NATIVE WOODLAND COMPOSITION AND DYNAMICS: A LONG-TERM PERSPECTIVE BASED ON A HOLOCENE POLLEN PROFILE FROM INIS OÍRR, ARAN ISLANDS, WESTERN IRELAND

Michael O'Connell and Karen Molloy
Palaeoenvironmental Research Unit, Department of Botany
National University of Ireland, Galway, Ireland
www.nuigalway.ie/pru
E-mail addresses: michael.oconnell@nuigalway.ie and karen.molloy@nuigalway.ie

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Abstract

A detailed Holocene pollen record, elaborated in the project TIMECHS, is presented from An Loch Mór, a deep lake at the north-eastern end of Inis Oírr, Aran Islands, western Ireland. Close interval sampling, identification of a wide range of arboreal and non-arboreal palynomorphs and a well constrained chronology have enabled woodland development and land-use history to be reconstructed in considerable detail. The pollen data are supported by stomatal records for *Pinus*, *Taxus* and *Juniperus*, all three of which were exceptionally important on Inis Oírr at various times during the post-glacial. The early Holocene woodlands were dominated by hazel, pine, oak and elm and also contained tall shrubs that are seldom recorded in pollen diagrams such as *Viburnum opulus*, *Rhamnus catharticus* and *Sorbus* (probably includes not only *S. aucuparia* but also broad-leaved whitebeams such as *S. aria* and *S. hibernica*). Particularly noteworthy features include the rather open character of the early Holocene woodlands and the evidence for two major perturbations, P1 and P2, which are ascribed to climatic oscillations. The former is of similar age to the 8.2 ka event, a cooling event first described from the Greenland ice cores. The latter perturbation is shorter but the movement of the pollen curves suggests a more pronounced cooling event. In the upper part of the profile, human impact in the form of farming activity (mainly pastoral but with an important arable component from c. AD 800 onwards) is the main, though not the only, forcing factor influencing woodland composition and extent. The final demise of woodland is dated to the late fifteenth/early sixteenth century though occasional trees probably survived into the late eighteenth century. The present-day almost treeless landscape is thus of relatively recent origin.

Introduction

Long-term perspectives on vegetation and particularly woodland development are dependent largely on reconstructions based on evidence gleaned from macrofossil and particularly pollen analyses. The potential of pollen analysis for elucidating the history of Irish vegetation and flora was first seriously realised in Jessen's (1949) classic paper *Studies in the Late Quaternary deposits and flora-history of Ireland* (cf. also earlier publications such as Erdtman 1924; White 1931; Mitchell 1940). In the meantime, many pollen profiles have been constructed from Ireland that elucidate aspects of interglacial, Late-glacial and post-glacial (Holocene) vegetation development in various parts of the country. Beginning with the earliest investigations, trees received particular attention, which is not surprising given the importance of woodland during the Holocene as a whole and also interglacial periods. From a methodological viewpoint, this is also understandable in that arboreal pollen (AP) normally constitutes the bulk of Holocene fossil pollen assemblages and, furthermore, pollen identification of AP is relatively easy even with non-sophisticated microscopy. An obvious exception is Taxus (yew), which went unrecognised in Holocene profiles from Ireland prior to the 1980s. This, and also omissions such as *Fraxinus* in the earliest profiles (e.g. Jessen 1949), reduce the value of results from earlier investigations for reconstructions to modern standards. Furthermore, considerable attention has been paid to the identification of the non-arboreal pollen (NAP) component in more recent investigations (largely ignored in the earlier investigations). The NAP component is essential for reconstructing farming history (Behre 1981) and also documenting changes in limnic and bog environments.

In this paper, the results of pollen analytical investigations of thick Holocene deposits taken from An Loch Mór, Inis Oírr, are presented. While woodland dynamics in a karstic situation such as the Aran Islands can hardly be regarded as typical for Ireland or even the comparable nearby Burren region, the results are of more than usual interest because of the exceptional habitat, the floristic importance and the archaeological evidence for long-term human impact on the natural environment in the Aran Islands. The pollen profile, in itself, is also exceptional given the high temporal resolution (261 pollen spectra), the variety of pollen taxa identified (some 180 palynomorphs; these include non-pollen palynomorphs, i.e. fungal spores, animal microfossils, etc.) and also the high pollen counts (in most spectra >1000; less in uppermost spectra where the pollen concentration is low).

The investigations formed part of the EU 4th Framework project, TIMECHS. Publications to date from this project include a detailed description of Holocene vegetation and land-use dynamics with particular reference to land-use and the archaeological record (Molloy and O'Connell 2004) and an account of tephra investigations and the implications of twelve microtephra layers for the chronology of the profile (Chambers *et al*. 2004). The present paper draws on the information contained in these papers and also the investigations of other TIMECHS partners that are detailed in the Final Report of TIMECHS (TIMECHS 2001; publications in preparation).

Site description

An Loch Mór (the large lake), lies in a sheltered, north/south-running valley at the eastern end of Inis Oírr (grid ref. L 990 020; 9° 30.3'W, 53° 03.5'N; Fig. 1), known in the anglicised form as Inisheer. The lake is c. 460 m long (excluding the neck at the southern end) by c. 200 m wide and attains a maximum depth of almost 23 m. Today, it is slightly brackish (c. 5‰) due mainly to the twice daily incursion of saltwater through the jointed 250-m-wide band of limestone bedrock (narrowest point) that separates it from the Atlantic Ocean at its northern end (aerial photograph, Fig. 1).

The lake is bounded to the north and north-west by low-lying small fields enclosed by high stone walls that are typical for the Aran Islands as a whole (Fig. 1). Today, the fields carry mainly species-rich pastures and meadows but, until the recent past, many of these fields carried crops of potatoes, rye and oats (see below). The soils are largely, or even perhaps exclusively, plaggen soils, i.e. they have been artificially created by the transport of sand and seaweed by the local farming communities onto more or less drift-free, karstic limestone bedrock (Conry 1971). The relatively high ground to the east of An Loch Mór, which slopes steeply to the lake, consists mainly of jointed limestone pavement with a rather sparse vegetation cover. The higher ground on the western side that extends southwards from Formna – a small settlement on high ground overlooking the north-west corner of the lake – slopes down to the lake in a series of cliffs and rock terraces. The short cliff faces and the narrow terraces are covered, to a large extent, with low shrub vegetation. Much of this consists of *Hedera* but taller shrubs such as *Crataegus monogyna*, *Prunus spinosa*, *Euonymus europaeus* and *Cornus sanguinea* are also common (higher plant taxonomy follows Stace (1991)).

The island is virtually treeless. *Corylus avellana* is known only as a nineteenth century record, and *Alnus glutinosa*, *Quercus* and *Ulmus glabra* are not regarded, in descriptions of the present-day and recent flora, as native to the Aran Islands. *A. glutinosa*, *Quercus robur* and *U. glabra* are present on Inis Mór; it is generally presumed that they have been planted (Webb 1980; Webb and Scannell 1983; Roden 1994). *Juniperus communis*, which is common on the two larger islands, was reported in the last century from Inis Oírr but, in the meantime, has become extinct, possibly through use in religious ceremonies on Palm Sunday (Webb 1980).

Today, pastoral farming (mainly cattle and also sheep), some fishing and increasingly tourism are the economic mainstays of the islands. In the past, however, tillage was important. In the 1940s, for instance, the Aran Islands had 139, 28 and 10 ha under potatoes, rye and oats, respectively (average data over 7 years; Central Statistics Office). In addition, there was a small wheat acreage due to the exceptional circumstances associated with World

War II. In all, c. 4% of the total land surface was under tillage, which is relatively high given the highly karstic terrain that includes extensive areas of limestone pavement. At that time, mainly farming and fishing supported a population of c. 2000 (in 1946 the population was 1971). In 1821 Inis Oírr had a population of 417; in 1996 the population was only 274. Since the onset of farming in the Neolithic, Inis Oírr was probably always populated and especially during the Medieval (Christian) period to which most of the archaeological field monuments relate (at least three Church/monastic sites and a late medieval tower house/castle (Fig. 1). Monuments relating to earlier periods include a large stone fort (cf. mid to late Bronze Age and also used in later periods; age assignment relies mainly on the results from excavations of Dún Aonghasa and other forts on Inis Mór; cf. Cotter 1996).

Methods

Coring was carried out using an Usinger piston corer in August 1996 in water depth of c. 23 m, i.e. the deepest part of the lake (Fig. 1). Triplicate, parallel, 8-cm-diameter cores (MOR1, MOR2 and MOR3) were taken within c. 4 m of each other, in 2-m overlapping drives. Core MOR1, the most complete Holocene core (c. 11.55 m of Holocene sediments) was used as the primary sample source for the pollen analytical investigations. Additional samples were taken from the parallel core, MOR2, to fill gaps between the first and second (3 samples) and second and third (16 samples) drives in MOR1. Samples of 1-cm thickness were used, apart from the basal part of the sequence, which was continuously sampled by taking mainly 0.5-cm thick slices. Four samples were also analysed from a 1-m top core taken by a Mackereth corer in June 1999 (designated as subzone D28). High representation of *Potamogeton* sect. *Coleogeton* pollen in the Mackereth core and the uppermost spectrum from MOR1 (c. AD 1950/60) shows that these two records overlap.

Pollen have been identified to the lowest taxonomic unit that is compatible with secure identification. Cereal-type pollen (includes only those pollen ≥41 μm) were distinguished from other Poaceae pollen on the basis of size of grain, pore and annulus, and *Secale*-type were distinguished as a separate taxon (cf. Beug 2004).

Data presentation

The primary pollen data are presented in percentage pollen diagrams relating to the earlier, and mid and later parts of the Holocene (Figs. 2 and 3, respectively). These are supplemented by pie and bar charts (Figs. 4 and 5, respectively). The percentage curves are based on a total terrestrial pollen (TTP) sum, i.e. aquatics, etc. are excluded from the divisor used for calculating the percentage values. Pollen concentration values (curves not provided) are also referred to where appropriate.

The pollen diagrams have been zoned as follows to facilitate description and evaluation. Major biostratigraphical units are recognised as superzones A-D (Table 1). The superzones are defined on the basis of large movements in several pollen curves, and especially the relative contributions of arboreal (AP) and non-arboreal (NAP) pollen taxa. The superzones, in turn, are divided into local pollen assemblage zones (referred to as zones; in some instances, subzones are also distinguished; Table 1) on the basis of less pronounced but nonetheless important changes in pollen representation.

The chronology for the pollen profile relies on several lines of evidence including AMS 14C dates, tephra, pollen stratigraphy and varve analysis (TIMECHS 2001). While the chronology is regarded as sound, it is important not to underestimate the error ranges that are inevitably associated with a chronology based on connecting points that are not absolutely fixed (apart from tephra-based dates). Dates are cited as calibrated AD/BC years (indicated as AD or BC). Dates in calibrated BP years (cal. BP; obtained by the addition of 1950 to AD/BC dates) and non-calibrated 14C years (BP) are also occasionally cited.

The classical pollen zones, i.e. Preboreal, Boreal, Atlantic, Subboreal and Subatlantic, are sensu Mitchell (1956) (cf. also Table 1.7a, Mitchell *et al.* 1996). These are used mainly as reference points; they are not intended to have any climatic and chronological (apart from the Elm Decline at the Atlantic/Subboreal transition) significance.

