forests

MDPI

Article

Palaeoecological Evidence for Survival of Scots Pine through the Late Holocene in Western Ireland: Implications for Ecological Management

Jenni R. Roche [1,2,*], Fraser J. G. Mitchell [2], Steve Waldren [2] and Bettina S. Stefanini [2]

1 Dublin Bay Biosphere Partnership, Dublin City Council, Parks & Landscape Services Division, Civic Offices, Wood Quay, Dublin 8, Ireland

2 Department of Botany, School of Natural Sciences, Trinity College Dublin, Dublin 2, Ireland; fraser.mitchell@tcd.ie (F.J.G.M.); stephen.waldren@tcd.ie (S.W.); stefanb@tcd.ie (B.S.S.)

* Correspondence: jennifer@tcd.ie; Tel.: +353-1-222-3370

Received: 29 April 2018; Accepted: 7 June 2018; Published: 13 June 2018

check for updates

Abstract: The dynamics of Scots pine (*Pinus sylvestris* L.) in Europe during the Holocene have been spatially and temporally complex. The species underwent extirpation and reintroduction in several north-west European countries. This study investigated the late Holocene vegetation history of a present-day pinewood in western Ireland, to test the widely accepted hypothesis that *P. sylvestris* became extinct in Ireland *c.* AD 400. Palaeoecological, chronological and loss-on-ignition analyses were conducted on a sediment core extracted from an adjacent lake. The pollen profile showed no major *Pinus* decline and a *Pinus* macrofossil occurred *c.* AD 840, indicating localised survival of *P. sylvestris* from *c.* AD 350 to the present. The available archival maps and historical literature provide supporting evidence for continuity of forest cover. The hypothesis that *P. sylvestris* became extinct in Ireland is rejected. The implications for ecological management are significant. We argue that *P. sylvestris* should be considered native to Ireland, at least at this site. As Ireland's only putative native *P. sylvestris* population and the western limit of the species' native range, this site is of high conservation value and must be carefully managed and monitored. Seed-sourcing for ex-situ forest restoration must be compatible with the long-term viability of the population in-situ.

Keywords: conservation value; ecological management; forest ecology; native status; palaeoecology; *Pinus sylvestris*; pollen analysis; the Burren; woodland ecology

1. Introduction

Palaeoecological data provide a valuable long-term perspective on contemporary ecosystem dynamics but are under-utilised in conservation management [1]. Site-based palaeoecological studies can provide an evidence base for conservation management decisions, particularly in determining land use history, assessing naturalness and setting appropriate targets for restoration. However, published examples in which palaeoecology is used to inform practical management decisions are rare [2].

Palaeoecological studies have shown *P. sylvestris* to be one of Europe's most dynamic tree species. Its postglacial history in northern Europe is considered particularly well known due to the abundance of its pollen and macrofossils [3]. Its distribution in Europe over the last 13,000 years has been mapped [4] and, in Britain and Ireland, over the last 10,000 years [5]. These maps record large-scale range shifts but may not detect fine-scale, local distribution patterns [6].

P. sylvestris is a pioneer species with broad ecological tolerances. Its distribution is heavily influenced by competitive interactions but it forms stable vegetation communities on nutrient-poor soils [7]. It was most abundant in European forests during the early postglacial when, in response to climatic amelioration, it migrated rapidly across the northern European lowlands at up to 150 km per century. It formed pioneer *Pinus-Betula* forests, which were most extensive from *c.* 9500–7000 cal BP (calibrated radiocarbon years before AD 1950) [4,8]. *P. sylvestris* then declined in the south, while its northern range limits continued to expand, colonising north-west Scotland *c.* 9900 cal BP and northernmost Fennoscandia by *c.* 8500 cal BP [9,10]. *P. sylvestris* underwent marked range reductions in north-west Europe *c.* 4500 cal BP. This *Pinus* decline is an important pollen stratigraphic marker, observed in northern Scotland, England, Ireland and Finland, probably due to a large-scale climatic shift to wetter conditions and associated competitive exclusion [11–15]. It appears that *P. sylvestris* became extinct in several north-west European countries including Denmark, the Netherlands, Belgium, England, Wales and Ireland [5,16–19].

