Post-glacial vegetation and landscape change in upland Ireland with particular reference to Mám Éan, Connemara

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ARTICLE INFO

Article history:
Received 26 June 2020
Received in revised form 15 September 2020
Accepted 13 January 2021
Available online xxxx

Keywords:
Holocene
Woodland history
Uplands
Pollen analysis
Human impact
Ireland

ABSTRACT

Holocene vegetation dynamics of mid-western Ireland are discussed with particular reference to the Galway and Mayo uplands, the development of upland blanket bog and the history of pine and yew. A detailed pollen profile from Mám Éan (Maumeen), a corrie lake, provides insights into environmental change in upland Connemara where, in recent decades, overgrazing and peat erosion have given rise to serious environmental concerns. Vegetation dynamics are broadly comparable to those in lowland Connemara and also upland sites in the Nephin Begs, Co. Mayo. The available evidence suggests corrie glaciation in the Younger Dryas. The oldest sediments show the usual early Holocene progression from open herbaceous communities to woody vegetation dominated by juniper, tree birch, and finally hazel. Tall canopy trees then spread, including pine, and elm and oak, and later alder (at ca. 7.7 ka). In the interval 10.2–4.8 ka, pine was dominant and for much of this time fires were frequent. There is a distinct mid-Holocene Elm Decline and a short Neolithic Landnam phase that is followed by woodland regeneration involving, at first, mainly pine and later yew. 14C dating of bog-pine from upland sites sheds new light on pine and upland blanket bog development in the mid-Holocene. It is shown that while blanket bog was initiated at Mám Éan by ca. 10.8 ka, the present-day treeless landscape has come about within the last 1000 years as a result of sustained human impact, that has also resulted in severe erosion of minerogenic and, more recently, peaty soils.

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1. Introduction

Uplands in Ireland, as in many parts of Europe, have been the focus of considerable attention by scientists, and especially naturalists, for a long time (e.g. Pethybridge and Fraeger, 1905; Welten, 1952). In recent times Irish uplands have received increased attention, as hot-spots for biodiversity (Hodd, 2012; O'Rourke et al., 2016), as sources of material for the study of Quaternary climate change and glaciology (Colhoun and Synge, 1980; Anderson et al., 1998; Wilson and Matthews, 2016; Ballantyne and Ó Cofaigh, 2017; Meehan, 2017; Barth et al., 2018; Taylor et al., 2018), as recreational areas of exceptional quality (Feenan, 1997; Lysaght, 2020) and as places where a good understanding of the complex roles played by natural processes, human impact (mainly farming), and climate change is crucial to formulation of appropriate management plans (Costello, 2020a, b). This has coincided with a growing public awareness of the many threats to uplands posed by changes in land-use, demography, climate and atmospheric pollution (Aherne et al., 2013; Hodd et al., 2014; Long, 2010; Viney, 2003).

The focus in this paper is on changes in vegetation, land-use and landscape since the end of the last Ice Age, approximately 12,000 years ago, in mid-western Ireland, i.e. the Galway and Mayo uplands (Fig. 1). The end of the last Ice Age (Weichselian; referred to in Ireland as Midlandian) is a convenient starting point in that lake-sediment accumulation began at most upland sites at that time, i.e. at/near the end of the Younger Dryas. During the Younger Dryas (ca. 12.8–11.7 ka; Rasmussen et al., 2014), Ireland experienced a particularly severe climate downturn that finds clear expression in many lake sediments, mainly located in the lowlands (Andrieu et al., 1993). In the uplands, the Younger Dryas is characterized by corrie glaciations that usually involved small glaciers developing in corries that had formed earlier, in pleniglacial times, a good example being that at Lough (L.) Nahanagan, Co. Wicklow, which is regarded as a type site for the Younger Dryas in Ireland (Nahanagan Stadial; see Mitchell and Ryan, 1997; Coxon, 2019a; Knight et al., 2019). Uncertainties, however, remain as to the frequency and extent of glaciation in Irish uplands during the Younger Dryas due mainly to difficulties associated with dating glacial features. Coxon (2019b, p. 37) suggests that “the mountain areas of Connemara hold many small moraines that are probably YD [Younger Dryas] in age” and describes two well-developed lateral moraines that lie between 200 and 300 m asl on the southern flank of the Maumturks, 3.2 km south-east of Mám Éan and tentatively ascribed to the Younger Dryas (Coxon, 2019c). It appears likely that glacier melting and the beginning of sediment deposition had commenced in most, if not all,
- Pollen profiles (lakes)
  1. L. Doo
  2. L. Kilnabinnia (L. Corslieve)
  3. L. Cleva
  4. L. Anaffrin
  5. L. Navroony (L. Auilding)
  6. L. Sheeeans
  7. Loch an Chorcaí
  8. L. Namackanbeg
  9. An Loch Mór

★ 14C dated bog-pine (>1)
★ 14C dated bog-pine (1)
Mo1 Shanvallycahill (4)
Gy1 Bunnacunneen (4)
Ky1 Carranstoohil (1 Lu)
Ky2 Hags Glen (5)
Ky3 Mangerton (3)
Ky4 Derrylea (1)
Ky5 Moll's Gap (1)
Ky6 Uragh Wood (1 Beta)
W1 Kippure (1 Lu)
W2 Sally Gap (1 Gr)
Mám Éan in Figs. 2 & 3
Table 1
Overview of the main pollen sites referred to in the text.

| Site number, name and locationa | Geography incl. co-ords (WGS84) and altitude (m asl); coring details | Geology and recent land use |
|-------------------------------|-------------------------------------------------------------------|----------------------------|
| Mám Éan (Maumturks, Connemara) | 53.49068, −9.64829; 245 m Core in N.W. part of lake, 1.5 m deep | Upland corrie lake (1.14 ha) in Dalradian quartzite and schist. Treeless, blanket bog, heath, rough grazing |
| Comparative sites (listed as in Fig. 1, i.e. north to south) | | |
| 1: L. Doo (Attrymas, Co. Mayo) | 54.05021, −9.09601 20 m; coring near center of lake | Lowland lake (6.3 ha). On psammitic at junction between Carboniferous limestone (lowlands) and granite (Ox Moats). Glacial deposits. Fertile pastures |
| 2: L. Kilnabinniaab (Nephin Begs, Co. Mayo) | 54.05002, −9.63898 310 m; coring in center, 6 + m deep | High elevation corrie lake (2.4 ha) in Nephin Begs, east of Corslieve Mountain (541 m). Bedrock: Dalradian quartzite. Scree, heath and blanket bog |
| 3: L. Clevala (east of Nephin Begs and north-west of Nephin, Co. Mayo) | 54.03973, −9.43567 60 m; coring near southern shore, 1 + m deep | Lowland lake (4.7 ha) on Carboniferous conglomerates between metamorphic rocks to west and Carboniferous limestone to east. Blanket bog, partly reclaimed for pastures |
| 4: L. Anafrina (Nephin Begs, Co. Mayo) | 53.05102, −9.72287 190 m; coring at 12 m (near deepest point, i.e. 14 m) to close of southern basin | A lake (11.5 ha) on psammitic and pelitic schist (Dalradian) with a partially drowned moraine (Weichselian glaciation) that divides the lake into two, equally sized basins. In catchment extensive heath; also blanket bog and rough pasture |
| 5: L. Navroonyab (south-east of Nephin Begs, Co. Mayo) | 53.91879, −9.58859 10 m; coring near center & deepest pt. (5 m) | Lowland lake (4 ha) on Dalradian schists & gneisses (mainly), between two lateral morainic ridges; catchment reaches 200 m asl. Extensive blanket bog and pastures |
| 6: L. Sheeana (Cleggan, Connemara) | 53.55686, −10.07608 15 m; coring at center in water depth of 5.5 m | Lowland lake (0.9 ha) on schist (mainly). Situated on a geological divide: fertile soils to north; less fertile to south where a thin covering of blanket bog is widespread |
| 7: L. An Chorcaill (Carna, Connemara) | 53.33701, −9.85402 10 m; coring towards southern edge of basin | Recently infilled lake (1.2 ha) on Devonian granite. Extensive blanket bog, heath, and rough pasture to the south |
| 8: L. Namackanbeg (Spiddal, Connemara) | 53.28522, −9.30061 87 m; coring near center of basin | Recently infilled lake (1.2 ha) on Devonian granite. Extensive blanket bog, heath, and rough pasture to the south |
| 9: An Loch Mór (Inis Oírr, Aran Islands) | 53.05903, −9.58036 1 m; cored in deepest waters (23 m) | Deep lake (64 ha) in a fault in karstic Carboniferous limestone. Typical Aran Island landscape of small fields, pasture, prior to 1950s arable. Also exposed bare rock |

Maumturk and Nephin Beg Mountain Ranges are referred to by the informal names Maumturks and Nephin Begs. Data sources: Mám Éan (Huang, 1994; this publication); Loughs Kilnabinnia, Clevala, Anafrina and Navroony (Bradshaw and Browne, 1987; Browne and Coxon, 1991; NEOTOMA); L. Sheeauns (Molloy and O’M. O’), a Comparative sites are numbered according to geographical location, north to south. ab Lake names as in Bradshaw and Browne (1987) in parentheses: L. Kilnabinnia (L. Corslieve); L. Navroony (L. Asling).

upland lake basins that had been occupied by ice, as the Younger Dryas ended and prior to the onset of full-glacial warming. (See Table 1.)

As in most studies of long-term Holocene change, the focus here is on, firstly, vegetation dynamics and in particular changes in woodland composition and extent, and also changes at landscape level that have mainly involved development of extensive, and often, all pervading blanket bog (Conaghan, 2000). Secondly, there is a focus on human impact in effecting major change. In Ireland, human impact has been regarded since G. F. Mitchell’s time as being the main driver of late Holocene change. In order to emphasize the importance of the human factor, Mitchell (1956) proposed a major modification of the up-to-then widely accepted classical zonation scheme for Irish pollen diagrams as originally proposed by Jessen (1949, minor modifications by Mitchell, 1951). This involved further subdivision of the second half of the Holocene, i.e. from the Elm Decline onwards, to more effectively reflect the role of human impact and major cultural and historical developments, rather than climate change.

The study of long-term change in Irish upland environments, particularly from the viewpoint of human impact, has not received a lot of attention up to now which is surprising given the importance of particular uplands during prehistory and also the historical period, which, in Ireland, starts at ca. AD 400. From the Neolithic onwards, Irish uplands such as the Burren, Co. Clare and Carrowkeel, Co. Sligo, have been the focus of much human activity (Bergh, 2016; Hensey et al., 2014). Given the sparse archeological evidence, the Galway/Mayo uplands were apparently not a focus of farming or other human activities, but yet the human factor cannot be ruled out. Particularly pertinent in this regard is the extensive use of these and other Irish uplands for summer farming – i.e. booleying, the Irish term for transhumance – the importance of which in post-Medieval times has been highlighted by recent research (Costello, 2016, 2020a; McDonald, 2016). In the last fifty years or so, land-use policies have been instrumental in effecting substantial changes in the use of upland environments and especially western uplands. Ireland joining the EU in 1973 resulted in substantial support for farming and especially farming in disadvantaged areas. Initially, the support took the form of ‘headage’ payments and resulted in a major increase in sheep numbers in the 1980s that particularly affected Galway and Mayo (these two counties at the time accounted for a quarter of Ireland’s sheep which exceeded two million; Bleasdale, 1998). This, in turn, brought about major and, invariably, undesirable changes in upland vegetation and has been blamed for serious upland peat erosion (Sheehy-Skeffington et al., 1996; McKee et al., 1998; Huang...
and O’Connell, 2000; Plate SM-PL-V; SM = online supplementary material). In the meantime, erosion has been reduced mainly as a result of reduction in sheep numbers brought about by adjustments in EU farming support schemes, including the introduction of Rural Environmental Protection Schemes (REPS) and cross compliance. Large- and small-scale afforestation schemes, that have been supported at national and EU levels (Molloy, 1992), have also brought about far-reaching change including adverse effects on stream-water chemistry and fish-life (Harrison et al., 2014). At the level of landscape, changes have also been dramatic as previously open countryside has been transformed by afforestation, involving mainly introduced conifer species (Viney, 2003).