Cultural periods are as generally recognised in the archaeological and historical literature relating to Ireland (cf. Molloy and O'Connell 2004; Waddell 1998). The Neolithic is regarded as beginning shortly before the Elm Decline which is usually regarded as dating to c. 5100 BP or 3800 BC. The Bronze Age is considered to begin at c. 2400 BC or 3900 BP. It is subdivided informally into early, middle and late Bronze Age, the transitions to middle and late Bronze Age being placed at c. 2000 BC (3700 BP) and 1200 BC (3100 BP), respectively. The Bronze Age/Iron Age transition, which is poorly defined in the archaeological record, is placed at c. 700 BC (2600 BP). The subdivision, late Iron Age (c. AD 100-500) is based on palynological criteria rather than the archaeological record. The subdivisions, early and middle Iron Age, are informal divisions though the latter equates approximately to the La Tène period. The beginning of the Medieval period is regarded as contemporary with the spread of Christianity, which also marks the beginning of the historical period. The mid-/later Medieval period includes historical developments such as the period of strong Viking influence (c. AD 830-1000) and the arrival of the Normans in Ireland (AD 1169) and their subsequent expansion.

Table 1. *Biostratigraphical zonation of profile MOR1, An Loch Mór, Inis Oírr.*

Superzone / Zones	Main features (pollen data, vegetation development and cultural period)	Depths (cm)* / Ages (approx.)
Superzone D / Zones D1-D2	Historical period characterised by strong human impact and final demise of woodland	2642-2226 / AD 500-1990
Superzone C / Zones C1-C9	Subboreal to early Subatlantic, i.e. from the Elm Decline to the end of the Late Iron Age Lull (prehistoric farming periods, i.e. Neolithic to Iron Age)	3210-2642 / 3650 BC-AD 500
Superzone B / Zones B1-B3	Boreal and Atlantic periods. Maximum woodland development. Spans the Mesolithic; probably includes the beginning of the Neolithic	3454.5-3210 / 8070-3650 BC
Superzone A / Zones A1-A2	Younger Dryas/Holocene transition and pre-Boreal (Corylus has not expanded)	3472-3454.5 / 9420-8070 BC

** Depths are with respect to the lake water surface; the water column is c. 23 m. Sediment depths have been adjusted to allow for expansion of the sediment after coring, etc.*

Description and interpretation of the fossil pollen record

Zone YD (end phase of Younger Dryas; 9500-9600 BC)

This zone relates to the final phase of the Late-glacial, i.e. the uppermost part of the Younger Dryas and is presented here for completeness and to give context to the Holocene part of the record. It includes two contiguous pollen spectra from the top of the Younger Dryas sediments. Non arboreal pollen (NAP) dominate (68%) with Poaceae, *Thalictrum* and Cyperaceae the main contributors. The vegetation was not only treeless but shrubs were also unimportant. For instance, *Juniperus* achieves only 1% and ericoids were not recorded. The sediments are highly minerogenic, which suggests active solifluxion, i.e. in-wash of raw, mineral-rich soils as a result of freeze-thaw action. The average air temperature in the warmest month may not have exceeded 6°C while the corresponding winter temperature may have been as low as -20°C (O'Connell *et al.* 1999; Atkinson *et al.* 1987). Such conditions are not conducive to the growth of tall shrubs and trees.

Zone A1 (Early pre-Boreal; 9500-8750 BC)

The Holocene record commences with zone A1, which consists of ten contiguous pollen spectra and so the record may be regarded as continuous.
Noteworthy features include:

- A gradual and sustained increase in *Betula*, fern spores (also fern annuli) and *Filipendula*.
- A sharp peak (28%) in *Juniperus*. The *Juniperus* stomata curve is almost continuous.
- Initial high values for Poaceae, *P. lanceolata* and *Campanula*-type. A single pollen of *Gypsophila fastigiata/repens*-type is recorded (subzone A1).
- Total terrestrial pollen concentration values increase steadily in this zone from an initial 17 300 to 61 400 grains cm^{-3}. This is accounted for mainly by an increase in the woody component (mainly *Betula* but also *Juniperus*).

Interpretation

The basal spectra record the transition from open grass-dominated to shrub-dominated plant communities, consisting mainly of juniper and also birch – presumably tree birch, *B. pubescens* – with a well-developed fern component. The continuous curve for *Juniperus* stomata, combined with substantial pollen representation, shows that juniper persisted locally while birch expanded. Herb communities were also important. These communities changed from being initially grass dominated with *P. lanceolata*, *Rumex* (possibly also *Oxyria*) and *Campanula* (may include *Phyteuma*; subzone A1) to communities where the relative importance of grasses and sedges declined and *Filipendula* (presumably *F. ulmaria*, the meadowsweet) flourished (subzone A1).

A mosaic of tall shrub and herb-dominated communities is envisaged for this time. As regards the presence of a thermophilous element, the evidence is not entirely unambiguous. *Pinus* and *Corylus* have values of 1% in several spectra. Overall pollen influx is low and so long-distance transported pollen, even if infrequent, is expected to be relatively well represented in percentage data. Rather significantly, *Pinus* stomata were not recorded.

At the base of the zone, the sediments change from highly minerogenic to lighter coloured, i.e. relatively marl-rich sediment with a noticeable silt component. The uppermost two samples are from dark, organic-rich fine sediments, i.e. sediments that are characteristic of the next zone. This probably signals a climate shift that was probably small, a conclusion based on the rather modest shift in composition of the pollen assemblage.

Succession involving expansion of thermophilous plants, such as hazel and tall canopy trees, might be expected, given the rather long time period represented (>700 years). It is assumed that climatic rather than edaphic conditions inhibited more rapid establishment and expansion of the full complement of thermophilous woodland species. Micropropagules were probably not available because plant migration, at a regional scale, was inhibited by unfavourable climate.

Zone A2 (Late pre-Boreal; 8750-8050 BC)

In this zone, a record based on fine resolution (mainly 0.5-cm thick samples; 15 spectra in all) continuous sampling is available. *Betula*, at c. 30%, dominates the pollen assemblage and *Corylus* begins to rise rather sharpy as the zone ends. *Juniperus* and also *Juniperus* stomata are well represented. In the upper part of the zone a substantial *Viburnum opulus* curve is initiated. This tall shrub is seldom recorded in Irish pollen diagrams (see below).

NAP continues to be well represented, especially *Filipendula*, Poaceae and *P. maritima*. There are minor but more or less continuous curves for other herbs such as *Helianthemum* and Asteraceae (cf. Liguliflorae and Tubuliflorae curves) as well as the ferns *Botrychium* and *Ophioglossum* that are associated with grassland. There are two records for *Gypsophila fastigiata/repens*. Today, *G. fastigiata* and *G. repens* have rather different distributions; the former is regarded as continental-type and the latter as strictly 'alpine' (cf. Webb and Moore 1982). Both species and also several of the other NAP curves (esp. *Helianthemum*, *Rumex*-type and *Caryophyllaceae taxa* (undifferentiated, i.e. excluding **Gypsophila**) suggest a continental-type climate in which winter temperatures were depressed. TTP concentration is higher than in zone A1 and interestingly *Juniperus* has similar concentration values to those in zone A1. This suggests that *Juniperus* percentage representation is depressed by the increased input of AP that consists mainly of *Betula*.

Interpretation

In this zone, birch (presumed to be tree birch, *B. pubescens*) achieved maximum development. Hazel was undoubtedly present at least towards the end of the zone (apart from the basal spectrum it is >1% and achieves 20% in the uppermost spectrum) when *V. opulus* (guelder rose) also achieved importance. Today, this tall shrub occurs sparingly on Inis Mór though it is common in the limestone areas of N. Clare and E. Galway. The pollen profile by Watts (1984) from Gortlecka, SE Burren, also shows a more or less continuous curve for *V. opulus* during the early Holocene. It was probably rather frequent on karstic terrain on the Aran Islands and in nearby Clare and Galway where limestone dominates (on-going investigations indicate that it was common in the Corrib lowlands (A. Bingham, unpublished data)).

Tall canopy trees were probably not yet locally present. *Pinus* achieves only c. 1%, *Quercus* is mainly <1% and only occasional pollen of *Ulmus* were recorded. Significantly, *Pinus* stomata were not recorded (points strongly to absence), which contrasts with the substantial record for *Juniperus* stomata.

Despite the strong development of birch-dominated woodland, open herb communities persisted. *Helianthemum* was relatively important throughout and also *Campanula* (probably *C. rotundifolia*) and possibly *Phyteuma* species, though this genus is not represented in the present-day Irish flora. *Empetrum* (crowberry; included in the curve for Ericoids) was also present (also in zone A1) but it was a minor element of the flora (<1%;), which is not surprising given the calcareous substrate.

Though climatic amelioration relative to conditions pertaining during zone A1 had occurred, the climate probably remained rather strongly continental with severe winters which would explain the poor development of thermophilous taxa. Lake levels appear to have been much shallower than today. This is suggested by a substantial *Littorella* curve (c. 2-3%; this semi-aquatic typically grows on gently sloping lake-shore where it is subject to more or less continuous immersion in rather shallow waters), consistent records for *Hydrocotyle vulgaris* (wet rather than submerged habitats) and the records for true aquatics such as *Myriophyllum spicatum* (main contributor to the *M. spicatum/verticillatum* curve). Precipitation was probably depressed and summer evapotranspiration levels were probably higher than today as a result of greater seasonality resulting from the orbital configuration of the earth *vis-à-vis* the sun at this time (Kutzbach and Ruddiman 1993).

As the zone ends, hazel had established itself locally (in uppermost spectrum it achieves 20%) and had begun to expand, mainly at the expense of birch. This was probably in response to climatic amelioration that also resulted in higher pollen productivity (pollen concentration has risen to 1.06×10^5 grains cm^{-3}).

Zone B1 (Boreal period; 8050-5310 BC)

In zone B1, arboreal pollen (AP) clearly dominates for the first time, with an average of 79%. The main contributors are *Corylus*, *Pinus*, *Quercus*, *Ulmus* and *Betula* in order of decreasing percentage pollen values. A high NAP diversity, however, persists though values are generally low. *Rhamnus catharticus* is represented by a continuous curve (no comparable records available for Ireland) and *V. opulus*, which expanded in zone A2, continues to be strongly represented. Alnus is consistently represented at low values (generally <0.5%) in the upper part of B1. Pollen concentrations are much higher than in zone A2. AP increase from c. 50 000 to c. 200 000 grains cm^{-3} mainly as a result of a large increase in *Corylus*.

Interpretation

Tall canopy woodland had developed though 100% closed cover was not achieved, which is most atypical for the Boreal period in Ireland and NW Europe generally.
Detailed palaeoenvironmental reconstruction is considered firstly in the context of three subzones (B1α, Bβ and B1γ) and, secondly, with respect to evidence for two perturbations in the woodland cover (P1 and P2). In subzone B1α, hazel expanded rapidly and became the dominant woodland species. It largely displaced birch. At the same time, pine expanded locally (cf. records of *Pinus* stomata) and presumably also at a regional level. Oak, and also elm, may have been present but as minor elements. Open areas persisted where herbaceous plants, such as Poaceae, *Filipendula*, Asteraceae (Liguliflorae and Tubuliflorae) and *P. lanceolata*, flourished.

In subzone B1β, pine expanded further, and oak and elm were almost certainly present but remained minor elements of the hazel (*Corylus* achieves highest overall representation at *c.* 50-60%) and pine-dominated woodlands. Juniper persisted but is greatly reduced in importance, especially near the lake (only one sample with stomata in zone B1). A slender curve for *R. catharticus* suggests local presence, presumably near the lake margin, i.e. the type of habitat that it frequently occupies in the Burren today and also on Inis Mór and Inis Meáin. Today, it is rare on both these islands and has not been recorded from Inis Oírr (Webb 1980). A rather substantial *Helianthemum* curve (continuous representation also in zone A2) and more or less continuous curves for several NAP (cf. *P. lanceolata, Filipendula* and Chenopodiaceae) indicate persistence of some open habitat devoid of woodland cover.