P. sylvestris colonised Ireland relatively early in the Holocene; one of its earliest records, evidenced by pollen and macrofossils, is from Gortlecka in the Burren *c.* 10,500 cal BP [20]. *Pinus* was the dominant arboreal pollen type in most western and upland sites for at least part of the early Holocene and an important component of raised bog, river valley and upland habitats. A major *Pinus* decline began *c.* 4500 cal BP, possibly due to climate change, competition with *Alnus glutinosa*, blanket bog expansion and human activity [5,6]. A late outpost occurred at Gortlecka; *Pinus* pollen and macrofossils were present *c.* 1050 $\pm$ 160 cal BP/AD 900 [20] but Watts, the author of that study, expressed concern that this date may be too young. The latest unambiguous record was a preserved stump from Clonsast Bog, a raised bog in County Offaly. This was directly dated to 1550 $\pm$ 140 cal BP/AD 400 [21], at which point *P. sylvestris* is widely believed to have become extinct in Ireland [6]. The species' supposed extirpation is of great interest as it is asynchronous between sites across Ireland and the apparent causal factors differ between sites [20].

P. sylvestris was reintroduced to Ireland in the mid-17th century and has been widely planted [22]. Due to its supposed extirpation and reintroduction, the native status of *P. sylvestris* is disputed, causing inconsistencies in conservation and forest management policy [23]. The Native Woodland Scheme provides funding to plant *P. sylvestris* when establishing or restoring native woodland [24] yet the Irish Peatland Conservation Council lists it as an invasive alien species [25]. Further palaeoecological research is urgently needed to determine if *P. sylvestris* became extinct in Ireland and to clarify its native status.

This study examines the late Holocene vegetation history of a pinewood in western Ireland, to test the widely accepted hypothesis that *P. sylvestris* became extinct in Ireland. Palaeoecological evidence is presented for localised survival of native *P. sylvestris* from 1600 cal BP/AD 350 to the present. The available historical sources and archival maps indicate a long history of woodland cover. Recommendations for the ecological management of the site are presented.

2. Materials and Methods

2.1. Site Description

Rockforest Lough (53.005, −8.958, Irish Grid Reference R 356 953) is situated 10 km north-east of Corofin, County Clare, western Ireland at 16 m above sea level (Figure 1). It lies on Carboniferous Limestone in the Burren, a karstic area covering over 300 km^2 and renowned for its rich archaeological heritage and plant diversity [26,27]. The climate is oceanic; mean rainfall is 1400–1600 mm and mean air temperature is 10 °C (1981–2010) annually. The prevailing winds at Shannon Airport, County Clare (1946–2010) are south-westerly [28].