Climate change is often regarded as of major importance in bringing about change in upland environments during the Holocene, though direct evidence for this is seldom available (but see Wilson and Matthews, 2016). Apart from the major oscillation at 8.2 ka, i.e. the 8.2 ka event (Ghilardi and O’Connell, 2012; Holmes et al., 2016), climate oscillations during the Holocene in Ireland are too small to be easily detected in lake sediments (Taylor et al., 2013). However, it is reasonable to suppose that abrupt, short-lived changes will find ready expression in lake sediments at sensitive upland locations where soils and vegetation are more easily affected than in more buffered lowland locations with much higher inertia levels (Taylor et al., 2017, 2018). In the 1970s and 1980s, as upland peat erosion became increasingly problematic in Britain and Ireland, several palaeoecological studies were undertaken. In Ireland, Bradshaw and McGee (1988) have shown that peat erosion commenced 1500 and 3000 years ago in the catchment of two lakes in Counties Donegal and Wicklow, respectively. These investigators concluded that neither climate nor grazing were implicated; rather it was a case of peat being inherently unstable upon reaching a certain mass, at which point peat erosion was inevitable. Also pertinent to the question of peat erosion is the high frequency of inverted 14C dates obtained from the upper sediments of Irish lakes that is attributable to erosion of ‘old’, and hence 14C-deficient carbon (e.g., Hiron and Thompson, 1986; O’Connell et al., 1987; Hall, 1990; Chiche et al., 2017). This phenomenon frequently relates to the last two millennia and is generally regarded as being caused by soil erosion (especially peaty soils) resulting from intensification of land-use, involving mainly grazing, rather than climate change or any other natural cause. Notwithstanding the downplaying of the importance of climate as implied above, its role in the widespread development of upland blanket bog cannot, and should not, be entirely dismissed (Smith, 1975; O’Connell, 1990). Wetter and cooler conditions beginning in the Bronze Age (see below) certainly favored blanket bog expansion.

The above is the general background to the investigations reported on here. This paper not only presents new data but is also a synthesis, of climate as implied above, its role in the widespread development of upland blanket bog cannot, and should not, be entirely dismissed (Smith, 1975; O’Connell, 1990). Wetter and cooler conditions beginning in the Bronze Age (see below) certainly favored blanket bog expansion.

2. Description of study areas

Connemara refers to the largely treeless (i.e. prior to recent large-scale afforestation) region in mid-western Ireland, characterized mainly by extensive blanket bog and mountains with peaks of bare quartzite that carry little or no vegetation due mainly to lack of soil. Though subject to repeated glaciation, glacial deposits are rather scarce and where they do occur, they often take the form of drumlins and small moraines that, as the source of reasonably fertile soils with good drainage, are often the focus for farming and settlement. Lakes, many small and invariably oligotrophic, are common and, in some parts, such as on Roundstone peninsula, are, together with blanket bog, a key component of the landscape. Several of these lakes today carry woodland on islands, a relatively recent development (Hannon and Bradshaw, 1989) facilitated by the cessation of grazing by cattle and sheep as the rural population collapsed from the mid-nineteenth century onwards.

The lake at Mám Éan (literally: ‘gap of the birds’; anglicized as Maumeen; the lake is unnamed in Ordnance Survey of Ireland (OSI) maps) is situated in a col in the Maumturk Mountain Range (Figs. 1–3; and Table SM-1 and Plates SM-PL-I, II and III. This kidney-shaped, corrie lake (164 × 80 m; 1.14 ha; 245 m above sea level (asl)), lies in a small depression on the eastern side of a relatively wide, hummocky and largely peat-covered saddle that provided a route over the mountain range, prior to the development of the present-day road system in the early 1800s. The route was important in the past as it facilitated communication between the extensive lowlands to the south and an important east–west route on the northern side that connected northern Lough Corrib and Lough Mask with Killary Harbour on the Atlantic coast. Farming, involving mainly sheep and cattle, is still actively pursued, and, in recent years, the site has been popular as a walking route (Fewer, 1998). It is also increasingly frequented as a place of pilgrimage where Ireland’s patron saint, Patrick, is remembered (Robinson, 1990, 2006). Indeed, it has attained an iconic status, it being well referenced in tourist and literary works; e.g. W.H. Bartlett’s drawing of the pass (Bartlett and Griffiths, 1833; Fig. 2B), dating to the early nineteenth century, is used on the cover of Bender (2015).

To the south-east of the lake, rocky ground, with thin peat cover, rises sharply to reach 715 m (Binn Mhór; Fig. 2A). On the flat but rather hummocky ground immediately to the west of the lake, shallow peat with small bog-pine timbers (two of these sampled for 14C dating; see below) has accumulated (Fig. 3). Here and elsewhere there is considerable peat erosion as evidenced by peat hags, some up to a meter tall (Plate SM-PL-III). Opposite the lake, at ~200 m distant, lies St. Patrick’s Bed and Holy Well, which is the focus of pilgrimage (Fig. 2). From here, the partly peat-covered ground rises steeply to 633 m (Binn Chaonaigh). Immediately to the north of the lake, the ground slopes more gently downwards into the Failmore River valley (Fig. 2; Plate SM-PL-I). One of the sources of the Failmore River is a small outflow channel from the northern end of the lake, which, in prolonged dry periods, dries out. The lake seems to be fed by surface drainage from the catchment and a few small input streams (Fig. 2A).

The catchment is developed on mid-Dalradian metamorphic rocks (Morris and MacDermot, 1995). A geological boundary runs east–west near the southern margin of the lake. Gray flaggy quartzite (Bennaboeela Formation) lies to the south while, to the north, there is a narrow strip of sandy schist (Streamstown Formation) and, at lower elevation, a calcareous-rich schist (Lakes Marble Formation) which, combined with substantial drift cover, results in generally more fertile soils on the northern side.

Drift cover is negligible in the gap. Striae (already recorded by Kinahan and Close, 1872) and pronounced glacially sculpted flutes are present (Coxon, 2019c, fig. 3.7.4). These, and the shape of roche moutonnée, suggest that local ice movement was from the south-west. This probably relates to late Midlandian glaciation when ice domes of exceptional scale and thickness were present so that all mountains in mid-western Ireland were overtopped during the Last Glaciation Maximum (LGM; ca. 26–24 cal BP) (Coxon, 2019b, p. 28; Roberts et al., 2020). Downslope to the south-west of the saddle, at about 150 m asl, patches of stony drift are present beneath generally thin (~50 cm) coverings of peat. Pine stumps, mostly small, sometimes with spreading roots and often with less than 100 rings, are common in that general area and also at high elevation near the lake (Fig. 2A; Plate SM-PL-IV). On the northern side, cirques close to the summits of the mountain range are well developed and there are extensive glacial deposits (mainly below 200 m) that carry mainly blanket bog and heath. The occasional farmsteads are sited on these deposits. Several pine timbers,
including large timbers, were noted at -100 m elevation on mineral soil, the peat having been removed by peat cutters (these are located immediately to the north of the area depicted in Fig. 2A; large pine timbers were also noted in basal peat in the Failmore River basin).

Mám Éan gap and the associated cliffs and surrounding higher ground support species of arctic-alpine/northern distribution such as Saxifraga oppositifolia, Salix herbacea, Thalictrum alpinum, Polystichum aculeatum and Diphasiastrum alpinum (Webb and Scannell, 1983;}

\[ \text{Fig. 2. A. Contoured map showing the pass, the associated path, and the corrie lake at Mám Éan. Areas with bog-pines preserved by blanket bog growth as noted during casual surveys are indicated. Elevation is in meters asl. Source of the base map is Mapy.cz (www.seznam.cz; accessed 22 June 2020). B. Hand-colored, engraved print depicting a pattern (pilgrimage) in the early nineteenth century at Mám Éan (view from the southern approach; Bartlett and Griffiths, 1835). Apart from the vertical exaggeration, it can be regarded as realistic. Note the complete lack of woody vegetation.} \]
moss and vascular plant nomenclature follow Atherton et al., 2010, and Parnell and Curtis, 2012, respectively). Saxifraga spathularis, regarded as an Atlantic (southern) species (Webb and Scannell, 1983), is common on low cliff faces and other shaded areas. This species, which is frequent in western and south-western Ireland, is otherwise rare in Ireland and Britain (BSBI Atlas, online; https://bsbi.org/maps, accessed 23 June 2020). Extensive blanket bog on the lowlands to the south-east has been partly afforested with conifers in recent decades. Otherwise, woody vegetation is rare and consists mainly of occasional Crataegus monogyna, Ilex aquifolium and Sorbus aucuparia; Corylus avellana, Salix spp., Quercus petraea and Lonicera periclymenum have been noted on the approaches to the gap from the northern (Maum) side. These woody plants grow in the shelter of rocks and gullies associated with mountain streams, i.e. in places that afford some protection from grazing by sheep and cattle. This suggests that the present treeless aspect is largely the result of strong grazing pressures rather than being climatically or edaphically determined.

About the lake, typical blanket bog and heath species, such as Calluna vulgaris, Erica tetralix, Rhynchospora alba, Trichophorum cespitosus, Molinia caerulea, Schoenus nigricans, Narthecium ossifragum, Pinguicula vulgaris and Nardus stricta, and Sphagnum spp. and Racomitrium lanuginosum are common. In the lake itself, aquatic species include Eriocaulon aquaticum, Lobelia dortmanna and Isoetes lacustris. Floating aquatics Nymphapha alba, Sparganium angustifolium and Potamogeton polygonifolius are locally dominant. In recent times, Menyanthes trifoliata has greatly expanded on the western side of the lake, possibly in response to increased peat erosion (Plate SM-PL-IV).

In addition to the investigations at Mám Éan, bog-pine timbers were sampled for $^14$C dating in the uplands at Bunnacunneen to the west of L. Nafooey, a part of Connemara referred to as Joyce Country that extends eastwards to the Carboniferous limestone lowlands of L. Corrib and L. Mask (Fig. 1B). The sampling area is characterized by extensive blanket bog, rounded hills and little or no settlement. Bog-pine timbers from other bog-bearing uplands, and especially the Killarney region, Co. Kerry, were also investigated (details below; Fig. 1; Plates SM-PL-VII to IX).

The Nephin Begs, the vegetation history of which is used for comparative purposes, consist of extensive uplands, mainly of quartzite but including sedimentary rocks (Sleeman, 1992). These uplands form the large landmass stretching from Clew Bay to the blanket bog-covered lowlands of north-west Mayo. The northern part of this landmass is included in the Ballycroy National Park, the most recent of Ireland’s six National Parks.

The study areas, and specifically Connemara where the main investigations took place, have a distinctly Atlantic climate. Though Connemara is relatively small, climatic conditions vary substantially not only with elevation but also with distance from the coast. This is particularly the case with rainfall which, in the uplands, can exceed 3000 mm y$^{-1}$ (main data source: Walsh, 2012; also https://www.met.ie/climate/climate-of-ireland, accessed: 11 June 2020). Precipitation is mainly as rain but snow on the uplands is frequent in winter and a light covering of snow, normally of short duration, in early spring is not unusual. The statistics that follow relate to the lowlands of north central Connemara for the period 1981–2010. Temperature: January 5–6 °C, July 15–16 °C; annual: 9–10 °C; rainfall: January 150–200 mm, April (the driest
month); 75–100 mm; annual: 1600–2000 mm. Wind is also an important factor. Mean annual wind speed is 5–6 m s\(^{-1}\). Severe wind gusts are frequent and gusts of 48 m s\(^{-1}\) are likely to be exceeded once in 50 years.

3. Methods

3.1. Lake coring, and pollen and macrofossil analyses

Coring took place on the 5 October 1991. A 1-m Mackereth corer was used to sample the top sediment. Cores from locations I, II and III were taken in water depths of 4, 3 and 1.5 m, respectively (Fig. 3). At location IV, where maximum water depth of 5 m was recorded, rock (presumably bedrock), overlain by a thin layer of coarse sand, was encountered and no soft sediment was recovered. At the other coring locations, the top meter of sediment was collected (at I: MAM Ia and Ib; at II: MAM Ia and IIb and at III: MAM IIIa; Fig. 3) and complete sequences were sampled by Livingstone corer at location III (MAM IIb and IIIc; i.e. duplicate cores).

