 BC as suggested by the increase in Poaceae: wild grass group

pollen percentages and concentrations and the reduction of *P. lanceolata* type pollen values (Fig. 6). An increase of pastoral farming activities during the phase of most intense human impact was also documented at nearby pollen sites (Stolze et al. 2012, 2013b). The abundance of *P. lanceolata* in grasslands declines notably with increasing grazing pressure (Sagar and Harper 1964).

The NPP record in LAR-2b suggests that deciduous trees in the area were likely infected with wood-decaying fungi (*Kretzschmeria deusta* and *Byssothecium circinans*). Human activities including land-use practices may have caused damage to local trees and consequently facilitated their infection with these pathogens. Intensification of agricultural activities and associated soil instability are reflected in a rise of terrigenous elements (Al, K, and Si) in the lake sediments and an increase in the sediment accumulation rate at the beginning of the Middle Neolithic I at 3590 BC (Figs. 4, 9). The highest sedimentation rate during the Neolithic was attained during this phase of most intense anthropogenic activities of the Middle Neolithic I.

The archaeological record corroborates an increase in human activity in County Sligo during the Middle Neolithic. An activity spike was identified at the causewayed enclosure at Magheraboy between 3700 and 3500 BC (Danaher 2007) and at the Carrowmore megalithic complex, whose structures were most intensely used during the Middle Neolithic I and the beginning of the Middle Neolithic II (Bergh and Hensey 2013). The radiocarbon evidence from the nearby Carrowkeel-Keshcorran megalithic complex suggests that the usage of the megaliths for deposition likely commenced during the later part of the Middle Neolithic I (Fig. 9).

The increased abundance of green algae and Nymphaeaceae basal hair cells (HdV-127) in LAR-2b likely reflects the larger nutrient input to the lake at this time. The floating-leaf community, including *Nuphar*, expanded and emergent macrophytes (*Typha latifolia*) thrived in the shallow water or on exposed mud along the lake shore. The presence *Spirogyra* zygospores suggests shallow and stagnant water (van Geel and van der Hammen 1978). *Cladium mariscus* grew in the shallow-water zone as part of the reed swamp or fen vegetation (cf. Conway 1942). Records of the testate amoeba *Arcella* suggest that open sedge fen vegetation occurred along the lake shore (cf. Prager et al. 2012). The NPP and pollen records indicate that Loughbrick Bay was a highly productive lake during the Middle Neolithic I.

Despite most intensive land use and maximum landscape openness during the Neolithic, inwash of terrigenous matter into the lake from the catchment did not notably increase. Rising Ca counts and inorganic carbon (LOI<sub>950</sub>) data suggest carbonate deposition in the lake during the Middle Neolithic I. As the down-core distribution of both geochemical proxies in LAR-2b diverges from the trend in the terrestrial elements, their increase points to enhanced authigenic

carbonate formation. Photosynthetic utilization of CO<sub>2</sub> by phytoplankton and submersed macrophytes is the main mechanism controlling the deposition of CaCO<sub>3</sub> in lakes (Wetzel 2001). Physical factors such as increasing temperatures can also contribute to authigenic carbonate formation (Kelts and Hsü 1978). Unlike the terrigenous elements, the count rates of P and Fe show low values in LAR-2b. This suggests an association of P with Fe. Due to the adsorption of P to Fe-bearing phases, precipitation and release of P at the sediment–water interface is determined by the redox state of Fe (Wetzel 2001). While oxygen-rich conditions at the sediment–water interface result in the formation of insoluble Fe phases and thus the precipitation of Fe-bound P, anaerobic or reducing conditions lead to the formation of soluble Fe phases and the release of Fe-bound P. The low count rates of P and Fe together with the inferred high productivity of the lake suggest that the production, sedimentation, and decomposition of organic matter led to anoxic conditions in the hypolimnion.