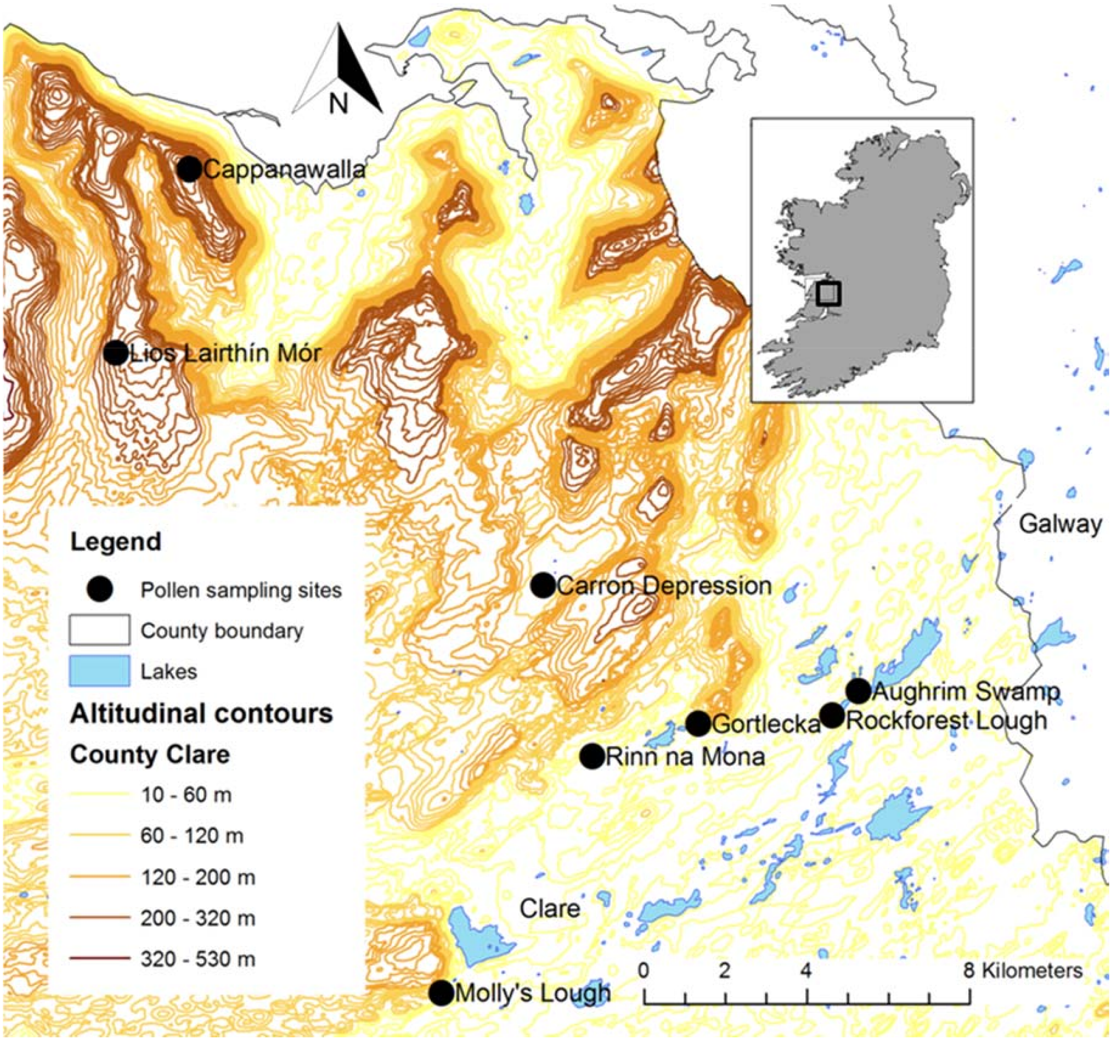

Figure 1. Location of Rockforest Lough and other pollen sampling sites mentioned in the text.

Satisfactory coring sites can be difficult to obtain in the karstic limestone of the Burren. Permanent lakes with brown algal mud are preferable to turloughs, swamps and lakes with carbonate mud, as pollen preservation is better and the hard water effect, which impairs radiocarbon dating, is less pronounced [20]. Rockforest Lough is a permanent lake *c.* 8 ha in area with a deep basin (7.48 m) and a shallower arm to the north-east. Its pollen source area is estimated to be 300–800 m (after [29]). The water level varies seasonally due to karstic hydrology [20] but the basin has not been known to dry out, at least in living memory (J. Cunningham, pers. comm.). It is bordered by reeds with pasture on glacial till to the south and limestone pavement to the north. Rockforest House is located on the south-western edge of Rockforest Lough (Figure 2). A pinewood occurs on limestone pavement *c.* 500 m to the south-west. Stunted, mature *P. sylvestris* is scattered through patchy *Corylus avellana* scrub. *P. sylvestris* regeneration is scarce. The species-rich vegetation was surveyed and classified as the *Corylus avellana–Brachypodium sylvaticum* pinewood type, which has affinities with Norwegian basiphilous pinewoods [23,30]. The woodland is located in the state-owned Burren National Park and the East Burren Special Area of Conservation, which is protected under the European Union (EU) Habitats Directive (92/43/EEC).