In the laboratory, whole core magnetic susceptibility (\(k\)) was measured in all core segments using a Bartington MS2 meter with a loop sensor that enabled a continuous record to be obtained. The core segments were then split open and the main stratigraphical features were noted following Troels-Smith (1955) guidelines. On the basis of these measurements and observations, cores MAM Ila (86–0 cm, mini-Mackereth core) and MAM IIIc (420–86 cm, Livingstone core; this combined sequence referred to as MAM III) were selected for detailed investigations.

Samples, consisting of 1 cm\(^3\) of sediment (2 cm\(^3\) in the case of two highly minerogenic, basal samples) from 1-cm thick slices, were taken at varying intervals (mainly at 4 or 8 cm). These were prepared for pollen analysis, following standard procedures as implemented in the Palaeoenvironmental Research Unit (PRU) (details in Huang, 1994). Sievings from the pollen sample preparations (fraction \(\geq 100 \mu m\)) were examined for macrofossils. Sand, charcoal fragments (referred to as macro-charcoal) and fibers, i.e. unidentifiable plant remains, were also noted. Estimates of relative abundance were made as follows: +, rare; 1, occasional; 2, frequent; 3, abundant and 4, very abundant. Later, for the purpose of obtaining material suitable for AMS \(^{14}\)C dating, 16 sediment samples of thickness 3 cm were sieved for macrofossils and the fraction \(\geq 100 \mu m\) was examined for macrofossils and other entities.

From the same depths as sampled for pollen analysis where possible, larger samples (2 cm thick, volume 39 cm\(^3\), in the interval 85–0 cm; otherwise 1 cm thick, volume 14 cm\(^3\)) were taken and the following measurements were made: bulk density, dry density, specific magnetic susceptibility and ash (mineral) content, i.e. loss-on-ignition at 550 °C. Specific magnetic susceptibility was measured using a Bartington MS2 meter and a dual frequency sensor (0.47 kHz and 4.7 kHz) connected to a PC. The meter was calibrated using a standard sample supplied by Bartington and readings were corrected for background and sample weight (details in Huang, 1994, 2002).

3.2. Bog-pine sampling for \(^{14}\)C dating

In connection with investigations into blanket bog initiation and expansion with particular reference to uplands, bog-pine timbers were sampled at the following locations (Figs. 1 and 3; Table SM-4; details of additional relevant samples from the literature are also indicated): (1) two small timbers (\(\leq 40\) years old) from at/close to the peat/mineral soil interface were sampled in shallow basin peat to the west of the lake at Mám Éan (250 m asl; Fig. 3); (2) four timbers (three stumps and a trunk; 40–100 years old) that rested on peat (\(\leq 40\) cm) in extensive blanket bogs at Bunnacunneen, 9 km north–north-east of Mám Éan, in northern Connemara (\(\sim 130\) m asl; many timbers revealed by peat cutting were present at or close to the base of the peat; Fig. 1B); (3) five timbers (four stumps and a trunk; \(\sim 40\) years old) in Hags Glen (\(\sim 300\) m asl), east of Carrantraoohil Mountain, on/near mineral ground (see Fig. 1C for these and other Kerry samples). A stump on mineral ground (Lu–773) from nearby (at 255 m asl) was sampled by Håkansson (1974). To the north-west of Moll’s Gap (213 m asl), and in the Owenreagh River valley, Derrytwe Townland to the north-east (95 m asl), a small and medium-sized stump, respectively, both on mineral ground in shallow, basin peat, were sampled; (4) three stumps (two on mineral ground; one on 60 cm of peat; 260 m asl) immediately to the east of L. Garagarry, Mangerton Mountain, in an area of extensive blanket bog; (5) a stump from a basin bog at 310 m asl adjacent to Uragh Wood (Little et al., 1996); and (6) two stumps on mineral soil in extensive blanket bog in the Wicklow Mountains (near Kippure and Sally Gap; 635 and 500 m asl; Håkansson (1974), and Brindley and Lanting, pers. comm., respectively) (Fig. 1A; Plates SM-PI-VII–IX).

In this project, the usual sampling procedure was followed that included cutting a slice of timber as close as practical to the base of the stump or near the base of a trunk. Subsequently, a subsample was taken — mostly timber from outer rings (details in Table SM-4) — and submitted to the \(^{14}\)C laboratory for dating.

3.3. Radiocarbon dating

Seven samples of lake sediment from core MAM III, 5–6 cm in thickness and \(\sim 100\) g wet weight, were initially taken for bulk \(^{14}\)C dating at depths corresponding to the position of major changes in the pollen stratigraphy (Huang, 1994, 2002). Conventional \(^{14}\)C dates were provided by the Gwice Radiocarbon Laboratory, Poland for these bulk-sediment samples. Macrofossil remains from 10 samples were later submitted for AMS \(^{14}\)C dating to Groningen Radiocarbon Laboratory (GR). \(^{14}\)C dates were returned for nine samples. CLAM (v. 2.2) (Blaauw, 2010) was used to construct an age–depth model for core MAM III (details in Table SM-3).

Sixteen bog-pine samples were submitted to GR for conventional \(^{14}\)C dating. These \(^{14}\)C dates and dates available from elsewhere (see Table SM-4), were calibrated using OxCal (v. 4.3) (Bronk Ramsey, 2009) and the IntCal13 calibration curve (Reimer et al., 2013).

4. Results

4.1. Lake sediments: Stratigraphy and results of physical measurements

Soft sediment accumulation at Mám Éan appears to be confined to the western side of the lake which is sheltered from the prevailing south-westerlies by elevated ground (Figs. 1–3). At the more exposed location IV, in 5 m water depth, there were no soft sediments. Presumably, water movement within this part of the lake, caused mainly by wind action and inflowing streams (though these are not well defined), prevented soft-sediment accumulation or caused its removal.

The stratigraphical features of selected cores (MAM Ila–c, MAM Ia and b) are depicted in Fig. 3 and details are given in Table SM-1. The long cores, MAM IIb and IIIc, had comparable stratigraphical features with gray-blue silt/clay at the base, followed by black silty gyttja with some sand-rich layers, then black fibrous gyttja, and finally black silty gyttja that included a conspicuous sand component in the uppermost part of the column. A tripartite stratigraphy as is typical of Late-glacial sediments in Ireland (Jessen and Farrington, 1938; Andrieu et al., 1993) was not present in either MAM IIb or IIIc (full sedimentary sequence retrieved in both instances) but the pollen data indicate that the early Holocene (and possibly the final phases of the Younger Dryas) is represented in the basal part of the core (see below). Mini-Mackereth cores MAM Ila and b consisted mainly of black gyttja with sand/silt enrichment between 19–33 cm and 7–35 cm, respectively.

The whole core magnetic susceptibility (\(k\)) results for the main cores are shown in Fig. 3. In the two long cores, MAM IIb and IIIc, the sharp transition from silt/clay to gyttja at the base corresponds with a distinct
fall in \( \kappa \) values (correlation \( \alpha \), Fig. 3). This marks the beginning of the Holocene (see Interpretation). Values for \( \kappa \) then fall consistently until -340-330 cm (depths quoted refer to MAM IIc unless otherwise indicated) where elevated values were recorded from a sand-rich gyttja. A similar feature was recorded in MAM IIIb (correlation \( \beta \)). Another sand layer (relatively thin) and elevated \( \kappa \) values were recorded at \(-260-250 \) cm, but there is no clearly corresponding feature in MAM IIb (see possible correlation \( \gamma \)). At 184 cm, the sediment changes to a black fibrous gyttja and at a few centimeters below this a trend towards lower \( \kappa \) values is initiated (low \( \kappa \) values persist between correlations \( \delta \) and \( \varepsilon \), but sediment accumulation in MAM IIb appears to have been considerably faster). The uppermost parts of the cores, including the mini-Mackereth cores, show considerable intra- and inter-core variation. Several of the cores include a sandy/silty layer that is highlighted by a thick vertical line in Fig. 3. This layer seems to represent a distinct erosional event/phase that is variably expressed at the different coring locations (thick and thin layers at MAM Ia, and IIA and IIIC, respectively). Why it is not represented in MAM Ila and IIb or in MAM IIb is unclear. Sedimentation rate in the upper half of MAM IIb is faster than MAM IIc, so it is likely that the uppermost sediments at coring position MAM IIc were not sampled by the Livingstone corer.

Bulk density, dry density and ash values, which reflect mainly changes in organic/inorganic content, are now considered. Bulk and dry density values are generally at 1.0-1.1 g cm\(^{-3}\), except for the basal minerogenic layers (below 380 cm; 1.1-1.8 g cm\(^{-3}\)) and the upper, mineral-rich sediments (above 80 cm; 1.1-1.25 g cm\(^{-3}\)). Dry density values follow a similar pattern, with the basal minerogenic layers (below 354 cm) giving values of 0.2-1.4 g cm\(^{-3}\) but otherwise the values are generally in the range 0.07-0.2 g cm\(^{-3}\), except for sediments between 72 and 66 cm where values of 0.2-0.24 g cm\(^{-3}\) were recorded. The ash values show the greatest variation and, as the most informative of the physical data, are presented in Fig. 3 (see also Huang, 2002). High ash values, mainly in the range 50-80%, indicate highly minerogenic sediments throughout. The clay/silt-rich basal sediments, as expected, gave the highest values (maximum: 96%) while the lowest values were recorded in the uppermost sediments (values fall from 46% to 27% between 16 and 0 cm, indicating a distinct increase in the organic component towards the top). These low values follow an interval with elevated values starting at 90 cm. Between 182 and 94 cm, ash values are depressed (53.3%) which, again, is as expected, given the different lithology (sediments are rather organic-rich and with fine fibers), and the distinctly negative \( \kappa \) values.

Specific magnetic susceptibility values \( (\chi_a \text{ and } \chi_d) \), being derived from single samples from which water was removed by drying, give, as might be expected, a sharper picture than the \( \kappa \) values (Fig. 3). They are usually regarded as reflecting variations in the abundance of ferrimagnetic iron oxides in the sediment profile that originate through inwash of primary or secondary minerals from the catchment (Oldfield, 2007; Hatfield, 2014). The \( \chi_d \) (specific susceptibility in a low frequency field) values were generally below 10 \( \times 10^{-9} \) m\(^2\) kg\(^{-1}\) which suggests that diamagnetic minerals, such as quartz and calcite, are the main minerogenic components of the sediment. The sand-rich layers at -330, 255 and 70 cm (also the sediment above 44 cm) gave distinctly elevated values as expected.

The \( \chi_d \) values are usually regarded as reflecting the relative contribution of fine viscous (\(-0.02 \mu m\)) magnetic grains, which are generally secondary and usually originate in the A horizon of mature stable soils that have been eroded from the catchment (Hatfield, 2014). From the base of the profile to 224 cm, \( \chi_d \) values are low. Particularly low values are recorded in the intervals with sand-rich sediments where \( \kappa \) and \( \chi \) values are high. This suggests that the ferrimagnetic minerals are coarse and non-weathered, i.e. primary, and originate from unweathered soil-parent material. Between 224 to 78 cm, \( \chi_d \) values are elevated while above this (up to 6 cm), the values are low, i.e. in the interval corresponding to strong inwash. The \( \chi_d \) curve appears to accurately reflect changing intensity of erosion with low values corresponding to intensive erosion and input of mainly unweathered mineral material (see also below). The elevated values in the top 6 cm may reflect diffusion of ultra-fine iron components from the sediment to the water column (Engstrom and Wright, 1984; Hatfield, 2014).

Overall, cores MAM IIb and IIc (excluding the uppermost sediments) share many similar features, and so it appears justified to regard core MAM IIc, combined with top sediments from MAM IIa, as a good source of evidence for Holocene environmental change within this potentially, highly dynamic environment.

### 4.2. Lake sediments, core MAM III. \(^{14}C\) dating and age–depth relationship

The results of \(^{14}C\) dating of lake-sediment samples, and the age/depth curve based on these dates and other fixed points are shown in Fig. 4. Additional details are provided in Table SM-3.