The establishment of very productive lake conditions, more reduced conditions in the hypolimnion, and remarkably high authigenic carbonate formation were also inferred for the phase of most pronounced human impact at Loughmeenaghan (Stolze et al. 2012). Its basin size also allowed the reconstruction of Neolithic lake-level changes, as changing water levels have a much larger impact on the aquatic vegetation and lake chemistry due its smaller water body. The Loughmeenaghan record indicates a drop in lake level at the beginning of the Middle Neolithic I in response to warmer and drier climatic conditions. It is likely that the expansion of the floating-leaf community in Loughbrick Bay was also related to a drop in lake level. Based on the lake bathymetry, a decline in water level should result in a spatial increase of the littoral zone in particular in the north and northeast of Loughbrick Bay (Fig. 3).

### Middle Neolithic II (LAR-2c; 3450–3040 BC)

Pollen zone LAR-2c largely corresponds to the Middle Neolithic II (3400–3000 BC). The onset of this period postdates the age of the lower pollen zone boundary by ~50 years (Fig. 9) and coincides with a change in the geochemical record (see discussion below). The NAP data indicate a decline in human activity around Loughbrick Bay at the beginning of the Middle Neolithic II (3450–3360 BC). The reduced levels of human impact including farming activities favoured the expansion of *Corylus*. A similar decline in human activities and concomitant increase in *Corylus* was also inferred from the Loughmeenaghan record (Stolze et al. 2012). Smaller-scale human impact occurred between 3360 and 3280 BC with a short rebound of more intense farming activities including the cultivation of wheat and barley at the end of this interval. The decline in disturbance and pastoral

pollen indicators in LAR-2c suggests that human impact further decreased after 3280 BC facilitating woodland recovery. *Fraxinus* began to expand from 3240 BC onwards. Total AP values of ~99% suggest closure of the woodland canopy at 3170 BC, with *Corylus*, *Ulmus*, and *Quercus* dominating on the well-drained soils and *Alnus* occurring in wet habitats including the lake edge. Elevated count rates of terrigenous elements indicate inwash of allochthonous material into the lake basin at the time of full woodland cover, suggesting a period of increased rainfall. Evidence for increased precipitation and/or storminess at that time has been documented at nearby Loughmeenaghan (Stolze et al. 2012), from Achill Island and Belderrig in County Mayo (Caseldine et al. 2005; Verrill and Tipping 2010), and at An Loch Mór, on the Aran Islands, County Galway (Holmes et al. 2007).

The decline of human impact during the Middle Neolithic II inferred from the Loughbrick Bay record is consistent with that observed at other pollen sites in County Sligo (Stolze et al. 2012, 2013b; Ghilardi and O’Connell 2013a; O’Connell et al. 2014). The archaeological record from County Sligo also indicates changing levels of activity. Anthropogenic activities ceased at the causewayed enclosure at Magheraboy around 3300 BC (Danaher 2007), whereas the use of the passage tombs at the nearby Carrowkeel-Keshcorran megalithic complex appears to have increased during the inferred period of small-scale human impact at Loughbrick Bay between 3360 and 3280 BC (Fig. 9). In Ireland, there is only little archaeological evidence for settlement activities between 3400 and 3000 BC (Whitehouse et al. 2014; McLaughlin et al. 2016).

Loughbrick Bay experienced a noticeable hydrologic change at the beginning of the Middle Neolithic II as suggested by a conspicuous shift in the values of proxies indicative of changes in the lake environment at 3420 BC. This is reflected in a drop in both the sediment accumulation rate and the representation of Nymphaeaceae basal hair cells (HdV-127) and an abrupt rise of the values of terrigenous elements and the non-combustible fraction. The NPP record indicates that this influx promoted phytoplankton growth despite declining human activity in the area. Unlike the Middle Neolithic I, the terrigenous elements show a negative correlation with both the sediment accumulation rate and Nymphaeaceae basal hair cells (HdV-127). The drop in HdV-127 suggests a decline of the floating-leaf community. The concomitant decrease in the sedimentation rate despite the abrupt high influx of terrigenous material into the lake basin indicates a sudden rise in lake level. The bathymetry of the Loughbrick Bay suggests that a rise in lake level would increase the horizontal area of sediment accumulation and result in a decrease of the sedimentation rate at the deepest point of the lake (cf. Bennett and Buck 2016). The inferred rise in lake level possibly points to increased precipitation, which is in agreement with observations from

Loughmeenaghan (Stolze et al. 2012) and Templevanny Lough (Stolze et al. 2013b). These multi-proxy records suggest multiple intervals of increased precipitation during the Middle Neolithic II.