In subzone B1γ, oak expanded further (especially above P1) and became more important than pine. Elm also expanded but to a lesser degree. A continuous curve for *Hedera* (ivy) is initiated (7100 BC), NAP increases somewhat in importance and *P. coronopus,* which today is strictly limited to a narrow coastal strip (unlike *P. maritima* which in Ireland occurs far inland, e.g. it is common in grasslands in the upper reaches of turloughs in the eastern Burren), forms an almost unbroken curve throughout this subzone. The importance of pollen of shrubby species, e.g. ivy, and the persistence and diversity of the NAP component point to woodlands with a relatively open character and possibly limited areas more or less totally free of trees. Subzone B1γ includes features referred to as P1 and P2 that are now considered.

Evidence for perturbations in the Boreal woodlands

Two perturbations, P1 and P2, were detected at an early stage of the analyses and have been elaborated in some detail by close interval sampling.

P1 (6500-6250 BC; 8450-8200 cal. BP). P1 spans a 14-cm interval (nine pollen spectra between 3406-3393 cm). Palynologically, it is characterised as follows:

1. Increased *Corylus* and *Juniperus* (achieves 10%; *Juniperus* stomata are also recorded; concentration values also show a distinct increase).
2. *Pinus*, *Betula* and especially *Quercus* values are depressed.
3. NAP remain more or less unchanged but the fern *Ophioglossum* is consistently recorded and *Pteridium* expands.

4 TTP concentration remains high but *Pinus* and *Quercus* decline as in the percentage curves.

Tall canopy trees (especially oak, birch and pine; cf. few *Pinus* stomata) declined at the onset of P1. The expansion of *Juniperus* (particularly mid-way in the perturbation) suggests increase in juniper pollen productivity and presumably also the juniper population. This was presumably facilitated by increased openness in the woodland structure that probably also stimulated flowering of hazel. The overall changes suggest substantial woodland perturbation that persisted over a rather long period (c. 250 years). Its cause presumably lay in an external forcing factor such as climate change (e.g. increased storminess, lower precipitation levels, etc.) that operated over a considerable period rather than a catastrophic event of short duration (within the perturbation there may have been a particularly short-lived sharp downturn that is signalled by the *Juniperus* peak).

Changes in the limnic environment are suggested by increased representation in the alga *Botryococcus*. However, *Pediastrum*, which often responds positively to perturbations in a catchment that result in increased mineral input through soil inwash, shows no response.

P2 (5650-5530 BC; 7600-7480 cal. BP). P2 spans an 8-cm interval (continuous sampling between 3361-3354 cm). Palynologically, it is characterised as follows:

1. *Corylus* representation decreases from 50% to 30%, approximately.
2. *Betula* increases (c. 4% to 14%); also *V. opulus* and, to a much lesser degree, *Juniperus* (from <1% to *c.* 2%). *Pinus* increases in the upper part of the interval.
3. NAP are somewhat elevated, especially Poaceae, but the *P. coronopus* curve is interrupted.
4. TTP concentration values are lower and especially *Quercus* and *Corylus*.

These features suggest rather profound changes as birch, pine and to a small extent juniper were favoured at the expense mainly of hazel and also oak. Herbaceous communities showed only a weak response, expressed mainly as elevated Poaceae representation. The beginning of the perturbation is marked by an expansion of *Pteridium*, a fern normally favoured by woodland disturbance and opening-up of the canopy.

These vegetation changes suggest increased continentality (less precipitation; increase in seasonality) that shifted the competitive balance away from hazel and in favour of birch. The subsequent expansion of pine at the expense of birch is comparable to developments characteristic of the early part of interglacial cycles. As in these cycles, this development was probably the result of a recovery in the thermal environment as climatic conditions similar to those pertaining before the perturbation were restored.

Two additional features in zone B1 are worthy of note. Firstly, the course of the *Alnus* curve which, apart from being indicative of the spread of alder, also marks the transition from the Boreal to the Atlantic period. A more or less continuous curve for *Alnus* begins immediately after P1, but in P2 the *Alnus* record consists of usually two, rather than single, pollen as hitherto in each spectrum. Alder was probably present from the end of P1 (6200 BC), at least at a regional level.

The second feature relates to a pollen spectrum derived from the calcite layer, M1 (depth 3380 cm), at approximately mid-way between P1 and P2 (forms the lowermost of four well-defined layers, M1-M4, in the lower part of the core sequences). The precipitation of calcite is normally associated with a shift in the chemical equilibrium within a lake that involves uptake of CO_2 by aquatic plants, including algae. Conditions must also be such as to inhibit re-solution of calcite as it descends through the water column and enters the sediment. Layer M1 was *c.* 15 mm thick and had a particularly sharp lower boundary. When sampling this layer for pollen analysis, care was taken not to include any of the adjoining organic-rich sediment.

The pollen spectrum shows slightly elevated values for *Pinus* and ferns, and lower values for *Corylus* and *Ulmus*. This suggests that the layer was formed in late spring/summer, i.e. after hazel had finished flowering and pine was still flowering (late May). AP concentration values are substantially lower (*c.* 50%), which is as expected if the layer was deposited within a short time period – possibly over several days or weeks.

Zone B2 (Early Atlantic period; 5310-4500 BC)

The base of zone B2 is regarded as the Boreal/Atlantic transition (BAT), a key feature of which is the rise in *Alnus,* which began to increase near the top of zone B1 (see above). The zone boundary is placed where *Alnus* exceeds 1% for the first time. The zone is also characterised by a steady decline in *Corylus* (from *c.* 50% to 35%). There is a marked rise in the aquatic *Myriophyllum spicatum* near the base of the zone.
Near the base of this zone, the lithology changes from relatively dark to a light grey, relatively marl-rich sediment. Upwards in the sequence, the marl content increases and laminations, which are seasonal (varves), were recorded from near the base of zone B3 to mid-C2 (Fig. 3B). Laminations, though weaker and less regular, begin immediately below P1 in subzone B1(where the marl content increases (Fig. 2A).

Interpretation

Alder expanded in the context of oak-pine-hazel-elm woodlands, but population levels remained modest. *Alnus* averages 2.4% in zone B2, and 7.7% over zones C1-C5, i.e. the interval during which it is most strongly represented. These values are low, particularly in the context of a very high pollen producer with high pollen dispersal. That alder failed to expand substantially is hardly surprising given the general scarcity of suitable wet habitat in the karstic terrain. The base of the zone and the expansion of *Alnus* is dated to 5300 BC (c. 6700 BP) but alder may have been present locally for a century or more prior to this (see zone B1; also supported by macrofossil finds; J.N. Haas in TIMECHS 2001).

Another major change during zone B2 was the decline of hazel in favour of oak. Hazel pollen production may have been adversely affected by increased shade from oak and pine, but it is likely that the contribution of hazel to the woody vegetation as a whole also declined. *Fraxinus* is consistently recorded (in 12 of the 15 spectra), which suggests presence of ash as a minor component of the woodlands. Near the top of the zone, *Taxus* pollen is recorded so that yew may also have been present as the zone ends.

Shrubs Smaller woody taxa such as *R. catharticus, V. opulus* and *Hedera* continue to be important. These shrubs are probably under-represented in the pollen record because of low pollen production and dispersal capacities, particularly given the largely wooded landscape.

The relatively high *Myriophyllum spicatum* values (also leaf fragments noted by J.N. Haas; TIMECHS 2001) for most of the zone suggest lowering in lake levels, which in turn points to less precipitation and/or increased temperatures especially during summer months and hence increased evapotranspiration levels. Such a climatic scenario is the opposite to that traditionally associated with the Atlantic period.

Pollen spectrum 3298 cm is from the well defined calcite layer, M2. *Pinus* and *Myriophyllum* have increased representation that, as in the case of M1, points to deposition during the summer period.

Zone B3 (Late Atlantic period including possibly the earliest Neolithic; 4500-3650 BC)

The course of vegetation development during the past *c.* 6500 years has been considered in detail in an earlier publication (Molloy and O'Connell 2004). The present account is confined to detailing the main developments with particular emphasis on woodland dynamics and the interplay of human activity and climate on vegetation developments.

Zone B3 is differentiated from the preceding zone mainly by the initiation of a substantial curve for *P. lanceolata* with an average value of 4.1% and a range 1.5-7.5%. This contrasts with occasional records in zone B2. The trend towards declining *Corylus* values continues and *Pinus* (also *Pinus* stomata) and *Quercus* are more strongly represented. Other features include the initiation of an *Ilex* curve and consistent records for *Fraxinus* and to a lesser extent *Taxus*. Pollen concentration values remain stable.

Interpretation

Woodland with oak, pine and hazel as the main components continued to dominate. The pine stomatal record indicates that pine was important in the vicinity of the lake shore. Tall shrubs such as *R. catharticus* and *V. opulus* continued to flourish and holly was an important element in the flora for the first time (from *c.* 4100 BC).

A strong expansion of *P. lanceolata* prior to the Elm Decline is unknown in NW European pollen diagrams. However, recent detailed pollen diagrams from western Ireland show a slender curve for *P. lanceolata* that began before the Elm Decline, i.e. at *c.* 4000 BC (5300 BP) in the L. Sheeauns profile, NW Connemara, where an *Ilex* curve is initiated at about the same time (Molloy and O'Connell 1991, O'Connell and Molloy 2001). Clearly, the opening up of the mid-Holocene woodlands and the development of grassland communities occurred earlier, and to a greater extent, in parts of western Ireland than previously realised. Another aspect of note is the failure of Poaceae and NAP in general (also *Pteridium*) to expand. Conditions that favoured ribwort plantain but not grasses and herbs of open habitat over a relatively long period are difficult to envisage from a present day perspective.

Woodland cover on Inis Oírr was probably never as closed as on the mainland and so an environmental change that adversely affected trees and tall shrubs would almost inevitably lead to openings in the woodland cover into which herbaceous species, which were already well represented locally (cf. P1 and P2), could expand.

There is lack of evidence as to the nature of the environmental changes that resulted in opening up of the woodland cover. Neolithic farming is a possibility though unlikely. Cereal-type pollen are recorded but these probably arise from non-cultivated grasses rather than cereals (Molloy and O'Connell 2004). It is generally accepted that there was a Neolithic presence in Ireland as early as *c.* 4000 BC (5300 BP), but secure evidence is not yet available for a presence several centuries prior to this (cf. O'Connell and Molloy 2001).

Varve formation was initiated immediately above the B2/B3 boundary, continued throughout zones B3 and C1 and ceased mid-way through zone C2 (Fig. 3B; T. Saarinen in TIMECHS, 2001). Within-lake conditions, at least as regards sedimentation processes (e.g. absence of perturbations that might give rise to mixing, etc.) were probably relatively stable throughout this period. Lake levels possibly rose, which is suggested by the decline in *M. spicatum* (Fig. 3B).

It is concluded that the human factor was not responsible for the significant shift in vegetation composition and woodland cover. Likewise, changes in edaphic conditions were hardly responsible given that any soil parent material deposited in the course of the last glaciation was probably already lost by the end of the Younger Dryas, i.e. the beginning of the Holocene (G. Schettler, unpublished data). The best explanation probably lies in climate forcing, though again it is difficult to envisage the nature of a climatic shift that could have resulted in such profound changes in the terrestrial vegetation.

Zone C1 (Early Subboreal/Earlier Neolithic; 3650-3350 BC)

A sharp fall in *Ulmus* representation is recorded across the lower zone boundary (from *c.* 6 to 0.7%) which is followed by a recovery. *Pinus* declines and *Pinus* stomata are recorded only in the two lowermost spectra. *Corylus* falls to overall lower representation (c. 23% as against 30%) but *Alnus* and *Betula* increase. Curves for shrubs such as *R. catharticus, V. opulus* and *Ilex* are interrupted and *Hedera* has very low representation. On the other hand, NAP and especially Poaceae, *P. lanceolata,* Liguliflorae and Rubiaceae, have increased representation (the pastoral indicator component of the NAP increases from *c.* 10% to an average of 26%; cf. Fig. 4). The concentration curves follow a similar pattern.