The age–depth curve is a smooth spline (smooth = 0.5) that takes cognizance of the following fixed points: five of the seven available conventional \(^{14}C\) dates (the omitted dates show inversions) and the nine available AMS \(^{14}C\) dates. In addition, the following points, based on pollen and/or lithology, have been used, namely the Lateglacial/Holocene transition (at 406 cm; 11,650 ± 99 cal. BP; Walker et al., 2009, 2019); the mid-Holocene Elm Decline (224 cm: 5800 ± 100 cal. BP; Parker et al., 2002; see also Kearney and Gearey, 2020), the secondary rise in Pinus (at 52 cm; 200 ± 50 cal. BP; reflects reforestation that began in Ireland, including Co. Galway, by the early eighteenth century; Dutton, 1824), and the top of the sediment column (ca. AD 1990). The Alnus rise at the Boreal/Atlantic transition (classical divisions of the Holocene are after Mitchell, 1956) is shown in Fig. 4 but this is not used for conventional \(^{14}C\) dates (the omitted dates show inversions) and the nine available AMS \(^{14}C\) dates. In addition, the following points, based on pollen and/or lithology, have been used, namely the Lateglacial/Holocene transition (at 406 cm; 11,650 ± 99 cal. BP; Walker et al., 2009, 2019); the mid-Holocene Elm Decline (224 cm: 5800 ± 100 cal. BP; Parker et al., 2002; see also Kearney and Gearey, 2020), the secondary rise in Pinus (at 52 cm; 200 ± 50 cal. BP; reflects reforestation that began in Ireland, including Co. Galway, by the early eighteenth century; Dutton, 1824), and the top of the sediment column (ca. AD 1990). The Alnus rise at the Boreal/Atlantic transition (classical divisions of the Holocene are after Mitchell, 1956) is shown in Fig. 4 but this is not used for...
curve construction. This feature, usually dated to ca. 7700 cal. BP in pollen profiles from western Ireland (Molloy and O’Connell, 2014), fits well with what the age/depth model suggests. An erosional event, centered on 323 cm and referred to as E1, is also shown in Fig. 4. On the basis of the age/depth model, this event dates to ca. 9000 cal. BP which suggests that it is not an expression of the 8.2 ka event but probably an older climate oscillation.

Compared with the age/depth model in Huang (2002), the main difference is that the mid and lower sediments are now considered to be older for a variety of reasons including: (a) use of Elm Decline to constrain the mid-part of the curve, (b) differences arising from use of a newer 14C calibration curve, and (c) an older age being assigned to the Late-glacial/Holocene transition (this follows Walker et al., 2009, 2019). Interestingly, if the 14C dates 8710 ± 120 BP and 6697 ± 100 BP had not been omitted in constructing the present age/depth model (they were used in Huang, 2002), that part of the core would have a still older age.

4.3. Bog-pine timbers: Results of 14C dating

Calibration outputs of 14C dates derived from pine timbers are plotted in Fig. 5. In addition to the 14C dates listed above (see Methods), four dates from the lowland site, Shanvallycahill (~20 m asl; details in O’Connell et al., 2020), located 12 km and 19 km distant from Bunnacunneen and Mám Éan, respectively (Fig. 1B), are included for comparison. The two timbers from Mám Éan yielded indistinguishable dates (centered on 4850 cal. BP; median calibrated ages rounded to nearest 10 years are cited unless otherwise indicated) and are similar in age to the four timbers from Shanvallycahill and a timber from Bunnacunneen (4340 ± 20 BP, i.e. 4890 cal. BP). Two timbers from nearby (at Bunnacunneen) are distinctly younger, i.e. ca. 4200 cal. BP, while a stump from the same area but at a somewhat lower elevation dated to 5960 cal. BP. In other words, there are at least three distinct periods, within the interval ca. 6000–4000 cal. BP, when pine grew in this upland area at times when peat was actively accumulating. The dates serve to confirm that peat initiation was a widespread phenomenon by 5000 cal. BP at the latest, while, in Bunnacunneen, it predated 6000 cal. BP (cf. CY-004; 5210 ± 20 BP locally, which is not surprising given the many substantially earlier dates for bog development in northern Co. Mayo (O’Connell et al., 2020).

The upland 14C dates from the Killarney region (Hags Glen, Moll’s Gap, Derrylea Townland (Td.) and Mangerton) span the interval 3700–5500 cal. BP. There are only two dates older than 5000 cal. BP, i.e. Lu-772 (4600 ± 65 BP) and GrN-33,055 (4620 ± 20 BP) while six dates fall in the interval ca. 4400–5000 cal. BP, i.e. the main interval for bog-pine. Two dates, 1810 ± 95 BP and 1790 ± 95 BP, from Ladies View, east of Moll’s Gap, are not shown in Fig. 5 (they are included in Table SM-4). These dates were obtained a long time ago, they are clearly outliers and, furthermore, there is uncertainty as to location (McGeever and Mitchell (2015) give very different altitudes for these timbers which are regarded as deriving from the same geographical location; see Table SM-4). Though these dates are frequently referred to (e.g. Mitchell, 1988; Bradshaw and Browne, 1987), they are omitted here because of the various uncertainties involved.

From the Beara Peninsula (310 m asl), south-east of Killarney, there is the 14C date 3720 ± 70, i.e. ca. 4100 cal. BP. (Little et al., 1996) which, though rather young, is not an outlier relative to the dates presented here. The dates from the Wicklow Mountains, i.e. 4200 ± 60 and 4570 ± 60 BP (near Mount Kippure and Sally Gap, respectively) derive from pine timbers at 636 and 500 m asl, respectively, i.e. the highest elevation for which 14C bog-pine dates are available. Both are from the basal peat and were sampled with the view to providing a terminus post quem for local peat growth. Interestingly, that at the higher elevation gave a date that lies more or less within the main interval for bog-pine dates while the latter is somewhat older (ca. 5230 cal. BP). It should be noted that the date cited for the Sally Gap sample is based on C-cellulose. The N-cellulose component, which was separately dated, returned an older date (4720 ± 50 BP; see Table SM-4). The dataset as a whole shows that most bog-pines are somewhat younger than 5000 cal. BP. However, over a period of a few centuries ending at ca. 5100 cal. BP, bog-pines may also have been relatively frequent in the uplands of Kerry and Wicklow.

4.4. Pollen profile MAM III: Pollen and macrofossil analyses – Data presentation

Pollen, macrofossil, and related data including charcoal, are presented in Fig. 6. An overview summary diagram is given in Plate SM-PL-V. The complete dataset is available in PANGAEA (O’Connell and Huang, 2020). For calculating the percentage data, total terrestrial pollen (TPP) was employed as a pollen sum (PS). This included bog taxa but Sphagnum spores were excluded as is normally done. A pollen count of 954 ± 131 (average and standard deviation; TTP only included) was achieved in the dataset and an additional slide was searched for pollen taxa not encountered during routine counting (there were recorded as ‘+’). Taxa outside the PS, such as Sphagnum, aquatic taxa and algae (Pedalium), and micro-charcoal, i.e. charcoal particles ≥37 μm (the average size of the added Lycopodium spores) are expressed relative to TTP + Σ taxa in the particular category.

The pollen profile has been zoned in the traditional way, i.e. boundaries are placed where major changes, as detected by careful visual scanning of the percentage plots, are recorded. The zonation is broadly similar to that in Huang (2002) but the number of zones is reduced from 11 to 10 and positioning of zone boundaries in the upper part of the profile, i.e. from zone 7 upwards (Elm Decline and later), has been modified.

Pollen taxa names generally follow Moore et al. (1991). Cereal-type are as defined by Beug (2015) but 40 μm was taken as the cut-off point for separating pollen of non-cultivated versus cultivated grasses. Critical pollen taxa that were separated with confidence include Corylus, Myrica, various Plantago and Plantago-like taxa, i.e. P. lanceolata, P. major/media, P. maritima and Littorela, taxa within the family Saxifragaceae (S. oppositifolia-type was recorded in five spectra) and ericoids (e.g. Calluna, Erica cinerea, E. tetralix and Empruetum). Minor taxa were combined into groups that include the following (the major pollen taxon within each group is given in parentheses): Tubuliflorae (Bidens-type), Fabaceae (Lotus-type) and Caryophyllaceae (Cerasium-type). Hymenophyllum spores were not identified to specific level during counting. Spores that were critically examined were assignable to H. wilsonii. Based on this and the infrequency of spores of H. unbrigense in Irish Holocene profiles investigated in the PRU, the Hymenophyllum records are regarded as predominantly, if not exclusively, deriving from H. wilsonii (cf. used in labelling curve to indicate that is some uncertainty in the identification; Fig. 6A). Isoetes microspores were separated, during counting, into I. lacustris and I. echinospora on the basis of size (Birks, 1973). It is probable, however, that the small numbers of spores classified as I. echinospora (see Huang, 2002) are merely small spores produced by I. lacustris. The frequent records of I. lacustris megaspores and the lack of records for megaspores of I. echinospora justfify referring all Isoetes microspores to I. lacustris (see Isoetes curve in Fig. 6B; I. lacustris is present in the lake today).

5. Reconstruction of Holocene environment change at Mám Éan

The following are the main considerations taken into account when interpreting the paleoenvironmental record. Mám Éan lake is small (1.14 ha), and off-center with respect to the flat, hummocky area of ~30 ha that constitutes Mám Éan gap (Figs. 2 and 3). Furthermore, the lake nestles under low cliffs that form part of the elevated ground that
risers sharply to the south-east. This steeply sloping ground, as well as the gently sloping ground to the west, are presumably important sources of runoff that transport the products of erosion (mineral and organic matter, including pollen, especially where peat has accumulated) directly to the lake. As regards the source area of aerial-borne pollen, this is assumed to be, in the first instance, the gap itself and the high ground at either side. It is also reasonable to assume that, given the exposure of the site to strong prevailing south-westerlies, pollen from further afield (see below), and especially from the extensive lowlands between Mám Éan and the peninsulas of Carna and Roundstone, is also well represented, especially after woodland clearances created openings, and ultimately a completely open landscape, that favored NAP dispersal.

An overview of the pollen profile and changes in vegetation and environment that it reflects follows and a summary is available in Table SM-2.

5.1. Lateglacial and early Holocene environments (to end of pre-Boreal; PAZs 1–3; ca. 11.95–10.6 ka)

On the basis of the available pollen, $^{14}$C and stratigraphical evidence, it is concluded that Lateglacial sediments, if present, are limited to the final years of the Younger Dryas. Given that corrie glaciation was a feature of the Younger Dryas in Ireland, and in particular western Ireland (Meehan, 2017; Coxon, 2019b), and the evidence now available from the lake at Mám Éan, it is likely that the basin was occupied by ice at least for a time during the Younger Dryas. The pollen spectra from the basal clays (PAZ 1) suggest tundra-like communities that were herb-rich, and included abundant clubmosses (Huperzia selago) and also crowberry (Empetrum nigrum) (Fig. 6). The presence of acidic heath communities is also suggested by records for Sphagnum leaves (these continue to PAZ 3) though Sphagnum spores are poorly represented (Fig. 6B). Several aquatics, including Myriophyllum, Potamogeton sect. Eupotamogeton (this reflects broad-leaved Potamogeton spp.) and Littorella, are recorded in PAZ 2. Aquatics and their reflection in the fossil record were presumably favored by low lake levels that were a feature of the early Holocene in Ireland and elsewhere in Europe (Holmes et al., 2007; Magny, 2004).

The rapid warming at the beginning of the Holocene (Alley et al., 2010; Rasmussen et al., 2014) presumably drove the expansion of, initially, juniper and then birch (presumably Betula pubescens; PAZs 2 and 3) and led to greatly increased pollen production (see pollen concentration curves and also AP pollen accumulation rate curve in Fig. 6B). Herbaceous pollen, however, continued to be strongly represented and also fern spores, so it is clear that woody vegetation failed to achieve dominance at this time. As regards the NAP component, noteworthy are the relatively high values for Rumex-type and Saxifraga. The former probably includes pollen of Oxyria digyna, an arctic-montane element that is rare in Ireland today (it is present on the Maumturks and the Twelve Bens). The latter includes several Saxifraga pollen types that may indicate several species associated with arctic-montane habitats. Included is Saxifraga oppositifolia (pollen of this taxon attained 0.1% and 0.5% in the basal spectra; 418 and 410 cm, respectively), a species rare in upland habitats in Ireland but, exceptionally, also recorded in lowlands at Lissouther, Connemara (Webb and Scannell, 1983).