#### Late Neolithic (LAR-3a; 3040–2640 BC)

Pollen zone LAR-3a covers about two thirds of the Late Neolithic (3000–2500 BC). The Late Neolithic is marked by minor human interference at Loughbrick Bay as indicated by the scarcity of *Pteridium aquilinum* spores, the intermittent occurrence of *P. lanceolata* type pollen at values below 0.1%, and arboreal pollen values of ~96% in LAR-3a. In the woodland, *Ulmus* and *Quercus* further expanded at the expense of *Corylus*. Despite the low activity levels, the archaeological evidence from Carrowkeel suggests use of the megalithic monuments (Fig. 9) and a change in the burial tradition after 2900 BC (Kador et al. 2018).

A change in the woodland composition occurred at 2720 BC as indicated by the decreasing *Ulmus* pollen percentages from 20 to 3%. The timing of this decline in the local elm population is consistent with that recorded at other sites in County Sligo where a Late Neolithic elm decline occurred between ca. 3100 and 2750 BC (Stolze et al. 2012, 2013b; Ghilardi and O'Connell 2013a; O'Connell et al. 2014). The expansion of *Fraxinus* and *Taxus* in the vegetation overlapped with the onset of this decline in *Ulmus*. The pollen and geochemical data in LAR-3a suggest that the spread of both tree taxa coincided with an elevated influx of terrestrial elements between 2890 and 2670 BC, despite a closed woodland canopy. This, and the increase in the sediment accumulation rate at 2890 BC, indicates a prolonged period of abundant rainfall during the Late Neolithic. Similar pollen and geochemical evidence was recorded at Loughmeenaghan for this period (Stolze et al. 2012). As *Taxus* grows best in a mild oceanic climate (Thomas and Polwart 2003), wetter conditions may have triggered the expansion of *Taxus* (Stolze et al. 2012). The spread of *Fraxinus* and/or *Taxus* around the Late Neolithic elm decline also occurred at other locations in County Sligo (Stolze et al. 2012, 2013b; Ghilardi and O'Connell 2013a; O'Connell et al. 2014). As *Ulmus glabra*, the only native elm species in Ireland, and *Fraxinus excelsior* have similar ecological requirements, including high soil moisture, high nitrogen content, and high pH (Thomas et al. 2018), a decline in the elm population would have facilitated the expansion of ash.

#### Late Neolithic/Chalcolithic (LAR-3b; 2640–2270 BC)

Pollen zone LAR-3b corresponds to the final centuries of the Late Neolithic and covers the Chalcolithic period. The pollen spectra in LAR-3b suggest a change in the woodland composition associated with the decline in the local

elm population that commenced in the Late Neolithic and lasted for about 150 years (2720–2540 BC). The increasing *Corylus* pollen percentages and concentrations suggest that the growing conditions for hazel ameliorated during this decline. Openings in the woodland canopy likely boosted pollen production in hazel due to increased light availability (cf. Feeser and Dörfler 2014). *Taxus* and *Fraxinus* further expanded, the latter growing nearby as suggested by clumps of immature pollen grains. Pine, previously a minor component of the vegetation, became rare or locally distinct by 2610 BC as suggested by *Pinus* subg. *Pinus* pollen values of < 1%. This event largely coincided with a major *Pinus* decline in the British Isles at ca. 2500 BC (Bennett 1984), possibly caused by wetter climatic conditions and a rising water table that had a negative impact on pine populations in particular at the margin of their distribution range (Lageard et al. 1999).