Interpretation

The classic Elm Decline of NW European pollen diagrams, which is datable to *c.* 5800 cal. BP (5100 BP), is recorded at the base of the zone. A Landnam-type event (clearance for Neolithic farming) was probably involved but, given the pronounced decline in *Ulmus* representation, a disease, with effects similar to recent Dutch Elm epidemics, may also have played a key role. The substantial increase in NAP, and especially Poaceae and *P. lanceolata*, suggests rather extensive grassland that was created at the expense of elm, hazel and also pine and oak. The interruption in the *Pinus* stomatal record suggests that pine growing near the lake margins was also cleared. Algal growth was favoured (cf. *Pediastrum* and *Botryococcus)* probably as a response to increased inwash that followed woodland clearance.

Zone C2 (Early Subboreal (later part); mid-Neolithic; 3350-3150 BC)

Zone C2 is essentially a transitional zone between C1 and C3. It is characterised by steadily increasing *Pinus* and *Corylus* curves. *Pinus* achieves a maximum for the profile (33%; also stomata are frequent). Poaceae values decrease steadily, *P. lanceolata* declines sharply and NAP, in general, decline. AP concentration values are exceptionally high at the top of the zone, which suggests greatly increased input of arboreal pollen.

Interpretation

Strong regeneration of woodland took place in a post-Landnam context, which lead briefly to the dominance of pine, at least in the vicinity of the lake. Hazel was also important in these pine-dominated woodlands. It is interesting that, at this time, pine out-competed oak and elm, both of which had begun to regenerate strongly as zone C1 closed, but yet failed to become the dominant trees. The re-establishment of a curve for *Juniperus* suggests that the pine, oak and hazel-dominated woodlands were not totally closed.

An expansion of pine at about this time (mid-Neolithic) is unusual in Irish pollen diagrams. Where an expansion is recorded, it dates to a few centuries later and is normally attributable to a so-called flush of pine on blanket bog surfaces (O'Connell and Molloy 2001). On Inis Oírr, however, there is no bog or possibility for bog development, yet pine had the competitive edge over the tall canopy deciduous trees, presumably as a result of an unusual combination of edaphic and climatic conditions.

Other indicators of environmental change at this time include the cessation in varve formation at 3173 cm, i.e. as *Pinus* expanded sharply. Above this, the sediment is dark, organic-rich and massive, and has few or only faint laminations. The sedimentation process has changed and the seasonal pattern, whereby calcite-rich sediments were deposited in spring and summer followed by darker, more organic-rich sediments in autumn and winter, has broken down. What caused these changes at *c.* 3200 BC is unclear; given that farming activity had already declined, climatic factors probably played a critical role.

Zone C3 (mid-Subboreal; late Neolithic;3150-2950 BC)

Arboreal pollen peaks in the profile (94%; also maximum concentration values are recorded). This is achieved through a major expansion of *Taxus,* which peaks at 37% (3158 cm; 3050 BC).

Interpretation

There is a major change in woodland composition as yew expanded to become the dominant tree. This occurred at the expense of all trees (ash is an exception though it remains a minor component; *Fraxinus* maximum: 4.3%) and especially pine. *Pinus* stomata are frequent, which suggests that, though pine declined, it still persisted in the vicinity of the lake where it may have successfully competed with *Taxus* (*Taxus* stomata are poorly represented). A fruit of *B. pubescens* suggests local presence of birch (J.N. Haas in TIMECHS 2001).

Low NAP (minimum 0.9%) and low values for tall shrubs (*R. catharticus, V. opulus*, etc.), and greatly reduced pollen diversity serve to further emphasise the closed woodland cover with high shade due to dominance of yew. Woodland regeneration was facilitated by much reduced – and quite probably cessation – of human activity, though it is assumed that the population dynamics of the various woody species were modulated by factors such as edaphic and climatic conditions rather than changing levels of human activity.

Zone C4 (mid-Subboreal (later part); early and mid-Bronze Age; 2950-1750 BC)

At the base of the zone, *Taxus* falls initially sharply to *c.* 10% and then in a series of steps to 4%, 2% and, from 3050 cm onwards (shortly after 2200 BC), to usually less than 1%. On the other hand, NAP have high values and especially Poaceae and *P. lanceolata*, both of which average 10%. Three subzones are recognised based mainly on movement in the NAP curves.

Interpretation

At the base of the zone, a major clearance is recorded that affected mainly yew, the dominant tree. This facilitated the short-term expansion of willow (*Salix*) and *Osmunda*, the royal fern. The clearance occurred in the context of pastoral farming (cereal-type pollen are rare until the early medieval period when rye was introduced). Fire was important and may have had a role in woodland clearance (peak in micro-charcoal). In the upper part of the zone there is a shift in woodland composition that favoured hazel at the expense of pine.

As the period progresses there is a gradual shift in woodland composition so that by the middle of the zone (c. 2100 BC) yew, though still present, was a minor component and pine became increasingly less important though the stomatal record indicates continued local presence.

The high diversity of NAP suggests grasslands with high species diversity, e.g. Liguliflorae (dandelion-type), Tubuliflorae (daisy-type), Rubiaceae (probably includes *Galium*, *Rubia* and *Asperula*) and *Botrychium* (moonwort, a small grassland fern). In subzone C4β, lower *P. lanceolata* values (average: 7.5%) and an increase in *Corylus* suggest reduction in farming intensity over about two centuries centred on *c.* 2100 BC. This is followed by a particularly intensive farming phase during which *P. lanceolata* averages 12.8% (*P. coronopus* also frequent here; subzone C4γ, i.e. shortly after 2000 to 1750 BC).

Spectrum 3036 cm is from the calcite layer, M4. The pollen composition is comparable to that in adjacent spectra. Pollen concentration, however, is low, which suggests rapid deposition.

Zone C5 (Late-Subboreal; most of Mid-Bronze Age and early part of Late Bronze Age; 1750-1050 BC)

Quercus, *Corylus, Alnus* and *Fraxinus* are well represented (at least equivalent to, or exceeding, the representation in C4) while *Pinus* declines steadily to reach 2.4% at the end of the zone. NAP representation falls steadily; *P. lanceolata*, for instance, averages 7.1% compared with 10.2% in zone C4 and other NAP curves are interrupted (e.g. *Filipendula*).

Interpretation

There is a shift from woodland in favour of grassland, presumably as a result of reduced farming activity particularly towards the end of the zone. Oak, hazel and alder were the main woody plants, ash and yew (local presence confirmed by shoot fragments in a sample from middle of zone; J.N. Haas, TIMECHS 2001) were of minor importance. Pine declined steadily in importance so that by the end of the zone it was probably less frequent than ash. Since other trees do not decline and human activity wanes, the decline of pine is hardly attributable to anthropogenic factors. Conditions were such that pine seems to have lost its competitive ability *vis-à-vis* other trees. This was probably the result of a shift in climatic conditions.

The expansion of *R. catharticus* is noteworthy as well as the short-lived increase in juniper at the end of the zone. Juniper expansion was probably facilitated by removal of oak and hazel. Farming activity at this time may have been extensive rather than intensive, which could explain the delayed response in *P. lanceolata* (does not expand until zone C6).

Zone C6 (early Subatlantic; late Bronze Age (most of)/Early Iron Age; 1050-400 BC)

Pinus representation has again halved (<5%; stomata only sporadically recorded) and *Quercus* has also substantially lower values. A feature of the zone is the increased representation of shrubs including *Juniperus, Rhamnus*, *Viburnum, Hedera* and *Ilex*. NAP are well represented with Poaceae and *P. lanceolata* averaging 15.8% and 10.1%, respectively.

Interpretation

At the beginning the zone, substantial woodland clearance took place involving all tall trees including oak. Though woodland had lower representation than at any time since the Boreal, woodland communities with hazel, oak, ash and elm probably still provided substantial cover. Pine was a very minor element though pine trees were probably common beside the lake (cf. the consistent stomatal record). Tall shrubs such as *Rhamnus*, *Viburnum,* and *Ilex* flourished, which suggests that farming (mainly pastoral) was probably extensive rather than intensive. The expansion of *Sambucus* is particularly noteworthy. While *S. nigra* is recorded in the flora of all three islands, Webb (1980) regards it as probably introduced. The evidence provided here suggests native status.

Increased flowering and better pollen dispersal of shrubby species as a result of the reduction in tall canopy trees are probably as important as population increases. The exceptionally high *Hedera* representation suggests that ivy was more important than today, which is difficult to envisage since it is now the main shrubby species and covers much of the sloping ground on the sheltered western side of the lake.

Zone C7 (mid-Subatlantic (1); mid-Iron Age (1); 400-150 BC)

This pollen assemblage is similar to C6, but *P. lanceolata* and Poaceae have lower representation at the bottom and top of the zone where small peaks in *Juniperus* (8 and 9.5%, respectively) are recorded.

Interpretation

A reduction in pastoral farming, especially at the beginning and end of the zone, facilitated some regeneration of woody vegetation, mainly oak, elm, ash and juniper, and ivy at the base of the zone.

Zone C8 (mid-Subatlantic (2); mid-Iron Age (2); 150 BC-AD 100)

This pollen assemblage is broadly comparable to zone C6, but the main tall canopy trees (*Quercus*, *Ulmus* and *Fraxinus*) have lower representation and NAP values are higher (cf. *P. lanceolata*, Rubiaceae, *Filipendula*, Liguliflorae and Tubuliflorae).

Interpretation

Woody vegetation, including trees and tall shrubs, has reached its minimum since the expansion of yew in the later Neolithic. The small increase in *Pinus* may simply be the result of overall low input of AP pollen (stomata are, however, recorded suggesting local presence). Farming, which continues to be pastoral based, but perhaps with a minor arable component, was the major factor determining the overall vegetation, including the low woodland cover.

Zone C9 (mid-Subatlantic (3); late Iron Age; AD 100-500)

In this zone *Juniperus* expands to 20.6%, there are more subdued increases in AP (*Corylus*, *Ulmus, Fraxinus* and *Taxus* near the top of the zone) and low NAP values (*P. lanceolata* averages only 2.5% and falls as low as 0.3%). The concentration values show a similar pattern.

Interpretation

This is considered to be the late Iron Age lull (LIAL), a period of woodland regeneration in Ireland (especially in western Ireland) that was favoured by reduced farming activity. The expansion of juniper at this time is unique in Irish pollen records.

The extent of juniper expansion on Inis Oírr as a whole cannot be determined on the basis of a single pollen profile. It was almost certainly the main shrub in the vicinity of the lake, a view supported by the stomatal record (stomata recorded in five out of eleven spectra). It is reasonable to assume that it was the main species on the island as a whole. Why other fast regenerating shrubs, such as hazel, responded to a much lesser degree is difficult to explain. Shrubs such as *Rhamnus*, *Ilex* and *Hedera* were better represented, though they remain of minor overall importance.

The expansion in yew at the top of the zone is noteworthy (peaks at 13%). In the course of the zone, *Pinus* falls to consistently less than 2%, which suggests that it had become locally extinct (very few stomatal records). Interestingly, records for cf. *Ustilago* (rust fungus; TIMECHS 2001) are interrupted in this zone, which suggests that suitable hosts (probably mainly grasses) were scarce due to reversion of pasture to shrubby vegetation as a result of greatly reduced farming pressure. Indeed, short-term cessation of farming cannot be excluded.

Zone D1 (late-Subatlantic (1); Early Christian/Medieval (incl. Viking and Early Norman periods); AD 500-1230)

Zones D1 and D2 relate to the historical period in Ireland. These zones are characterised by more or less stepwise decline in AP interrupted occasionally by short-term minor recoveries, and the rise to dominance of NAP taxa. Subzones are indicated in both zones to highlight minor, yet significant shifts in AP and especially NAP curves.