The lithology and physical measurements indicate that high levels of erosion persisted, probably caused by solifluction, until near the end of PAZ 3 (ca. 10.6 ka). This, combined with high NAP representation, suggests persistence of cold temperatures that undoubtedly impeded the spread and expansion of more thermophilic species, including Corylus (hazel). It is noteworthy, however, that a slender curve for Osmunda (royal fern; given that its spore is large and heavy, regional and probably local presence can be assumed) is initiated at the base of PAZ 3. This Atlantic species, which is frequent in wet habitats where grazing is restricted in western Ireland, including present-day Connemara, has been present since ca. 11,500 cal. BP. A substantial clump grows today at the lake edge (Plate SM-PL-1V). There are early Holocene records for Osmunda at Loch an Chorcail, Carna (semi-continuous in this profile) and at Dolan, near Roundstone (O’Connell and McDonnell 2019; Teunissen and Teunissen-van Oorschot, 1980). The present-day Atlantic distribution pattern of this interesting fern appears to have been established early in the Holocene (Birks and Paus, 1991).

As regards possible pre-Boreal oscillations (Borzenkova et al., 2015), the slow sediment accumulation rate, combined with rather large sampling intervals, results in a record with temporal resolution that may be too coarse to identify short-term oscillations such as recorded elsewhere in Europe during this period.

5.2. Early Holocene, Boreal period (PAZs 4 and 5; ca. 10.6–7.6 ka)

Development of tall canopy woodland is well progressed in PAZ 4 (10.6–10 ka) and further important changes take place in PAZ 5 (10–7.6 ka). As is usual in Irish Holocene pollen records, Corylus expansion precedes and outpaces that of Pinus. Hazel seems to have been already present in Connemara towards the end of PAZ 3 and, in the lake, I. lucustris flourished. The expansion of I. lucustris was probably favored by reduced mineral soil erosion, as woody vegetation expanded and herbaceous communities were out-competed and contracted. As regards heathy vegetation, Empetrum was no longer important but there was now heath present that included Calluna (pollen; also twigs and a flower head recorded) and the mosses Sphagnum and Racomitrium (records for Racomitrium (not identified to specific level) and also R. lanuginosum and R. fasciculare; Fig. 6B, Table SM-3). The continuous persistence of Juniperus in the pollen record to ca. 7.4 ka is exceptional in Irish pollen records and suggests a degree of openness probably connected with upland conditions (prostrate juniper, usually infertile, is frequent today above ca. 300 m in the Maumturks and the Twelve Bens; personal observation).

From the beginning of PAZ 5 and perhaps earlier, elm and probably also oak were present in woodlands that were dominated by pine and hazel, the former having greatly increased in importance (Pinus achieves 34% in subzone 5a). A more or less continuous curve for Hedera – ivy is a thermophilic species (Iversen, 1944) – begins in subzone 5a. At the top of subzone 5a and in 5b, Pinus and Corylus oscillate considerably and in opposing directions. P. sylvestris (only this species of pine comes into consideration) as essentially a boreal-type, continental tree (Carlisle and Brown, 1968) is expected to be favored by colder conditions while return to warmer climate can be expected to favor Corylus. Betula, another cold-tolerant tree, shows little response and NAP remain steady but Pteridium increases and there is a short continuous record for Hymenophyllum (probably exclusively H. wilsonii). Given that birch did not expand and that bracken and Wilson’s filmy fern appear to have been favored, a major climate oscillation is not envisaged. Climate perturbations are known from ca. 9.2 ka but not of the magnitude associated with the 8.2 ka event (Ghilardi and O’Connell, 2012; see also below). Macro-charcoal is plentiful for the first time at the base of subzone 5b. This suggests local fires that presumably added to any disturbances that may have been caused by climate oscillation. Whatever the precise factors, there was increased erosion in the catchment as shown by the elevated magnetic susceptibility values (both $\chi_{dr}$ and $\chi_{2\theta}$) in parallel cores lIb and lIIc, and conspicuous sand in core lIc.

Fig. 5. Results of calibration of $^{14}$C dates of pine timbers. Probability is schematically indicated, and 1σ and 2σ ranges (lines beneath dates) and also the median age (cross) are indicated for each date (derived from OxCal; see text).
In subzone 5c, Poaceae are well represented (average: 7%) and Calluna continues a slow rise. Local presence of Calluna is confirmed by records for twigs and a flower head (Fig. 6B; Table SM-3). Erica tetralix — its curve starts in subzone 5a — is consistently recorded so blanket bog communities are now well established. The main change in AP involves an increase in Pinus, a minor rise in Betula and a distinct decrease in Corylus at 294 cm (8.07 ka). These changes may be connected with the 8.2 ka event that involved a substantial decline in temperature and especially winter temperature (Ghilardi and O’Connell, 2012; Torbenson et al., 2015). It is not possible to be definitive, however, in the absence of more detailed data.

5.3. Mid-Holocene, Atlantic period (PAZ 6; ca. 7.6–5.6 ka)

The woodlands continued to be dominated by pine and oak, elm made a modest contribution and alder expanded but did not become an important tree (Alnus averages only 4.4%). Fraxinus has a curve which, though slender (average: 0.2%), may indicate local presence of ash. In subzone 6b (254 cm; 6.5 ka), there is a well-expressed erosional event that is shorter but more intense than that recorded in subzone 5b. Oak and elm appear to be favored while pine and especially hazel decline. NAP show only minor response. Poaceae and Filipendula register a small increase, and there are records for P. lanceolata but only ‘+’ values, i.e. records outside the pollen count.

Towards the top of subzone 6c a curve for P. lanceolata is initiated and Poaceae begin to rise. Representation of charcoal (both micro- and macro-charcoal) and sand particles also increases. These changes, and the initiation of an Ilex curve starting at the base of the subzone, suggest disturbance and an opening-up of the woodland cover. Comparable changes in pre-Elm Decline contexts have been documented at several sites in Ireland and especially western Ireland (O’Connell and Molloy, 2001; Molloy and O’Connell, 2004; Stolze and Monecke, 2020) so it seems that minor disturbance/opening-up of woodlands was widespread by ca. 6 ka and thereafter.

Given the lack of strong evidence for erosion during subzones 6b and 6c (magnetic susceptibility and ash values are rather high but the alga, Pedialium, which is known to respond positively to erosion, has low values), it may be that the pollen data are reflecting regional rather than specifically local change at Mám Éan.

5.4. Mid-Holocene, Neolithic period (PAZ 7; ca. 5.6–4.5 cal. BP)

As in most Irish pollen diagrams, even where Ulmus has low representation, the Elm Decline at Mám Éan is well defined (subzone 7a). Not only Ulmus (from 9.2% to 2.8% across the zone boundary), but also Pinus and Quercus decline (percentage, concentration and pollen accumulation values). Poaceae values almost double and curves for other taxa indicative of grassland, such as P. lanceolata, Filipendula and Ranunculus, show minor increases. Two cereal-type pollen were recorded at the Elm Decline (222 cm). Both pollen are Triticum-type (maximum dimensions: length: 55.5 and 56.6 μm; annulus + pore diameters: 13.3, 14.4 μm; pore diameters: 5.6 μm). These dimensions are particularly large for Triticum-type pollen (Beug, 2015) so there can be a good degree of certainty that they derive from wheat which, presumably, was being cultivated by early Neolithic farmers in the region, though hardly in the vicinity of the lake given the overall unsuitability of the terrain (rocky with little or no glacial deposits) for cereal cultivation.

As there is no evidence for increased soil erosion, it is presumed that the fluctuation in the pollen curves reflects regional as much as, or even more than, local changes. Given the rather sharp decline in AP, a Landnam-type event, i.e. clearance of woodland in the context of Neo- lithic farming is envisaged for this time, in addition to a disease factor that differentially affected elm. Interestingly, fire does not appear to have been involved in the clearances or in farming generally at this time. The distinct increase in Calluna and Sphagnum suggests the expansion of bog and heath but it should also be borne in mind that open conditions per se would have greatly facilitated dispersal of pollen and spores arising from bog and heath communities (cf. Åkesson et al., 2015; Marquer et al., 2020).

Subzones 7b and 7c indicate a continuing dynamic situation from the view points of woodland and landscape development. In the former subzone, which spans ca. 5.4–5.1 ka, pine expanded to become dominant with oak, and elm also recovered. There is a distinct decrease in NAP, and especially Poaceae and also P. lanceolata. Woodland recovery has taken place at the expense of grassland rather than bog and heath. At the base of subzone 7c (ca. 5.1 ka), there is a sharp decline in Pinus, and Taxus, which was initiated at the top of subzone 7b expands. Other changes include an increase in Poaceae (but P. lanceolata was not recorded during routine counting), and interestingly also Juniperus increases to 1.4%. Magnetic susceptibility data and an increase in ash values suggest increased erosion. Cause and effect are particularly difficult to disentangle here. Given that there is little evidence for human impact and farming activity is known to have declined rapidly after an initial surge in the early Neolithic in western Ireland (O’Connell and Molloy, 2001) it is unlikely that human activity is a primary driver. Climate instability seems to have been a feature of the mid-Holocene (e.g. Caseldine et al., 2005; Magny et al., 2006; Taylor et al., 2018) but hardly of the severity required (see, for example, Taylor et al., 2013, 2017) to effect the changes in human activity and vegetation dynamics that are reflected in pollen and also other evidence (Whitehouse et al., 2014). In mid and late subzone 7c, a dynamic situation continued with Pinus increasing strongly before declining rapidly as Taxus peaks to 13.3%. Pinus fails to recover after this. The distinct decrease in woodland as the zone ends is the result of increased farming impact that is manifested in higher Poaceae and the re-establishment of a P. lanceolata curve. A curve for Nathorischium ossifragum is established at the top of subzone 7b which probably signals a shift towards increased wetness especially during subzone 7c (after ca. 5 ka) during which N. ossifragum further expands. Today, N. ossifragum is common on bogs locally and in the wider region.

5.5. Woodland and land-use, Bronze Age onwards (PAZ 8; ca. 4.5 cal. BP to recent times)

This long interval is characterized by a landscape that is open but by no means treeless, and that sustains a more or less continuous farming presence. Envisaging the pollen source area is particularly challenging given the site location and the desirability of distinguishing between conditions prevailing within the gap and the immediately associated higher ground, and the extensive lowlands to the south-west of Mám Éan. The rather smooth character of most curves, and especially curves indicative of pastoral farming, e.g. P. lanceolata and very low values of taxa indicative of arable farming (see NAP2, i.e. cereals and weeds of arable contexts in Fig. 6A), suggests that the pollen (especially the AP component) is reflecting mainly the regional situation. Elevated micro-charcoal values, which contrast with little macro-charcoal, also serve to emphasize the regional character of the record during PAZ 8. Furthermore, absence of major disturbance in the catchment is more than...
suggested by the lithology (organic-rich gyttja with fine fibers), and low magnetic susceptibility and ash values. The reconstructions that follow should be regarded as applying mainly to the Connemara lowlands unless otherwise indicated.

Subzone 8a–d may be regarded as reflecting general and also specific changes in vegetation and farming, starting in the closing phases of the Neolithic and extending to the early historical period (the historical period in Ireland is usually regarded as beginning at ca. AD 400 with the introduction of Christianity; Aalen et al., 2011). In subzone 8a (4.5–3.5 ka), woodlands, though rather strongly impacted by farming and hence more open, continue to dominate. Pine, the dominant woodland tree since at least 10 ka, plays very much a subordinate role in what are now mainly deciduous woodlands of oak and hazel, but also with birch, ash, yew, rowan, holly, juniper and ivy. As expected given the change in lithology (organic-rich with fine fibers), aquatic pollen has increased representation (especially Potamogeton and Nymphaea, i.e. large-leaved floating aquatics; P. polygonifolius fossil already recorded in subzone 7b and 7c; Fig. 6B, Table SM-3), and there are occasional pollen records for E. aquaticum and L. dortmanna, which give the low pollen productivity and dispersal capacity of these species, are regarded as signifying local presence in the lake.