Despite AP values of ~95%, increased values of *P. lanceolata* type pollen and *Pteridium aquilinum* spores suggest that human pressure on the landscape around Loughbrick Bay somewhat increased at the transition from the Late Neolithic to the Chalcolithic period. These activities including woodland clearance may have involved burning as suggested by the presence of charred plant fragments in the sediments (Table 2). Increased amounts of macro-charcoal particles were also observed in similar pollen-stratigraphic levels at Templevanny Lough (Taylor et al. 2017a). The non-arboreal pollen spectra suggest that pastoral and arable farming were practiced, including cultivation of barley from 2520 BC onwards. The phytoplankton record suggests that these farming activities resulted in nutrient input and enhanced algal growth in the lake water. There is a notable rise in the count rates of the terrigenous elements Al and K in the sediments and the sediment accumulation rate at 508.5 cm, indicating a notable inwash of allochthonous matter into the lake basin at 2380 BC. The sediment accumulation rate remained high between 2380 and 2290 BC. As this is associated with a decline in disturbance indicators, in particular *P. lanceolata* type pollen, this event seems to be best explained by a period of increased rainfall.

A rise in *P. lanceolata* type, Poaceae: wild grass group pollen, and *Pteridium aquilinum* spore values in the uppermost samples of LAR-3b indicate that agricultural activities intensified at 2290 BC. Increasing pressure on the landscape at that time was also inferred from the Cooney Lough (O'Connell et al. 2014) and Lough Dargan records (Ghilardi and O'Connell 2013a). Evidence for *fulachta fiadh* and burnt mound material suggest possible domestic activities around Magheraboy on Cúil Irra peninsula at the transition from the Late Neolithic to the Chalcolithic (Danaher 2007).



## Neolithic farming in the Lough Arrow region and other parts of County Sligo

This study from Loughbrick Bay provides a well-dated, high-resolution multi-proxy record for Neolithic farming activities in southeast County Sligo, where the large aggregation of megalithic monuments (Fig. 2) attests to intense Neolithic settlement activities. Together with the high-resolution multi-proxy records from Loughmeenaghan (Stolze et al. 2012) and Templevanny Lough (Stolze et al. 2013b), the Loughbrick Bay record allows the reconstruction of Neolithic land-use patterns in the archaeologically important Lough Arrow region.

### The beginning of farming (Early Neolithic I and II)

The Loughbrick Bay and Templevanny Lough records suggest an initially modest anthropogenic impact on the landscape as indicated by low abundances of *P. lanceolata* type pollen and other anthropogenic indicators and high AP values of above 90%. While pastoral farming activities prevailed at Templevanny Lough, there is also evidence for cereal cultivation at Loughbrick Bay during this initial phase of modest human impact. High AP values possibly suggest that cereal cultivation was practiced in small cleared plots in the woodland which is poorly reflected in pollen diagrams (Whitehouse et al. 2014). The earliest possible cereal type pollen grains date to 3770 BC and 3740 BC, respectively (Table 3). This suggests an onset of cereal cultivation at the end of the Early Neolithic I. However, identification of *Triticum* type pollen at 576.5 cm provides an unambiguous start date of arable farming at Loughbrick Bay at 3720 BC. At nearby Loughmeenaghan, the onset of wheat cultivation was dated at 3770 BC (Stolze et al. 2012). Unlike the Loughbrick Bay record, the evidence for arable farming at Loughmeenaghan coincides with the initiation and steep increase of the *P. lanceolata* type pollen curve, suggesting a rapid change to the new economy at that site. These dates are consistent with the evidence for the onset of arable farming at Lough Dargan (Ghilardi and O'Connell 2013a) and Cooney Lough (O'Connell et al. 2014) located north of the study area (Fig. 1). The evidence from County Sligo is in agreement with the onset date of arable farming determined for Ireland at ca. 3750 BC (Whitehouse et al. 2014).

### The main phase of crop cultivation (Early Neolithic II and Middle Neolithic I)

The main phase of arable farming at Loughbrick Bay persisted for about 280 years, covering the Early Neolithic II and the Middle Neolithic I (3720–3440 BC). The presence of both arable and pastoral farming indicators (Fig. 9) suggests that both farming practices were conducted at Loughbrick

Bay during that time. Wheat was the main crop between 3720 and 3490 BC (Fig. 6; Table 3). A charred grain of hexaploid wheat dating to 3630–3350 BC (95% confidence interval) has been recorded from Magheraboy (Cooney et al. 2011), supporting the use of wheat during this time. The archaeobotanical evidence from Ireland suggests that emmer wheat was the dominant cultivated grain during the Early Neolithic II and Middle Neolithic I (Whitehouse et al. 2014; McClatchie et al. 2019).