Zone D1 is characterised by decreasing AP values (especially *Corylus*; *Quercus* representation is rather stable) and increased NAP diversity and percentage values equivalent to those pertaining prior to the LIAL (zone C8).

Interpretation

At the beginning of the zone there was substantial clearance (subzone D1). Scrubby vegetation was most affected, e.g. hazel, *R. catharticus*, holly, ivy, etc., while tall canopy trees such as oak seem to have been spared. Elm, ash and yew probably still survived locally, but in greatly reduced numbers (especially yew). Grasslands with high species diversity (cf. *P. lanceolata*, *P. maritima*, Liguliflorae, *Rumex*-type, *Filipendula*, Fabaceae, etc.) flourished in the context of increased farming activity associated with the beginning of the Christian period.

Subzone D1β is differentiated from D1α mainly by a continuous record for cereal-type (*sensu lato,* i.e. including *Secale*) pollen. *Secale* pollen was first recorded near the top of D1α (0.2% at 2597 cm, i.e. *c.* AD 770), but expands in D1β (5.4% at 2573 cm, i.e. *c.* AD 880). The rise in importance of an arable component in the farming economy, with rye as a main crop, is further emphasised by the increased representation of pollen of arable weeds (cf. Brassicaceae, *Artemisia* and Chenopodiaceae).

Zone D2 (late-Subatlantic (3); post Norman arrival to present; AD 1230-1990)

This pollen assemblage is characterised by the lowest AP (average 19.8%) and the highest NAP (57%) for the whole of the Holocene. The NAP component is also distinctive on account of the relatively large contribution by cereal-type pollen and especially *Secale* (average: 3.2%), and pollen of arable weeds (average: 9.6%). For the first time, *Sanguisorba minor* (salad burnet; a grassland herb, common today about the lake) is recorded and forms a continuous curve in the upper part of the sequence.

Note: subzone D2δ consists of the uppermost four spectra from a 1-m Mackereth core taken in August 1999; these spectra are regarded as spanning the interval *c.* AD 1960 and 1990.

Interpretation

Zone D2 reflects the final phases in the creation of a tree-free landscape. The trend towards a treeless landscape was already established by the end of subzone D1β (*c.* AD 1230; this date is constrained by dates derived from Hekla 1 tephra (AD 1104) and Veiðivötn tephra (AD 1477) at 2526 cm and 2416 cm, respectively; Chambers *et al.* 2004). Hazel, oak, alder and birch probably still had a considerable role in the island flora until at least mid-way in subzone D2β, i.e. prior to *c.* AD 1500. Persistence of hazel until at least 2336 cm (base of D2γ; *c.* AD 1750) is quite plausible (cf. Webb (1980) refers to an old but unconfirmed record for hazel on Inis Oírr). Written records show that juniper survived into the late nineteenth century (Colgan 1893), which is also suggested by pollen records in several spectra (top of D2β and D2γ). Oak probably also survived in small quantities until at least the eighteenth century (see also Molloy and O'Connell 2004). It is assumed that the rise in population associated with the late eighteenth century and which led to the Great Famine (1845-1847) was instrumental in the final demise of most woody species.

The NAP component of the pollen record of zone D2 is also of interest in that it provides insights into farming practice about the lake that are probably applicable to the Aran Islands as a whole. In subzone D2α, *Secale*-type representation is very low but Poaceae, *P. lanceolata* and other herbaceous taxa are well represented. These changes suggest a decline in cereal growing and perhaps farming activity generally. Apart from holly, however, there is no regeneration of woody species.

In subzone D2β cereal-type pollen (including *Secale*-type) is well represented. This indicates sustained arable farming with rye as the main crop. Brassicaceae are strongly represented. This family includes several species characteristic of arable and disturbed habitats, e.g. *Raphanus raphanistrum* and also *Sinapis arvensis* and *Capsella bursa-pastoris*. According to Webb (1980), however, these species may be introductions to the Aran Islands. *R. raphanistrum* subsp. *maritimus* is frequent today on Inis Oírr and subsp. *raphanistrum* was recorded in the mid-nineteenth century on all three islands (Webb 1980). It is quite likely that *Raphanus* was the main contributor to the Brassicaceae curve.

This period of considerable arable activity extended from the early fourteenth to the early nineteenth century with possibly a shift towards a more pastoral-based farming system from the late fifteenth century onwards (cf. higher Poaceae and *P. lanceolata,* and lower Brassicaceae representation).

In subzone D2γ, *P. lanceolata* has particularly high representation and Brassicaceae are poorly represented. This subzone spans much of the nineteenth and twentieth centuries when potatoes replaced rye as the main arable crop (see Introduction). The potato (*Solanum tuberosum)* is generally silent in pollen records because of low pollen productivity and dispersal and so is not normally recorded in pollen diagrams. The uppermost spectrum, which has greatly increased Poaceae representation, relates to *c.* 1950 and possibly reflects the beginning of the decline in farming activity associated with the later part of the twentieth century.

In the uppermost spectrum of subzone D2γ and continuing into subzone D2δ, there is a sharp rise in *Potamogeton* sect. *Coleogeton* (Fig. 2), which reflects the recent expansion of *Potamogeton pectinatus* in the shallow northern part of An Loch Mór. This aquatic has probably been favoured by higher nutrient/pollution inputs as well as brackish conditions.

Discussion and conclusions

Pie and bar charts are presented in Figs. 4 and 5, respectively, which summarise the main developments as regards woodland dynamics and farming history, and the population dynamics of the most important trees. In evaluating these data (also the pollen diagrams) it is important to bear in mind the differential pollen production and dispersal capacities of the various pollen taxa. In general, arboreal taxa (AP) have better pollen dispersal than non-arboreal taxa (NAP) in that most of the AP are wind pollinated and, furthermore, arboreal pollen are liberated much higher above ground level and so have a greater opportunity of becoming effectively airborne.

Trees that are known to be strongly over-represented in the pollen record include alder, pine, hazel and birch, oak and yew (listed in order of decreasing representation) while ash may be under-represented. On the other hand, holly and several other shrubby plants such as *R. catharticus*, *V. opulus, Sorbus* and *Hedera*, are under-represented often due to a combination of factors that may include low pollen production, poor pollen dispersal (many are insect pollinated) and location beneath tall canopy trees which in itself often inhibits flowering and diminishes dispersal capacity. Long-distance transport is also an important factor, particularly in the case of trees such as pine, which has pollen that are liberated in early summer (May) when warm convection air currents and low rainfall facilitate long-distance transport. In the present instance, however, long-distance transport is not regarded as a major factor given the island location in the Atlantic and downwind with respect to the main landmasses represented by Counties Clare and Galway. Furthermore, in the case of pine, yew and juniper, a stomatal record provides secure evidence for local presence insofar as the stomata are from leaves that presumably derive exclusively from within the catchment and most likely from close proximity to the lake.

Non-arboreal taxa with substantial to high pollen production and good dispersal (anemophilous species) include important indicator taxa such as Poaceae, *P. lanceolata*, *Rumex* and *Secale*. On the other hand, there are several indicative herbaceous plants such as cereals (excluding *Secale*), Fabaceae (clover family), Liguliflorae (dandelion-type) and Tubuliforae (daisy-type) that are under-represented mainly because of cleistogamous flowers that severely limit pollen dispersal. Low pollen representation of the latter may therefore be highly indicative of farming activity and human impact generally.

As regards changing patterns in woodland cover during the course of the Holocene, the pie charts serve to highlight the following features:

- The highly diverse vegetation cover during the Preboreal, i.e. the initial *c.* 700 years of the post-glacial (zones A1 and A2). The main woody plants were initially juniper and later birch (presumably the tree birch, *Betula pubescens*).
- The Boreal begins shortly before 8000 BC with the expansion of hazel (zone B1, Figs 2A and 4). From this until the end of the Neolithic (c. 3000 BC), AP was at *c.* 80% or more, with the exception of zon C1 when it fell to <70%. Zone C1 includes the Elm Decline – elm differentially affected by disease – and Neolithic Landnam, i.e. the first substantial woodland clearance by a farming culture. Grassland taxa expand to 26% of TTP; prior to this grassland taxa represented 10% or less (Fig. 3). Interestingly the Atlantic woodlands in the vicinity of An Loch Mór appear never to have been fully closed. The

densest woodlands (at least in terms of shade) developed towards the end of the Neolithic (zone C3) when yew became the dominant tree.

- The Bronze Age and the Iron Age are represented by zones C4 to C9. During C4 and C5, though there was considerable opening up of the woodland cover, woodland continued to be of major importance (AP averages 66%). During this time, woodland composition changed to the disadvantage of pine (see below). In zones C6-C8 (end of Bronze Age to mid-Iron Age), AP oscillates at about 50% which indicates further substantial inroads by farming into woodland cover. The impact was severest in zone C8 (150 BC-AD 100) when grassland indicators expanded to 42% at the expense of both AP and tall shrubs.

Zone C9 is distinctive in that both AP and tall shrubs (mainly *Juniperus*) expand and together constitute 73% of TTP.

In Zones D1 and D2 (the historical period), the final and most significant phases in the creation of the present-day open, treeless landscape is recorded. In the final zone (D1), AP averages 21%. Given the known scarcity of woody vegetation over recent centuries, it is assumed that much of this pollen represents long-distance transported pollen (e.g. *Corylus* from the Burren and *Pinus* from plantations in Clare and Galway). It should be borne in mind that the relative importance of this component in the percentage data is exaggerated because of overall low pollen input.

The increase in the arable/disturbed biotope is another distinctive feature of zones D1 and D2 (averages almost 10% in D2). The importance of the arable component in the farming economy is undoubtedly under-represented since widespread cultivation of the potato commenced in the late eighteenth century. Agricultural statistics for the period 1926-1950, for instance, give an average of 48 ha under cereals (mainly rye) and 215 ha under potatoes on the Aran Islands (total area: 4685 ha). Yet, *Solanum tuberosum* pollen is not recorded as it is silent in pollen records.

As regards the changing contribution of various woody species to overall woodland composition, the main highlights are as follows (cf. bars charts, Fig. 4; also pollen diagrams, Figs. 2A and 3A):

- Hazel was already present in the final phase of the Preboreal, i.e. at *c.* 8100 BC.
- Hazel achieved more or less full expansion within *c.* 150 years of the beginning of the Boreal period (7900 BC).
  Pine was locally present – based on pollen (3%) and stomatal records – from near the beginning of the Boreal (8000 BC).
  Pinpointing the arrival of oak and elm is difficult. Oak is consistently represented in zones A1 and A2 while elm is only consistently represented in the mid and upper part of zone A2, a pattern that continues into B1 (cf. subzone B1a). Oak may have been present from the beginning of the Boreal, i.e. as hazel began to expand rapidly, and elm was probably present as the maximum expansion of hazel was achieved. By 7200 BC (3429 cm), both trees were well established in the context of pine and hazel-dominated woodlands (Fig. 2A); subsequently oak became more important than pine, which, in turn, was more important than elm in the Boreal and Atlantic woodlands (cf. zones B1-B3).
- Two periods with woodland perturbation are recorded during the Boreal. In the first perturbation (P1; 6500-6250 BC), juniper and probably also hazel expanded at the expense of oak and pine; in the second (P2; 5650-5530 BC), which was shorter but more severe, birch expands mainly at the expense of hazel. P1 falls within the 8.2 ka event which was first highlighted in stable isotope records from Greenland (cf. O'Brien *et al.* 1995; Alley *et al.* 1997) and has, in the meantime, been detected in a wide variety of proxies (e.g. von Grafenstein *et al.* 1998; Tinner and Lotter 2001), including a .^{18}O and a high resolution trace element record from a speleothem from Crag Cave, Co. Kerry (McDermott *et al.* 2001; Baldini *et al.* 2002). The data from Crag Cave point to cold dry conditions that were initiated abruptly at c. 6400 BC (8350 cal. BP) and ended, also abruptly, at 6360 (8310 cal. BP). The P1 event at An Loch Mór lies within the same period as that recorded at Crag Cave, though P1 is clearly of much longer duration. In the case of woody vegetation, a lag between change in environmental conditions and species response can be expected, but a lag extending over many decades is unlikely. The P2 event, which is distinctly shorter and more severe, is also a possible correlative with the

8.2 ka event but, given the age that is ascribed to P2, such a correlation is unlikely. The information presented here clearly indicates that there is a distinct possibility of finding perturbations in the Boreal part of Holocene pollen records from western Ireland that are ascribable to climatic change. Further research is required to clarify the nature of these changes and their relationship to proxy records from other parts of the northern hemisphere.