In subzone 8b (3.5–2.3 ka), woodlands, and especially oak, contract (the persistent low AP concentration and influx values in this and subsequent subzones are particularly noteworthy; Fig. 6B), and grasslands expand due, no doubt, to increased farming (P. lanceolata and most NAP have increased values) in the later Bronze Age. Pine and yew persist but only as minor woodland components. In the latter part of this interval (early and mid-Iron Age), the Hedera and Ilex curves are interrupted suggesting absence of these shrubs in the vicinity of the lake and also hinting at lack of local woodland. It is interesting that ash content shows a steady increase in subzone 8b which suggests increased erosion (supported by increased Isoetes and Pediastium; Fig. 6B) that is expected given the lack of woodland cover.

Subzone 8c (2.3–1.2 ka) starts with further reduction in woodland cover and increased farming activity, possibly associated with the upsurge in activity that was a feature of the La Tène period (starts at ca. 300 BC) in Ireland (Armit et al., 2013). The upper part of the subzone indicates weak woodland regeneration (especially hazel; also ash). This development relates to the early centuries of the first millennium AD and may be regarded as a weak expression of the Late Iron Age Lull that often finds strong expression in pollen profiles from western Ireland including Connemara, e.g. at Derryinver (Molloy and O’Connell, 1993).

In subzone 8d (1.2–0.88 ka; AD 750–1270) a substantial shift towards less woodland cover is recorded. Hazel is particularly adversely affected. Higher values for Calluna and Myrica suggest further expansion of bog/heath communities. There is increased erosion (elevated magnetic susceptibility and ash values) which may be partly responsible for the increased representation of bog/heath taxa and especially Calluna as a result of peat inwash.

At the start of PAZ 9 (0.88–0.35 ka, AD 1270–1600), final deforestation is recorded. The only major contributor to AP is Corylus and, to a lesser extent, Alnus, and, in both cases, it can be assumed that long-distance pollen transport plays a major role as shown by Huang and O’Connell (2000) at Ballydoo Lough, eastern Connemara. During PAZ 9 and for most of PAZ 10, there is greatly increased erosion of mineral material. High Poaceae and NAP generally (especially P. lanceolata) indicate substantial levels of human activity (pastoral and also arable farming), presumably mainly in the lowlands but, in the case of pastoral activity, also extending to the uplands. Climate change, including unfavorable conditions associated with the start of the Little Ice Age (LIA) in the fourteenth century (cf. Oliva et al., 2018), might be expected to hinder use of the uplands, but socio-economic developments were probably of greater importance (cf. Davies, 2007) and especially in times of population increase such as experienced between ca. AD 1750 and 1840 (this led to, and ended with, the Great Famine, AD 1845–1852), when the population rose sharply and resulted in extensive and intensive use of uplands in Connemara and elsewhere in Ireland (Aalen et al., 2011; Costello, 2020a, b).

PAZ 10 reflects changes during recent centuries. The age/depth model suggests that the base of the zone dates to AD 1600 but, given the chronological uncertainties that inevitably arise from a greatly accelerated sediment accumulation rate (Fig. 4), the dating should be regarded as indicative. Nevertheless, re-assurance as to overall accuracy is provided by the rise in Pinus (also AP generally) at the base of PAZ 10 which reflects the widespread planting of pine that had commenced in the region by the mid-eighteenth century (Dutton, 1824). Records for Picea in the uppermost three spectra, which reflect afforestation in the twentieth century, also help anchor the chronology. The totally treeless aspect of the landscape prior to recent afforestation is artistically attested to by the evocative sketch of a pattern (pilgrimage) by the English artist W.H. Bartlett who toured Ireland in the early nineteenth century (Bartlett and Griffiths, 1835; Fig. 2B). W. Evans, another English artist, made several sketches showing treeless landscapes during a sojourn in Connemara in 1838 (Plate SM-PL-I). In recent decades, the uplands of Connemara have been intensively grazed by sheep and, to a less extent, cattle. The overgrazing that resulted, especially in the late twentieth century, has led to severe peat erosion (see Introduction). These developments are reflected in the sharp increase in organic content of the uppermost sediments (Fig. 3). The expansion of M. trifoliata in the shallow western part of the lake in recent years suggests that peat erosion continues apace, a view supported by casual observations in the catchment.

6. Discussion

6.1. Vegetation dynamics in mid-western Ireland with particular reference to Pinus sylvestris and Taxus baccata

The long-term environmental record from Mám Éan and the new 14C dates from bog-pine timbers at Mám Éan and other upland sites in western Ireland contribute substantially towards our knowledge of changes in vegetation, landscape and land use in upland environments in western Ireland. The overall developments are similar to what is known from Ireland generally and include the following: (1) rapid response by shrubby species and especially Juniperus and Betula to early Holocene warming, (2) major expansion of Corylus (see KD1, i.e. key development (KD) 1, in Fig. 7) with Pinus expanding at about the same time, and Ulmus and Quercus expanding later and to a lesser degree, (3) expansion of Alnus (marking the Boreal-Atlantic transition; KD2) and a mid-Holocene Elm Decline (KD3), (4) expansion of Taxus and substantial increase in human impact (latter at KD4), (5) greatly increased human impact (after the Late Iron Age Lull) starting at ca. AD 400 (KD5), and (6) beginnings of re-afforestation (ca. AD 1750; KD6). In order to further explore these and other developments at a wider geographical scale and to obtain insights into the possible forcing factors involved, data from other sites in the region have been compiled and are presented in Fig. 7.

Criteria that have guided the selection of comparative sites (nine in all) are as follows. The sites should not be too distant from Mám Éan so as to facilitate exploration of small-scale variation (most sites are within 30 km; L. Doo at 80 km to the north-east is the most distant, followed by An Loch Mór at 48 km to the south), the emphasis should be on upland sites but lowland sites are included as they provide useful comparanda (five of the sites are at ≤ 60 m asl), and small to medium-sized lakes are preferred since their records reflect local rather than wide regional developments. Furthermore, their records are not unduly influenced by pollen derived from local mire vegetation as is often the case in peat-derived profiles. The largest lake by far is An Loch Mór at 64 ha but, given its relatively isolated location in the Atlantic Ocean, the record that it provides may too be regarded as local. None of the cores selected are from marginal locations within the sampling basin.
was based mainly on pollen stratigraphy (only one 14C date was available in the original paper by Bradshaw and Browne (1987) the chronology in Holmes et al. (2020). As regards the four upland cores from Co. Mayo, the increase begins: 10850; 2, Boreal-Atlantic transition (peak ~740 m; highest: 783 m), the main impediment to tree growth being lack of soil at high elevation, rather than elevation or exposure. Interestingly, Bennett (1996) suggests that, while Scots pine in the Cairngorms, central Scotland achieved dominance up to ~800 m asl during the Holocene, the uppermost parts of the region remained open. Today, native stands of P. sylvestris are known from as high as 675 m in eastern Scotland (https://www.brc.ac.uk/plantatlas/plant/pinus-sylvestris, accessed 19 May 2020).

Based on the profile from L. Kilnabinnia the expansion of pine at this, the highest location for which data are available, would seem to be delayed vis-à-vis the other sites. This, however, should be regarded as more apparent than real given that the chronology of this and other upland sites depends on a combination of relative (palynology) and 14C dating (see Table SM-5). Nevertheless, the data facilitate comparison of the timing of spread and expansion of the tree and shrub pollen taxa at each particular site though there are limitations resulting from the often rather large sampling intervals. Bearing that caveat in mind, the succession as recorded at Mám Éan, namely expansion of Juniperus, then Betula (most likely B. pubescens), Corylus followed closely by Pinus, then a slow expansion of Ulmus and Quercus and finally Alnus at ca. 7700 cal. BP, seems to be followed at all upland sites. Quercus representation is often about double that of Ulmus, and Alnus never achieves high values. Thus, in the study region, the upland woodlands in the period leading up to the mid-Holocene and the Elm Decline at 5.8 ka consisted primarily of pine and oak, with elm, alder and birch constituting minor components. Hedera is recorded starting early in the Holocene (at ca. 9.8 ka at Mám Éan) while Ilex is not consistently recorded until ca. 6 ka. Similar patterns in the expansion of trees and tall shrubs have been observed in upland pollen profiles from Northern Ireland, except that there not only have Ulmus and Alnus low pollen representation, their early Holocene expansion is also considerably delayed (Pilcher, 1973; Pilcher and Larmour, 1982). The importance of soils, the fertility of which is influenced largely by bedrock and glacial geology, can be seen in profiles from L. Doo and L. Sheeauns. At these sites, pine played a subordinate role to other trees presumably as a result of the competitive advantage afforded to oak and elm by the more fertile soils. A notable feature in these profiles, that is shared with many other Irish diagrams, is the expansion of Pinus immediately prior to the rise of Alnus (Mitchell, 1956). The rise of Alnus, that often, though not always (see, for example, Fossitt, 1994) occurs at the expense of Pinus, is usually envisaged as alder replacing pine in wet lowland habitats (e.g. Bennett and Birks, 1990) which is, indeed, plausible. These vegetational shifts can, however, also be seen as a response to the substantial

Fig. 7. Selected pollen percentage data for Mám Éan and other sites from mid-western Ireland plotted to a calibrated time scale. By default, curves are plotted to y-axis +1 (y = 1); if not y = 1, the curve is labelled and the relevant axis is indicated. A total terrestrial pollen sum is employed. *: * indicates records for Taxus that are outside the pollen count. For An Loch Mór, in addition to the standard curve, weighted average curves (3 points, mid-point double weighted) are provided for Pinus and Plantago. Key points in vegetation/land-use history for Ireland are indicated along the top of the diagram (numbers within circles). These events (no., event and chronology in years cal. BP) are as follows: 1, PreBoreal-Boreal transition (Corylus increase begins); 10850; 2, Boreal-Atlantic transition (Alnus increase begins); 7700; 3, Elm Decline: 5800; 4, Neolithic-Bronze Age transition: 4300; 5, Prehistory/History transition: 1550; 6, Afforestation: 200.
re-organization of the climate system that followed the 8.2 ka event (Alley and Ágústsdóttir, 2005; Borzenkova et al., 2015). This undoubtedly resulted in long-term adjustments within the competing tree populations. As regards the 8.2 ka event, in the profiles presented it is clearly expressed only at An Loch Mór (Molloy and O’Connell, 2014). At Mám Éan, the increase in Pinus and decrease in Corylus recorded in subzone MAM III-5c may be imputable to a climatic oscillation but more detailed analyses are needed to confirm that the short-lived but severe 8.2 ka climate downturn was responsible.

In recent times there has been much discussion on the role of fire in Holocene vegetation development and whether fires were natural or caused by people (Schworer et al., 2014; for Ireland see Hawthorne and Mitchell, 2016). Given the low population density in Ireland during the Mesolithic and the paucity of evidence for a Mesolithic presence in the geographical area under consideration (Woodman, 2015), it is reasonable to assume that fires in the region have natural causes such as lightning strikes. Bradshaw and Browne (1987) present charcoal curves for the Nephi Beg upland profiles. L. Navrooney has elevated charcoal representation during the Boreal/Atlantic periods. Charcoal values (macro-charcoal especially; Fig. 6B) at Mám Éan are also high somewhat before this time (ca. 9.4–8.2 cal. BP). It appears reasonable to assume that this is connected with the prominence of Scots pine at these sites, which, as a conifer, is more flammable than hardwoods and is also more tolerant of regular burning (Carlisle and Brown, 1968; Feurdean et al., 2017). Noteworthy also are the elevated charcoal values recorded in the L. Kilnabinnia profile between –200 and –100 cm (Bradshaw and Browne, 1987). According to the age/depth model, this corresponds to ca. 3500–1500 cal. BP. Given the large sampling intervals in this part of the profile and the weak dating control (no 14C dates in this part of the profile), it is impossible to say if fires were occasional or frequent. The charcoal curve is particularly high at and above −149 cm, i.e. the late Iron Age (ca. 2.2 ka and later). Presumably this reflects local fires but whether natural or human in origin is difficult to say. Anthropogenic indicators, and especially P. lanceolata, are poorly represented which suggests little or no human impact.