*Hordeum* type pollen is also documented in the Loughbrick Bay sediments. This pollen type includes pollen of both cultivated and non-cultivated grasses. Because records of *Hordeum* type pollen are sparse and coincide with the occurrence of the anthropogenic indicator *P. lanceolata* type, this pollen type is tentatively interpreted to represent barley. In addition to wheat, barley was also present at the end of the Early Neolithic II (3640–3610 BC) and beginning of the Middle Neolithic I (3570 BC). The Irish archaeobotanical evidence indicates that naked barley was common during the Early Neolithic II (Whitehouse et al. 2014; McClatchie et al. 2019). In the later Middle Neolithic I, barley became the main crop at Loughbrick Bay between 3470 and 3440 BC. Pastoral farming increased during this period after 3550 BC.

The end of the main phase of farming activities including cereal cultivation coincided with the inferred lake level rise at 3420 BC, likely in response to wetter climate (Fig. 9). The appearance of *Drechslera* type spores in the lake sediments between 3420 and 3360 BC is noteworthy. This spore type is produced by fungi that are common pathogens in uncultivated and crop plants such as those of the Poaceae family, which includes barley and wheat (Sivanesan 1987). Infection of crop plants, often facilitated by high humidity (Shaner 1981; Prescott et al. 1986), can result in low yield or considerable loss (Gaur et al. 2006).

Unlike Loughbrick Bay, arable farming at Loughmeenaghan was limited to the Early Neolithic II, where wheat was cultivated for a period of approximately 140 years from 3770–3630 BC. A shift towards pastoral farming practices occurred at the transition to the Middle Neolithic I. Although *Hordeum* type pollen was documented, its nearly continuous presence in the Loughmeenaghan record was interpreted to reflect the occurrence of *Glyceria* along the lake margin rather than cultivation of barley. The only cereal type pollen documented at Templevanny Lough is *Hordeum* type. Based on its association with other pollen types, it was also related to the presence of *Glyceria* (Stolze et al. 2013b). Stable isotope and chironomid data indicate a pastoral based farming economy at this site during the Neolithic (Taylor et al. 2017a).

The palynological evidence from sites located further north of the study area also show local variations in farming practices. While cereal cultivation at Lough Dargan was practiced during the Early Neolithic II and Middle Neolithic

I (3730–3480 BC; Ghilardi and O’Connell 2013a), evidence for arable farming at Cooney Lough is scarce. It has been suggested that mainly pastoral-based farming was practised (O’Connell et al. 2014).

### Decline and abandonment of arable farming (Middle Neolithic II)

Farming impact at Loughbrick Bay declined during the Middle Neolithic II. The pollen record suggests that pastoral farming practices predominated during the 1st century of this period. This is consistent with the evidence from Loughmeenaghan (Stolze et al. 2012) and Templevanny Lough (Stolze et al. 2013b). The presence of *Hordeum* and *Triticum* type pollen in LAR-2c indicates a brief rebound of arable farming between 3310 and 3300 BC. The Lough Dargan pollen record also shows evidence for a short-lived interval of arable farming during this time (Ghilardi and O’Connell 2013a). The paucity of arable farming evidence from County Sligo is consistent with the Irish record where cereal grains were recovered from very few Middle Neolithic II sites (McClatchie et al. 2016). After 3300 BC, human interference with the landscape notably declined in the Lough Arrow region as suggested by low and intermittent *P. lanceolata* type values and rise in AP percentages documented in the pollen records from Loughbrick Bay, Templevanny Lough, and Loughmeenaghan. By the end of the Middle Neolithic II, the woodland had recovered. This decrease in human activity is consistent with an inferred lull in settlement activities in Ireland between 3330 and 3000 BC (Whitehouse et al. 2014).