- The Boreal and Atlantic woodlands probably never gave full cover (cf. in B3, *P. lanceolata* averages 4.2%). This is highly unusual. It is assumed that the highly karstic and uneven terrain in the vicinity of the lake resulted in woodlands with relatively open and fragile structure that were not well buffered (low inertia) to withstand environmental shifts such as those that gave the features P1 and P2.
- Alder expanded at *c.* 5300 BC (Boreal/Atlantic transition). Subsequently, it pollen representation remains mainly less than 5%, though it averages 10% in zone C5. Given that alder is normally strongly over-represented in pollen records, it is concluded that it was generally of minor importance. Alder was probably present locally from the beginning of P2 (upper part of B1) and may even have been present as a rare tree from immediately after P1, i.e. from shortly before 5500 BC.
- Woodland regeneration that followed a Neolithic Landnam phase (C1) involved rapid regeneration of secondary woodland, firstly of pine (in C2, *Pinus* achieves 33%, the maximum for the Holocene), which was then displaced by yew as the dominant (in C3, *Taxus* averages 26% and peaks at 37%). *Taxus* is recorded mainly as single pollen in the upper part of B3 and C1, which may indicate rare presence. It is assumed that a climatic change, rather than lack of competition from other trees resulting from clearances, favoured a rapid expansion of yew at *c.* 3150 BC. The period of yew-dominated woodland ended even more rapidly some 200 years later as a result of renewed farming activity in the late Neolithic/early Bronze Age.
- By the mid C5 (later Bronze Age; 1500 BC), *Pinus* had declined to generally <5%, i.e. it was a relatively minor tree with respect to oak (Figs. 3A and 4). This change occurred in the context of reduced farming. It is assumed that pine was not as competitive as previously, possibly due to a climatic shift.
- Considering the Holocene as a whole, the last *c.* 2200-year period (the uppermost zones, i.e. C8 to D2) is exceptional in that woody vegetation was greatly reduced and more or less ceased to contribute in any meaningful way by the end of the period. Within this interval, zone C9, i.e. the Late Iron Age Lull (LIAL), is exceptional. During this zone which extends from *c.* AD 100-500, *Juniperus* averages 12% and peaks at 24%, values only exceeded at the beginning of the Holocene (zone A1). Hazel, ash and yew (briefly only) also increased.
- The upper part of zone D1 records the expansion of arable farming based on rye cultivation (at/before AD 800). In D2 there is further farming expansion and the final demise of woodland communities begins (c. AD 1250). Hazel and oak probably survived in some numbers into the 1700s when increasing population saw the final demise of more or less all woody vegetation. In some spectra, *Corylus* – a high pollen producer and frequent in the nearby Burren – falls to <5%.
- The elevated values for *Pinus* throughout zone D2 and also the occasional stomatal record raises the possibility that pine became extinct only in very recent times on Inis Oírr. In this connection, AMS ^{14}C dating of pine charcoal collected from an eroding margin of the upper layer of debris (shell, animal bone and small charcoal fragments; charcoal identification by M. Dillon) from the midden at Teampall Chaomháin, a medieval church *c.* 1 km east of An Loch Mór yielded a date of 610.45 BP (GrA-24632), which corresponds to AD 1295-1409 (2s confidence level). This suggests local presence of pine as late as the 14th century and supports the view that at least some of the *Pinus* pollen recorded in zone D2 is of local origin (for further discussion on the late survival of pine in Ireland see Feehan (2000), Molloy and O'Connell (2004); Nicholls (2001)).

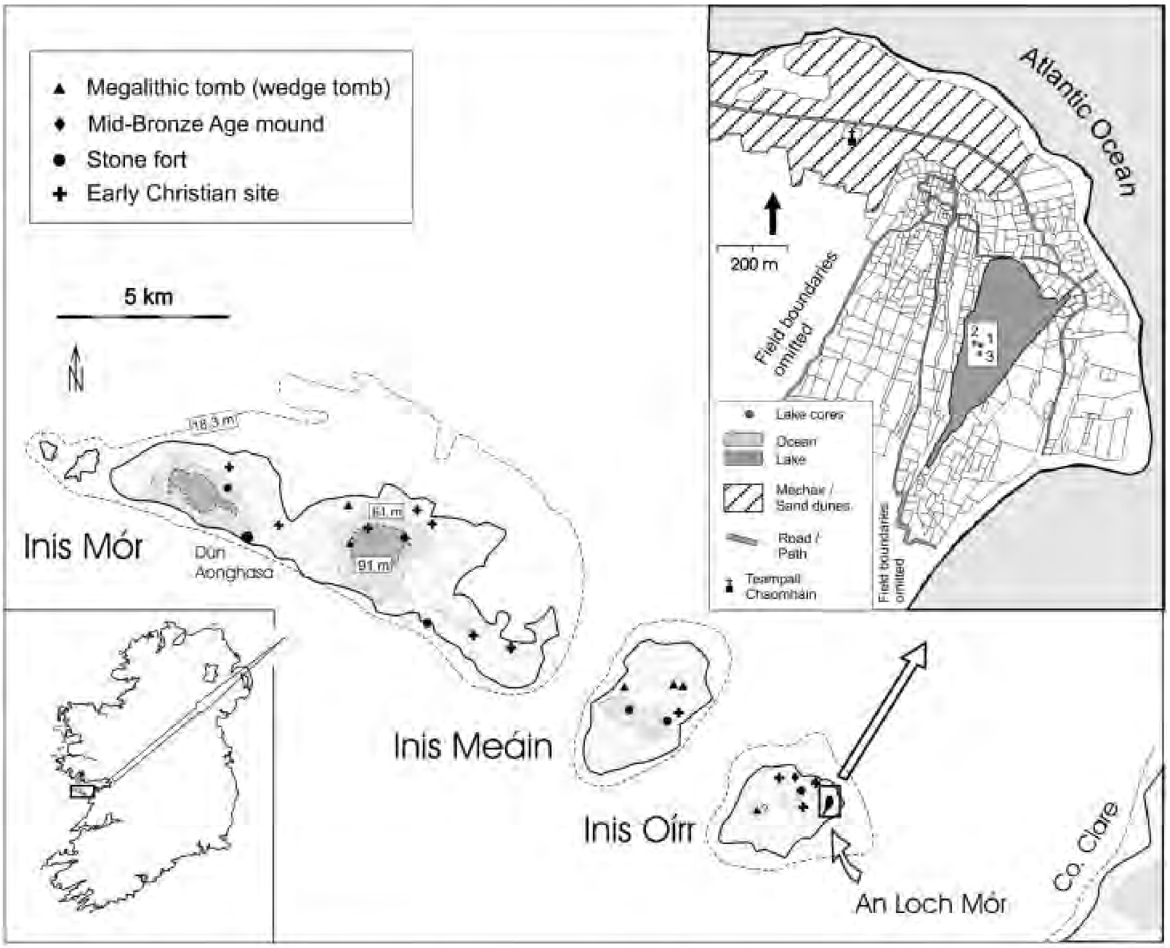


Fig. 1. Maps showing location of the Aran Islands off the west coast of Ireland, and detailed maps of (a) the Aran Islands and (b) the north-east corner of Inis Oírr including An Loch Mór. On the map of the Aran Islands contours at 100 ft (61 m) and 200 ft (91) OD, the 10-fathom (18.3 m) bathymetric line, and the main archaeological sites are indicated. In the detailed map showing An Loch Mór, the coring locations are indicated and also field boundaries as indicated on the OS 6-inch map (1:10 560 scale; revised 1899; little change in the meantime), machair and sand dunes and the main roads and paths.