The degree to which upland sites, and particularly the sites under consideration here, are part of the distinct patterns of human impact on the Irish landscape from the mid-Holocene onwards (from ca. 6000 cal. BP: see Introduction) is of particular interest given the general lack of archeological evidence for human activity in the study area. In many detailed Irish pollen diagrams, a P. lanceolata curve starts prior to the Elm Decline when there may already be a Neolithic presence, but it is not until immediately after the Elm Decline that major impact involving woodland clearance, i.e. Landnam, registers (e.g. Molloy and O’Connell, 1987, 2003; Stolze and Monecke, 2020). This impact normally finds clear expression in a substantial rise in NAP, including Poaceae, P. lanceolata and a suite of NAP pollen taxa that often includes cereal-type pollen. As to be expected, these features are best expressed in lowland sites such as L. Sheeauns which is located in north-west Connemara at the center of a cluster of megalithic tombs several of which are datable to the early Neolithic (Molloy and O’Connell, 1991). Unfortunately, there is no pollen profile available from the Connemara lowlands in the vicinity of Mám Éan that might help with the interpretation of the rise in NAP (mainly Poaceae but also P. lanceolata and other herbs). Given that the shift from AP to NAP is not inconsiderable, it is likely that early Neolithic clearances extended into Mám Éan gap and resulted in local clearances of the dominant tree, namely pine, which recovered when farming pressure declined (Figs. 6A and 7). At L. Kilnabinnia, on the other hand, Plantago is not recorded during the Neolithic so there was probably no farming which is not surprising given the elevation (310 m asl; Plate SM–PL–VI). More detailed records (as regards both temporal resolution and detailed analyses), however, are desirable at this and the other upland sites before arriving at definitive conclusions. In the L. Kilnabinnia profile, for instance, there are only five spectra relating to the Neolithic, i.e. a period of >1500 years.

The opening-up of the landscape that occurred at the beginning of the Neolithic also led to increased representation of bog and heath pollen taxa. This, undoubtedly, also signifies an expansion of blanket bog and heath communities, facilitated, in part at least, by woodland clearances, and soil deterioration and acidification that presumably followed. Blanket bog and heath at Mám Éan, and also in lowland areas, long predated woodland clearances by Neolithic farmers so it is probably best to avoid imputing a close connection between Neolithic farming per se and bog expansion (cf. Huang, 2002). Early Holocene expansion of bog is evident at L. Kilnabinnia, the most upland site, and is particularly pronounced at the lowland site, Loch an Chorcaill, where consistently high values for Ericoids and other bog and heath taxa are recorded, beginning early in the Holocene (Fig. 7; O’Connell and McDonnell 2019). Similarly, in the Rosses, west Donegal, Fossitt (1994) shows local development of blanket bog in the lowlands concomitant with the spread of tall canopy trees, i.e. prior to 10 ka. Results of 14C dating of pine timbers in lowland sites in Co. Mayo, which indicate pines growing in blanket bog contexts from as early as 8.5 ka (O’Connell et al., 2020), also support the idea of early presence of patches of blanket bog that probably later acted as foci for further bog expansion when climatic conditions became favorable for bog expansion (see also below).

In addition to the Elm Decline and Landnam, key events during the mid-Holocene in western Ireland include woodland regeneration that followed the Elm Decline and Landnam, and a pine flush, i.e. widespread establishment of pine on bog that is reflected in bog-pine timbers near the base of or within peat, and elevated Pinus values in pollen diagrams, often followed by a sharp decline that eventually led to pine completely dying out (at ca. 2 ka in Connemara; Molloy and O’Connell, 1983); Pollen diagrams, from the 1980s onwards, have shown that in regenerated woodlands (ca. 5300–4900 cal. BP), not only was Fraxinus important for the first time in the mid-Holocene but even more so Taxus, though only at some sites (Fig. 7). At An Loch Mór and L. Nammackanbeg, for instance, Taxus has substantial peaks (37% and 26%, respectively). At L. Sheeauns, on the other hand, Taxus is recorded only as ‘+’ in four spectra (4260 TTP counted in these samples). At Mám Éan a rather strong rise in Taxus (peak 13.3%) is recorded that is regarded as indicative of local yew expansion. Yew probably persisted, regionally and perhaps locally but with greatly reduced population size, until ca. 2200 cal. BP; Fig. 6A). As regards the Nephi Beg suite of profiles, Taxus is recorded in three of the four profiles, but there is no obvious pattern and the values are low (highest at L. Cleva where values range from 0.2 to 1.5%; records in 15 spectra, i.e. 31% of the total) especially given that yew is a high pollen producer and has good dispersal (Bradshaw, 1981). Furthermore, this fertile lowland site (L. Cleva) would be expected to provide favorable habitat. At L. Navrooney there are no records for Taxus. The pollen may have been overlooked as it is rather easily confused with other pollen types. The profile, however, extends only to ca. 4000 cal. BP. In a pollen profile from Blackloon Lough, on the lowlands to the south-east of Clew Bay, little Taxus pollen is recorded (<2%; Cunningham, 2005), and in a pollen diagram from nearby Owenduff which spans the interval 3.7–2.6 ka there are no records for Taxus (Plunkett, 2009). At L. Fark, in the fertile Mayo lowlands south of Balla, Taxus achieves modest values (~3%; Fuller, 2002). As regards islands off the Galway/Mayo coast, the available records suggest that Taxus generally failed to expand. Holocene records from Achill Island do not mention Taxus (Caseldine et al., 2005; McKeown et al., 2019), there are minor records from Clare Island (Coxon and Hennessy, 2019) but at Church Lough, Inishbofin, Taxus achieves 6% at ca. 4500 cal. BP (O’Connell and Ni Gráinne, 1994). In general, it seems that yew played only a minor and patchy role in the wider north Connemara/south Mayo region during the Holocene which contrasts with its substantial role in the Galway Bay region (Loch an Chorcaill, L. Nammackenbeg, An Loch Mór and also L. Atalia (O’Connell and Molloy, 2017)). Interestingly, however, the placename Mayo, which probably has medieval origins, is an anglicization of ‘Maigh Eo’, i.e. ‘Plain of the Yew’.
As regards the role of pine on upland blanket bog as revealed by $^{14}$C dates derived from bog-pine timbers, the phenomenon is broadly similar to that identified for north Mayo (O’Connell et al., 2020), i.e. that the main period is centered on ca. 4.9 ka. The general synchronicity supports the idea of dry bog surfaces, the result of a shift towards drier and perhaps also a warmer climate, that favored pine germination and establishment on bog surfaces. Many of the trees in the Irish uplands reported on here lived for a short period only (typically 40 years; outer rings mainly used for dating so the $^{14}$C dates are generally indicative of end-of-life) so it would appear that optimal conditions were short-lived. Gear and Huntley (1991) demonstrated a major but short-lived expansion of pine into northern Scotland that began ca. 4450 BP (ca. 5.1 ka) and lasted less than three centuries (ca. 4.84 ka). Similar expansions at about this time have been reported by Daniell (1998) and (ca. 5.1 ka) and lasted less than three centuries (ca. 4.84 ka). Similar expansions at about this time have been reported by Daniell (1998) and Tipping et al. (2008) from north-central and north-eastern Scotland, respectively. In all cases, climate shifts involving increased dryness followed by wetter conditions are suggested as the main driver. It is envisaged that the onset of wetter conditions not only resulted ultimately in the demise of pine but also expansion of blanket bog and increase in the rate of peat accumulation so that bog-pine preservation ensued.

6.2. Pollen taxa with low representation but of particular biogeographic interest

Arboreal pollen taxa in profile MAM III that fall into the above category are Tilia (14), Tsuga (13), Fagus (3), Picea (3), and Juglans (2) (number of occurrences out of a total of 70 spectra are given in parentheses; Fig. 6B). No more than a single pollen was recorded for any of these taxa in a particular spectrum (percentage values are at only ~0.1%; the ‘+’ frequencies, which are included in the number of occurrences given above, are 9, 8, 2, 2, 2, respectively). The oldest records are for Tilia and Tsuga (8.1 ka and 9.2 ka, respectively) while the youngest records are for Juglans (AD 1150 and 1850) and Picea (twentieth century). As indicated elsewhere, Picea records reflect recent afforestation in the lowlands of Connemara and perhaps further afield. The other records are regarded as due to transport from a distance, Tsuga being a extreme case in that the pollen probably originated in North America. As has been pointed out by Stolze and Monecke (2017), taxa such as above are regularly recorded in Irish pollen profiles. The Holocene profile from L Namackanbeg, Spiddal, is a case in point. This profile, consisting of 106 spectra with high pollen counts, has records (mainly single pollen) for Tilia, Fagus and Carpinus as follows (no. of spectra indicated; dates refer to the earliest records): 12 (8.55 ka), 19 (3.4 ka) and 4 (2 ka), respectively. When initially published, these records were not regarded as a basis for confidently deducing local or even regional presence of these trees (O’Connell et al., 1988). As argued for by O’Connell and Molloy (2019), it is best to continue to regard these pollen — records from recent time excepted — as indicative of long-distance transport and the trees in question as introductions to Ireland effected by people, in most instances in late historical times (Everett, 2014).

Records for E. distachya and E. fragilis pollen types are also of interest. These derive from the base of the profile (basal four spectra, prior to the expansion of Corylus; E. distachya: two records; E. fragilis: three ‘+’ records), with a single record ‘+’ record for E. distachya-type from 294 cm (8.1 ka). Ephedra pollen is rather frequently recorded in Irish (e.g. in the L. Navrooony profile, there are several Ephedra pollen (not distinguished to type) records from Lateglacial sediments; Singh (1970) has records for E. distachya-type from north-east Ireland, and there are several records from British Lateglacial contexts (Godwin, 1975). Ephedra is a strong pollen producer and its pollen are well dispersed (Godwin, 1975) so the records are not necessarily indicative of a local or regional presence. Given the low representation of both taxa, it appears best to regard the present records as due to long-distance transport rather than presence of plants locally or indeed elsewhere in Ireland, and it is especially likely that the E. fragilis-type records (presence in Britain and Ireland is highly unlikely for biogeographical reasons; Birks, 1973; Godwin, 1975) and that of E. distachya-type from 294 cm (8.1 ka; at this time, woodland dominated) are due to long-distance transport.

The scattered records for Diphasiastrum-type, on the other hand, are probably indicative of local presence. The most likely parent of these spores (nine single-spore records in all) is D. alpinum (alpine clubmoss) (see Moore et al., 1991). North-western Connemara, including the Maumturks, is one of the main centers for this Arctic/montane species in Ireland (BSBI Atlas, online; https://bsbi.org/maps, accessed 16 June 2020; Webb and Scannell, 1983). The scattered distribution of the fossil records within the pollen profile is assumed to be due to low spore production, poor dispersal and probably also distance of the source plants from the lake, rather than any interruptions in the presence of the clubmoss on the Maumturks during the Holocene.

As regards the aquatic species, the records for E. aquatim are of greatest interest given that the species is present today in the lake together with its typical companion species, i.e. Lobelia dortmannana and Littorella uniflora (White and Doyle, 1982; Arts and den Hartog, 1990). L. dortmannana is probably the main contributor to the pollen taxon Digitalis/Lobelia-type. L. unifora is also represented though not strongly (only five records; maximum value: 0.9%; Fig. 6B). The species is present in many Irish oligotrophic lakes today, so a presence in the littoral parts of Mān Ėan throughout the Holocene is likely. Regarding E. aquatim, there are only four records, the earliest dating to 3.3 ka (150 cm; Fig. 6B). There are no records in the upper samples (most recent record is from 80 cm; ca. AD 1000), and this despite its presence in the lake today (there is no reason to believe that it is a recent arrival). The lack of recent records serves to emphasize how under-represented this species is in pollen records (O’Connell and Ni Chráinne, 1994). In the upland lake profiles from Co. Mayo, it is recorded only at L. Navroo where 3 and 5 pollen (0.4% and 0.9%, respectively) were recorded at near the top of the profile (140 and 160 cm, respectively; ca. 4 ka) which points to local presence in the mid-Holocene (it is present in this area today; BSBI Atlas, online; https://bsbi.org/maps, accessed 16 June 2020). The strongest record from Connemara is that from Loch an Chorcail where Erica caulis pollen was recorded in 37 spectra (highest value: 1.1%; the earliest record dates to 6.7 ka; O’Connell and McDonnell 2019). At nearby Roundstone (profile Roundstone II), Jessen (1949) records Erica caulis pollen starting in the Atlantic period (pre-Elm Decline), similar to Loch an Chorcail. The species has a similar history at L. Gowlanaganower, on Inishbofin (O’Connell and Ni Chráinne, 1994). Given the distinctiveness of its pollen (Furness, 1988; Plate SM-PL-VI), it is surprising that so much uncertainty remains regarding the details of its Quaternary history. There are several interglacial records from Ireland (Gorton, which is probably equivalent to OIS 11; Coxon and Waldren, 1995; Preston and Croft, 1997). It is clear, however, that this North American species has been present in Connemara and more widely in western Ireland, for at least 7000 years. Where, and if, it survived glaciations and the manner of its spread in the early Holocene to make Connemara its European headquarters have yet to be clarified.