### Low-level human impact (Late Neolithic)

The pollen record in LAR-3a indicates only weak anthropogenic impact during the Late Neolithic, which is consistent with the observations at Loughmeenaghan (Stolze et al. 2012) and Templevanny Lough (Stolze et al. 2013b). Although cereal type pollen was reported from Lough Dargan at the beginning of the Late Neolithic, it has been suggested that based on the scarcity of other anthropogenic indicators and low Poaceae pollen values farming activities had ceased in the lake’s catchment (Ghilardi and O’Connell 2013a). The Loughbrick Bay multi-proxy record indicates that low-level anthropogenic activities coincided with periods of wetter conditions during the late Middle Neolithic II and most of the Late Neolithic.

### Renewal of farming activity (Late Neolithic/Chalcolithic)

The presence of a cereal type pollen grain and slightly elevated values of pastoral farming and other disturbance indicators at 522.5 cm likely suggest a return to arable and

pastoral farming activities at Loughbrick Bay at the end of the Late Neolithic (2670 BC). Farming activities somewhat intensified in the following centuries, but accelerated at 2290 BC. A Late Neolithic return to agricultural activities at nearby Templevanny Lough occurred at 2720 BC (Taylor et al. 2017a). Cereal cultivation at Cooney Lough (O’Connell et al. 2014) and Lough Dargan (Ghilardi and O’Connell 2013a) recommenced at the beginning of the Chalcolithic period.

*Hordeum* type pollen was the only cereal pollen type documented in Chalcolithic sediments at Loughbrick Bay from ca. 2500 BC onwards, suggesting that barley was the cultivated crop. In comparison to the main phase of crop cultivation in the earlier Neolithic, wetter conditions prevailed during the Chalcolithic. This is in particular shown by the high count rates of terrigenous elements in the lake sediments despite relatively closed woodland cover at 2380 BC. Barley has a wide ecological range and tolerates cooler and wetter conditions than wheat.

## Conclusions

The high-resolution pollen record from Loughbrick Bay provides evidence for Neolithic farming at a site centrally located within an archaeologically important landscape. The inferred timing and nature of farming practices are in concert with Neolithic farming activities in County Sligo and Ireland. The main period of arable farming with wheat being the dominant crop occurred during the Early Neolithic II (3750–3600 BC) and Middle Neolithic I (3600–3400 BC). There is evidence for the recurrence of short periods of crop cultivation during the later Neolithic, with barley being the preferred cereal. Integration of the palynological evidence with proxies that reflect changes in the lake shows that interruption of arable farming often coincided with periods of wetter climatic conditions. The lack of evidence for cereal cultivation at the beginning of the Middle Neolithic II (3400–3000 BC) coincided with a pronounced hydrological change in the lake. The record of fungal spores derived from pathogens that are known to attack cultivated grasses suggests that both climatic and biotic factors may have had an impact on farming practices at that time.

Comparison of the multi-proxy records from within the archaeologically important area in southeast Sligo shows local variations in landscape use during the Neolithic. Human impact and farming practices were of longer duration and more multifaceted at the centrally located lowland site at Loughbrick Bay. This site is characterised by a high visibility of the megalithic monuments in the Bricklieve Mountains and Moytirra uplands. The Bricklieve Mountains likely represented a visually prominent karst upland during the Neolithic (Stolze 2019). The radiocarbon dating evidence from

the Carrowkeel-Keshcorran megalithic complex indicates that the deposition of artifacts in the megalithic monuments mostly coincided with farming at Loughbrick Bay.

In contrast, Neolithic human impact, including farming, was more limited in the periphery of the archaeologically rich landscape around Lough Arrow. While there is evidence only for pastoral farming at Templevanny Lough located in the southwest of the Bricklieve Mountains with limited views of the monuments, both arable and pastoral farming was practiced at Loughmeenaghan. Remains of a passage tomb are found in the vicinity of this lake and the megalithic monuments on the plateaus of the Bricklieve Mountains to the south can be easily seen. This suggests that the landscape around Lough Arrow was well-structured. Sites for farming and settlement in the lowlands seem to have been deliberately chosen based on local landscape characteristics.

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