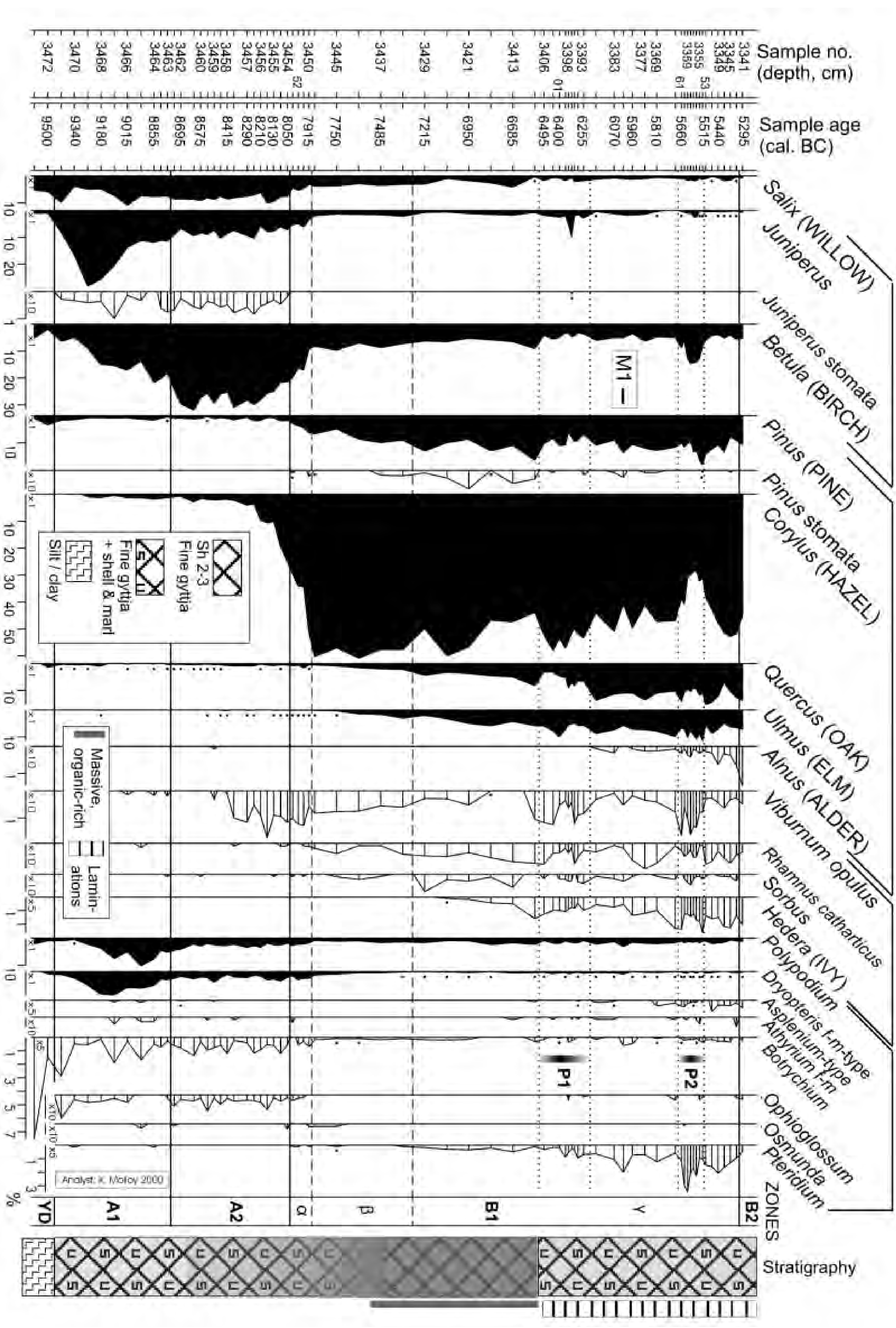


Figure 2A. *An Loch Mór, Inis Oírr MOR1, early Holocene (1)*

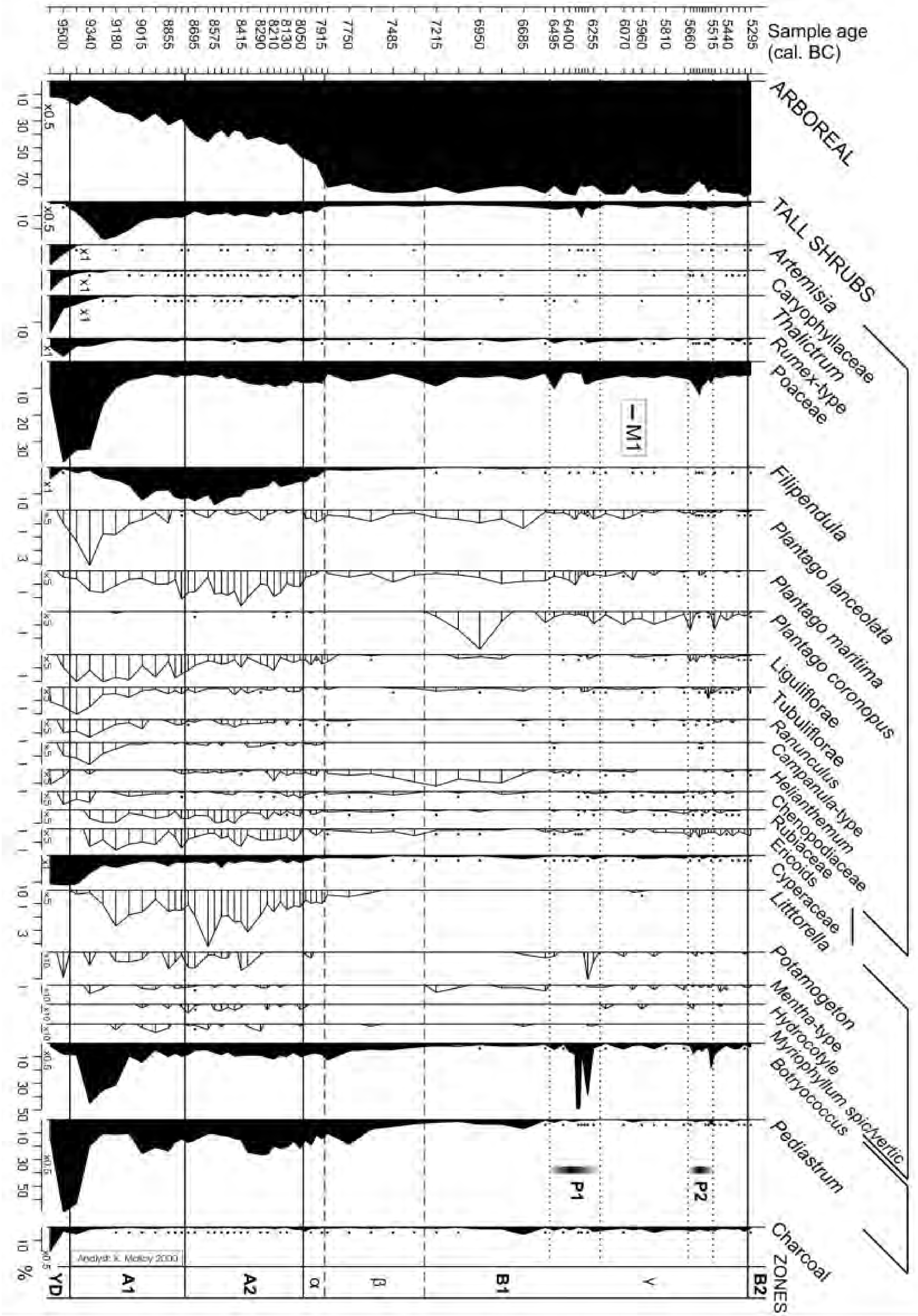


Figure 2B. *An Loch Mór, Inis Oírr MOR1, early Holocene (2)*

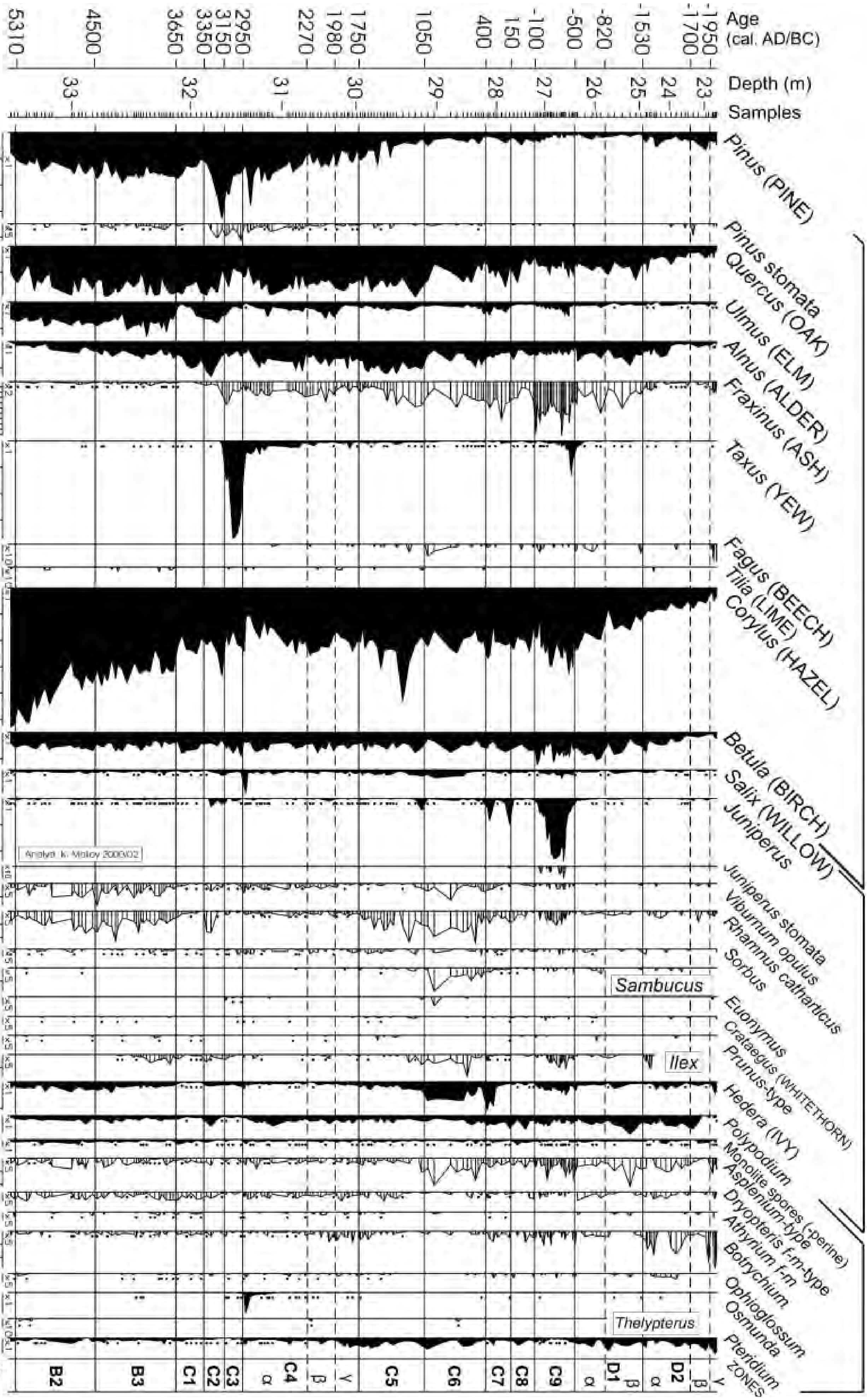


Figure 3A. *An Loch Mór, Inis Oírr MOR1, mid & late Holocene (1)*

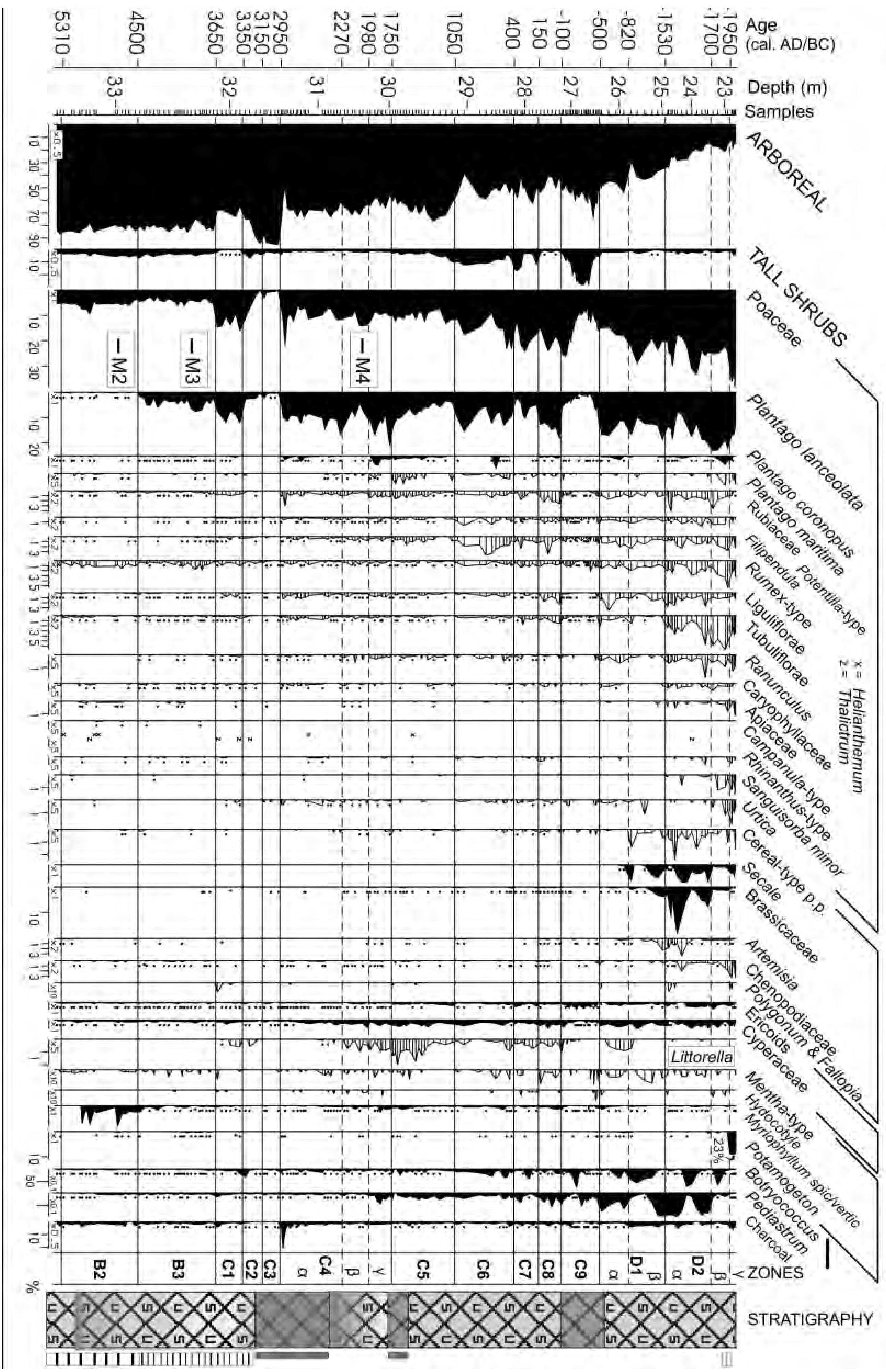


Figure 3B. *An Loch Mór, Inis Oírr MOR1, mid & late Holocene (2)*

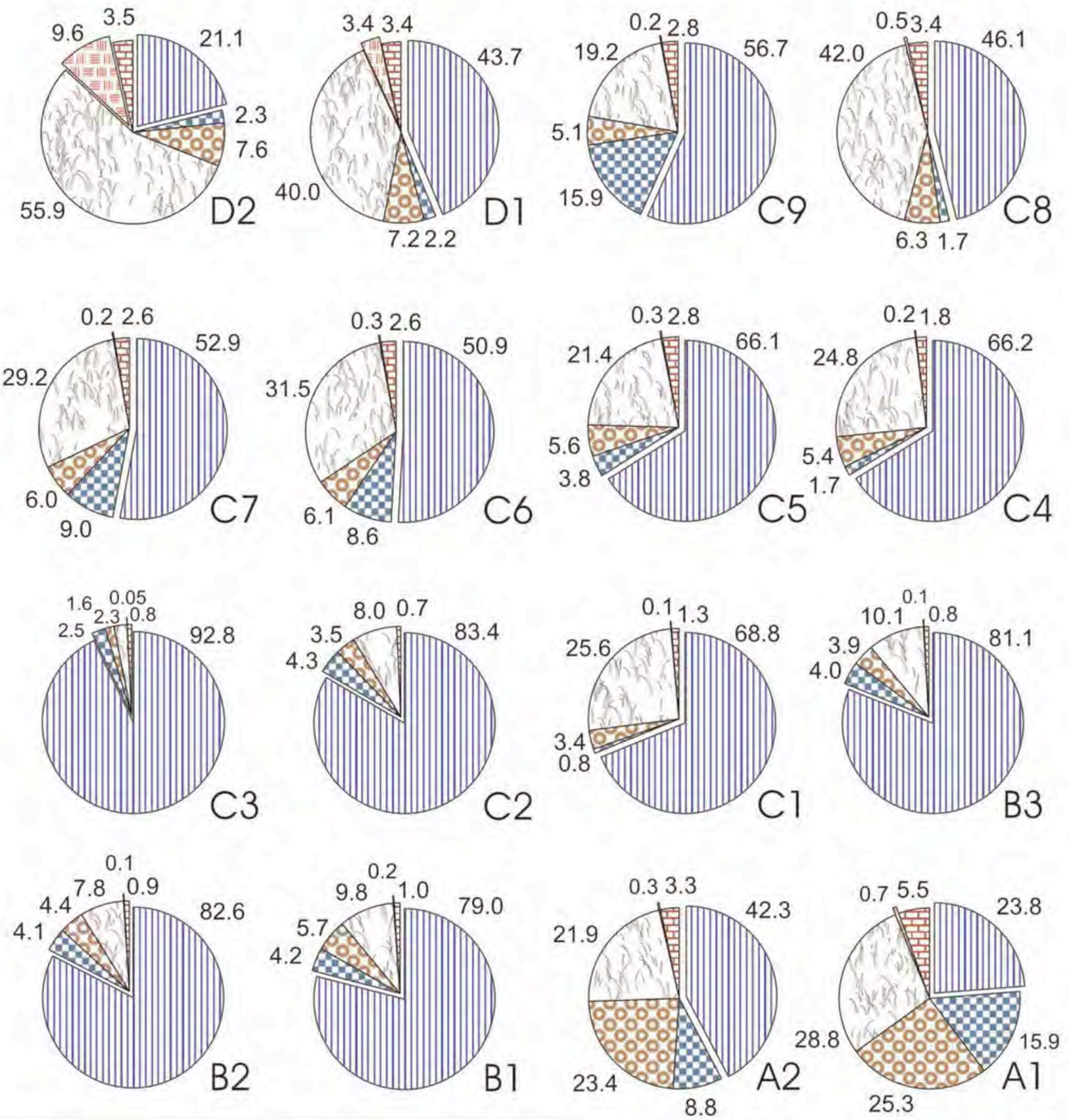
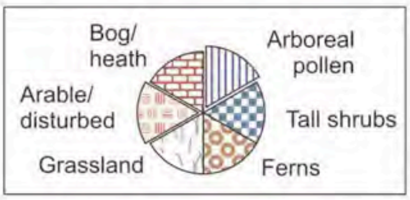


Fig. 4. Pie charts showing mean percentage representation of composite pollen groups (those included in the PS) in the Holocene PAZs from An Loch Mór. The mean values are also indicated beside the respective segments.



Zone	Cal AD / BC	Periods
D2	AD 1230-1990	Late Norman to present
D1	AD 500-1230	Early Medieval/Viking/Early Norman
C9	AD100-500	Late Iron Age Lull
C8	150-AD100	Mid-Iron Age (2)
C7	400-150	Mid-Iron Age (1)
C6	1050-400	Late BA/Early Iron Age; Subatlantic begins
C5	1750-1050	(Mid)/Late Bronze Age
C4	2950-1750	Early and Mid-Bronze Age
C3	3150-2950	Late-Neolithic
C2	3350-3150	Mid-Neolithic
C1	3650-3350	Earlier Neolithic; Subboreal begins
B3	4500-3650	Later Atlantic; earliest Neolithic?
B2	5310-4500	Atlantic period begins
B1	8050-5310	Boreal period begins
A2	8750-8050	Late pre-Boreal
A1	9450-8750	Early pre-Boreal

Note: ages are in calendar/calibrated years; AD years are indicated; otherwise years as BC.

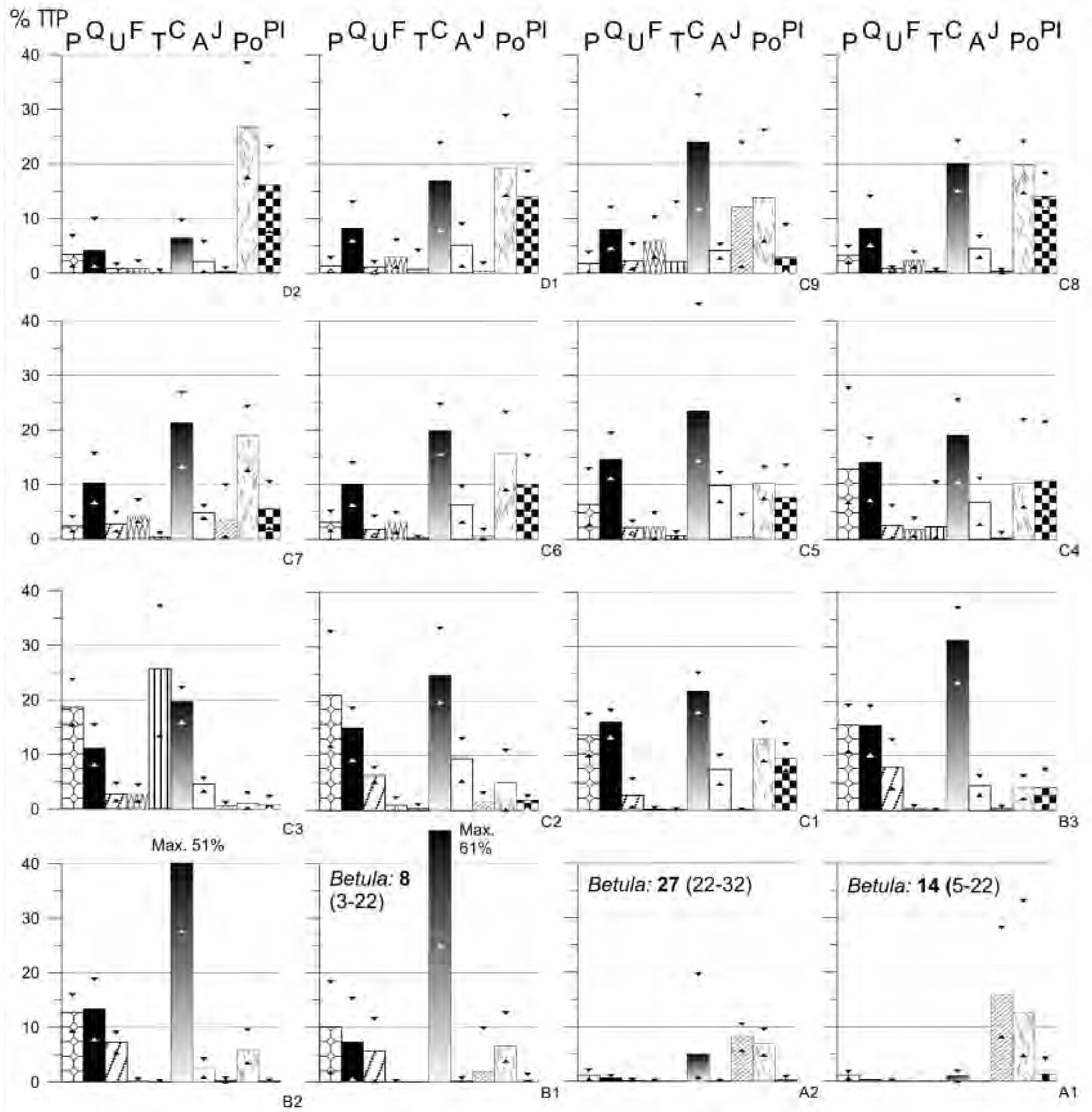


Fig. 5. Bar charts showing representation (mean, maximum and minimum percentage values) of selected taxa from An Loch Mór in the PAZs delineated in the pollen diagrams. *Betula* values are indicated in zones A1, A2 and B1 only where the early Holocene expansion and decline of birch are recorded (mean is in bold; max. and min. are within parentheses).

Legends to Figures