7. Conclusions

Based on the results of palaeoecological investigations of lake sediments from Mān Ėan, a corrie lake in the Maumturk Mountains, Connemara, a record of Holocene environmental change during the last ca. 12 ka is provided. The course of vegetation development follows the broad outline of that recorded from lowland Connemara and other sites in western Ireland, the data for which are summarized in this paper.

The importance of pine during the early and mid-Holocene (ca. 10.2–4.8 ka) in the uplands at Mān Ėan is demonstrated. The first substantial opening-up of the landscape occurred as a result of human activity in the early Neolithic (ca. 5.6 ka). This is envisaged as occurring mainly, but not solely, in the lowlands. After a farming phase (mainly
pastoral) that lasted over 200 years, woodland regeneration followed that involved most trees and especially pine. Later yew spread and expanded largely at the expense of pine which by 4.7 ka had ceased to be the local dominant, never regained its importance and probably became regionally extinct before 2 ka.

A major reduction in woodland began at ca. 4.5 ka, i.e. towards the end of the Neolithic, in the context of increased farming. Further substantial reductions took place at ca. 3.5 ka and 2.3 ka, again in the context of increased human activity in the mid–Bronze Age and Iron Age (La Tène period), respectively. It was not, however, until the late Medieval period (ca. AD 1200) that the present treeless aspect came about, again in the context of substantial farming.

Three soil erosional phases were detected in the lake-sediment cores. In the early Holocene, soils had stabilized by ca. 10 ka with the development of more or less full woodland cover. The first erosion phase occurred at 9.2 ka and was accompanied by fluctuations in Pinus and Corylus that may indicate a climate oscillation of regional significance. A second erosion event is recorded at 6.4 ka which is not distinctly reflected in the pollen data. It may be the result of a weather event rather than a sustained shift in climate. In the upper part of the profile, i.e. starting at ca. AD 800, strong erosion is recorded. This is connected with the final stages of deforestation and increasing use of the uplands for pastoral farming. The uppermost sediments are highly organic which presumably reflects increased peat erosion as sheep numbers increased sharply, beginning in the mid-1970s.

Comparison with pollen profiles from the wider region indicates considerable fine-scale spatial variation in woodland composition and especially the role of pine and yew. Pine is generally more important in the uplands but here too it declines sharply at or before 4 ka, a decline that ultimately leads to extinction. Yew, on the other hand, is recorded only at some sites. Its expansion invariably occurs in the context of woodland regeneration after early Neolithic woodland clearances. Peak expansion occurs at or shortly after 5 ka. This is also a period characterized by bog-pine as shown by 14C dates presented here and also previously published 14C dates. It is suggested that these developments, and especially the bog-pine dynamics, are indicative of climate change that involved less precipitation and possibly also higher temperatures, followed by a climate downturn of an enduring nature.

Long records for local presence of biogeographically interesting species including Osmunda regalis, Hymenophyllum (probably exclusively H. wilsonii), Diaphisatum alpinum and Ericaulon aquaticum are highlighted. On the other hand, frequent but mainly single-pollen records for trees such as Tilia, Fagus and Tsuga are ascribed to long-distance pollen transport rather than presence of these trees in Ireland prior to widespread introduction that commenced in the seventeenth century.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.revpalbo.2021.104377.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The investigations reported on here were initiated in the context of a research programme into upland farming in mid-western Ireland led by G.W. Smillie and M.A. Morgan of University College Dublin (UCD), and funded by Eolas, the Irish Science and Technology Board. Mechanized transport to the coring site at Mám Êan was provided by Collette, the Irish state body responsible for forestry. The farming communities of Recess and Maum facilitated access to Mám Êan and access to other sampling sites was facilitated by local communities. Help with the investigations at Mám Êan was provided by A. Bleasdale, E. Ni Ghráinne and E. Moorey (coring), K. Molloy (constructive comments on the draft manuscript), and A. Overland (additional pollen counting). NUIG Research Development Fund aided purchase of magnetic susceptibility equipment. P. O’Rafferty assisted with sampling bog-pine timbers, R.L. Hodd gave advice on bog-pine in the Killarney region, and A.L. Brindley and J.N. Lanting (Groningen) made available bog-pine 14C dates from the Wicklow Mountains. Pollen analytical and other data by P. Browne and P. Coxon of Trinity College Dublin (TCD) from four upland lakes in Co. Mayo, and available on NEOTOMA, PANGAEA and ResearchGate, were availed of. Permission was granted by P. Coxon, National Gallery of Ireland and the Royal Irish Academy to reproduce a photograph of coring at L. Kilnabinnia, a watercolor of Maam Valley by W. Evans and drawings of Ericaulon pollen by K. Jessen, respectively. The above contributions, help and support are gratefully acknowledged. Above all, I wish to acknowledge the invaluable inputs by C.C. Huang, who was involved from the beginning with obtaining and investigating the lake sediments at Mám Êan, in the context of his PhD research at the National University of Ireland Galway (NUIG).

References

Aalen, F.H.A., Whelan, K., Stout, M., 2011. Atlas of the Irish Rural Landscape. 2 ed. Cork University Press, Cork.

Aherne, J., Burton, A., Scott, H., Whittfield, C., Wolniewicz, M., 2013. Influence of Transboundary Air Pollution on Acid-Sensitive Lakes and Soils: Survey of Upland Acidic Systems (SIAS) [EPA CCRP Report Series No. 31]. Environmental Protection Agency, Dublin.

Akkesson, C., Nielsen, A.B., Broström, A., Persson, T., Gaillard, M.-J., Berglund, B.E., 2015. From landscape description to quantification: A new generation of reconstructions provides new perspectives on Holocene regional landscapes of SE Sweden. Holocene 25, 178–193.

Alley, R.B., Augustiädottir, A.M., 2005. The 8k event: Cause and consequences of a major Holocene abrupt climate change. Quat. Sci. Rev. 24, 1123–1149.

Albrow, R.B., Andrews, J.T., Brigham-Grette, J., Clarke, G.K.C., Cuffey, K.M., Fitzpatrick, J.J., Funder, S., Marshall, S.J., Miller, G.H., Mitrovica, J.X., Muhs, D.R., Otto-Bliesner, B.L., Polyak, L., White, J.W.C., 2010. History of the Greenland Ice Sheet: paleoclimatic insights. Quat. Sci. Rev. 29, 1728–1756.

Anderson, E., Harrison, S., Passmore, D.G., Mighall, T.M., 1998. Geomorphic evidence of Younger Dryas glaciation in the Macgillycuddy’s Reeks, west south Ireland. Quat. Proc. 6, 75–80.

Andrieu, V., Huang, C.C., O’Connell, M., Paus, A., 1993. Lateglacial vegetation and environment in Ireland: First results from four western sites. Quat. Sci. Rev. 12, 681–705. 

Armitt, I., Swindles, G.T., Becker, K., 2013. From dates to demography in later prehistoric Ireland? Experimental approaches to the meta-analysis of large 14C data-sets. I. Archaeol. Sci. 40, 433–438.

Arts, G.H.P., den Hartog, C., 1990. Photogeographical aspects of the West European soft-water macrophyte flora. Acta Bot. Neerl. 39, 369–378.

Atheyton, L., Bosanquet, S.D.S., Lawley, M., 2010. Mosses and Liverworts of Britain and Ireland. A Field Guide, British Bryological Society, Plymouth.

Averdieck, F.-R., 1971. Zur postglazialen Geschichte der Eibe (Taxus baccata L.) in Nordwestdeutschland. Flora 160, 28–42.

Ballantyne, C.K., Ó Coileáin, C., 2017. The last Irish ice sheet: Extent and chronology. In: Coxon, P., McCarron, S., Mitchell, F. (Eds.), Advances in Irish Quaternary Studies. Atlantis Press, Amsterdam, pp. 101–149.

Barth, A.M., Clark, P.J.L., Clark, J.R., Roe, G.H., Marchant, S.A., McCabe, M.A., Coffey, M.W., He, F., Czuczzone, J.K., Dunlop, P., 2018. Persistent millennial-scale glacier fluctuations in Ireland between 24 ka and 10 ka. Geology 46 (2), 151–154.

Bartlett, W.H., Griffiths, H., 1835. A Pattern in Connemara. Plate (a hand-coloured engraving) included in: Coyne, J.S., Willis N.P. 1841. The Scenery and Antiquities of Ireland. G. Virtuer, London.

Batchelor, C.R., Branch, N.P., Carew, T., Elsia, S.E., Gale, R., Lafferty, G.E., Matthews, I.P., Meddens, F., Vaughan-Williams, A., Webster, L.A., Young, D.S., 2020. Middle-Holocene environmental change and archaeology in coastal wetlands: further implications for our understanding of the history of Taxus woodland. Holocene 30, 300–314.

Behre, K.-E., 1981. The interpretation of anthropogenic indicators in pollen diagrams. Pollen Spores 23, 225–245.

Bender, A., 2015. Israelites in Ein. Exodus, Revolution, and the Irish Revival. Syracuse University Press, Syracuse (New York).

Bennett, K.D., Birks, H.J.B., 1990. Postglacial history of alder (Alnus glutinosa (L.) Gaertn.) in the British Isles. J. Quat. Sci. 5, 123–133.

Bergh, S., 2016. Turfing Hill F Place-making and mountains in prehistoric Ireland. LAC2014 Proceedings, p. 12.http://lac2014proceedings.nl/ last accessed: 16 June 2020.

Beug, H.-J., 2015. Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. 2 ed. Friedrich Pfeil, München.
Walker, M., Head, M.J., Lowe, J., Berkelhammer, M., Björck, S., Cheng, H., Cwynar, L.C., Fisher, D., Gkinis, V., Long, A., Newnham, R., Rasmussen, S.O., Weiss, H., 2019. Subdividing the Holocene Series/Epoch: Formalization of stages/ages and subseries/subepochs, and designation of GSSPs and auxiliary stratotypes. J. Quat. Sci. 34, 173–186.

Walsh, S., 2012. A Summary of Climate Averages for Ireland. 1981–2010. Climatological Note No. 14. Met Éireann, Dublin.

Webb, D.A., Scannell, M.J.P., 1983. Flora of Connemara and the Burren. Royal Dublin Society and Cambridge University Press, Dublin and Cambridge.

Welten, M., 1952. Pollenanalytische Stichproben über die subrezente Vegetationsentwicklung im Bergland von Kerry (Irland). In: Lüdi, W. (Ed.), Die Pflanzenwelt Irlands. Hans Huber, Bern, pp. 85–99.

White, J., Doyle, G., 1982. The vegetation of Ireland. A catalogue raisonné. In: White, J. (Ed.), Studies in Irish Vegetation. Dublin, Royal Dublin Society, pp. 289–368.

Whitehouse, N.J., Schulting, R.J., McClatchie, M., Barratt, P., McLaughlin, T.R., Bogaard, A., Colledge, S., Marchant, R., Gaffrey, J., Bunting, M.J., 2014. Neolithic agriculture on the European western frontier: The boom and bust of early farming in Ireland. J. Archaearol Sci. 51, 181–205.

Willis, K.J., Bennett, K.D., Birks, H.J.B., 1998. The late Quaternary dynamics of pines in Europe. In: Richardson, D.M. (Ed.), Ecology and Biogeography of Pinus. Cambridge University Press, Cambridge, pp. 107–121.

Wilson, P., Matthews, J.A., 2016. Age assessment and implications of late Quaternary periglacial and paraglacial landforms on Muckish Mountain, northwest Ireland, based on Schmidt-hammer exposure-age dating (SHD). Geomorphology 270, 134–144.

Woodman, P., 2015. Ireland’s First Settlers. Time and the Mesolithic. Oxbow Books, Oxford.