Fig. 1. Maps showing location of the Aran Islands off the west coast of Ireland, and detailed maps of (a) the Aran Islands and (b) the north-east corner of Inis Oírr including An Loch Mór. On the map of the Aran Islands contours at 100 ft (61 m) and 200 ft (91) OD, the 10-fathom (18.3 m) bathymetric line, and the main archaeological sites are indicated. In the detailed map showing An Loch Mór, the coring locations are indicated and also field boundaries as indicated on the OS 6-inch map (1:10 560 scale; revised 1899; little change in the meantime), machair and sand dunes and the main roads and paths.

Fig. 2. Percentage pollen profile, MÓR1, from An Loch Mór. Spectra from the lower part of the profile are shown, i.e. two spectra from the Younger Dryas, Preboreal, Boreal and a single spectrum from the base of the Atlantic period. The profile is drawn to a calibrated time scale.

The pollen curves are grouped to reflect the main physiognomical/ecological plant groups. Individual pollen curves that are not shaded have a magnified horizontal scale (scale indicated at the base of each curve). A closed circle is used where the value is low and the scale is such that the presence of a taxon may not otherwise be clearly shown.

The pollen taxa are presented as follows: in **2A** trees, tall shrubs and ferns and in **2B** composite curves for AP and tall shrubs and individual curves for NAP, aquatics, algae and charcoal (particles <37 μm). A TTP is used for calculating percentage representation, i.e. aquatics, algae and charcoal are excluded.

Fig. 3. Percentage pollen profile, MÓR1, from An Loch Mór. Spectra from the upper part of the profile are shown, i.e. two spectra from the end of the Boreal and the remainder of the profile. The profile is drawn to a calibrated time scale. In spectra from 2451, 2458, 2481 and 2497 cm, *Pediastrum* counts were entered as 9999, the maximum permitted by the plotting programme; the counts ranged between 10800 and 16700. For conventions and other details consult the legend to Fig. 2.

Fig. 4. Pie charts showing mean percentage representation of composite pollen groups (those included in the PS) in the Holocene PAZs from An Loch Mór. The mean values are also indicated beside the respective segments.

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