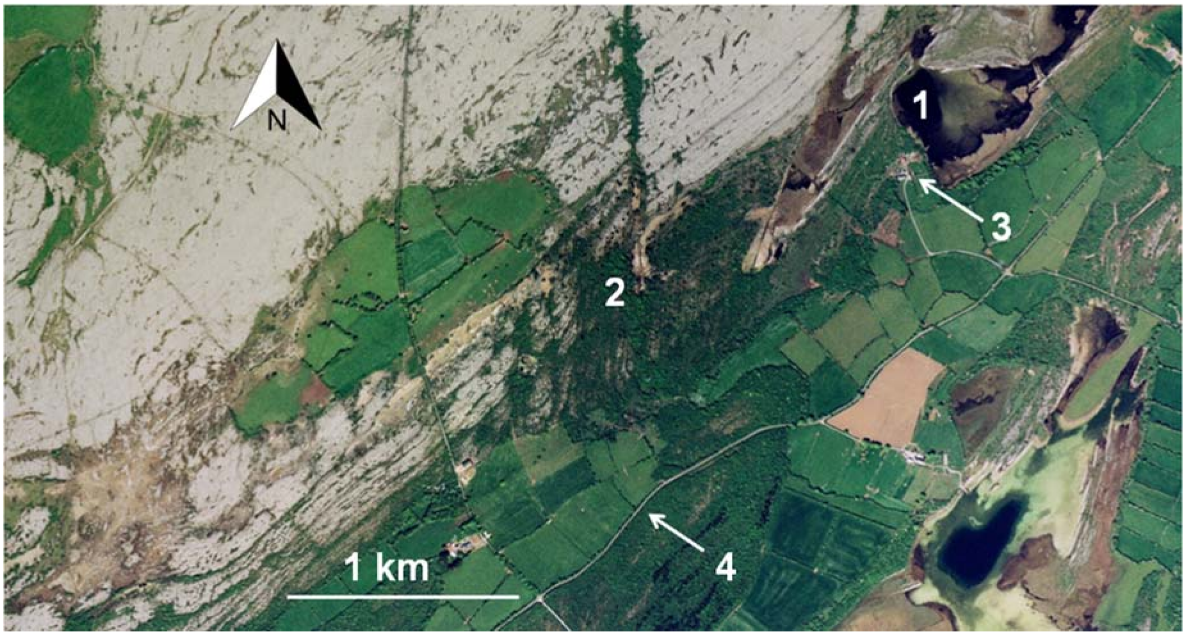

Figure 2. Aerial photograph (2000) showing the locations of (1) Rockforest Lough, (2) Rockforest Wood, (3) Rockforest House, (4) Corofin to Gort road/*Bealach an Fhiodhfail* [31].

2.2. Coring

Coring was conducted in the deepest area of Rockforest Lough on 18–19 June 2008. A short core (RFB, 81 cm) was extracted with a modified rod-operated plexiglass piston corer, preserving the sediment-water interface, and vertically extruded at 1 cm intervals on-site. The lower sediment (RFC) was sampled to a depth of 153 cm using a Livingstone corer [32]. The cores were wrapped on-site, stored at 4 °C and sliced at 1 cm intervals in the laboratory.

2.3. Loss-on-Ignition (LOI)

To ensure sufficient material, 2 cm thick samples were used for LOI analysis. Using a Thermolyne Type 6000 furnace, oven-dried, weighed samples were ignited for five hours at 550 °C to estimate organic content and three hours at 950 °C to estimate carbonate content [33]. The LOI profile was used to match the cores.

2.4. Chronology

Spheroidal Carbonaceous Particle (SCP) extraction followed Rose [34,35] with some modifications due to abundant fine material and low SCP numbers [14]. Sample dry weights were increased to 0.6–4.7 g; solvent volumes were increased accordingly. To remove fine material and facilitate counting, samples were filtered using a 10 μm sieve. To avoid the hard water effect, terrestrial plant macrofossils were sieved or hand-picked from the sediment. Eight macrofossil samples were radiocarbon dated using accelerator mass spectrometry (AMS). A chronology was generated using Bchron (version 3.1.4 with the IntCal13 calibration curve), a Bayesian modelling method which uses stochastic linear interpolation [36].

2.5. Pollen Analysis

Pollen analysis was conducted on 1 cm thick samples at 8 cm intervals, reducing to 4 cm in the upper core. Sediment subsamples of 0.5 cm^3 were treated by standard methods [14,37]. *Lycopodium* tablets were added to enable pollen concentration calculation [38]. Samples were mounted in silicone oil and counted with an Olympus BX40 microscope at 400× magnification and 1000× under oil immersion when required. Slides were systematically checked for *Pinus* stomata during routine pollen counting. Pollen and spores were identified following Moore et al. [37], the illustrations of Beug [39] and Reille [40] and a reference collection held by Trinity College. Nomenclature followed Moore et al. [37], excepting the aggregation of the Urticaceae, *Polypodium*, *Rumex* and Coryloid taxa. Coryloid pollen was assumed to be *Corylus avellana*, which is much more frequent than *Myrica gale* in the Burren [26]. A minimum of 400 identifiable terrestrial pollen and spores were counted from each sample. Indeterminate grains were also counted. A percentage pollen diagram was generated with TILIA version 2.0.19 [41]. The pollen sum was total terrestrial pollen and spores including indeterminate grains. The latter were included to reduce overrepresentation of *Pinus* as its distinctive pollen morphology makes it less likely to be classified as indeterminate. Concentrations were examined to ensure that no major changes arose that were not observed in the percentage pollen diagram.

3. Results

3.1. Loss-on-Ignition (LOI)

The sediment comprised homogeneous brown algal mud. Mineral input was relatively stable from 153–35 cm (Figure 3), with a mean of 32.0%. It increased abruptly at 33 cm, with a mean of 34.4% until the present. Peak values exceeded 38.6% at 7–11 cm.

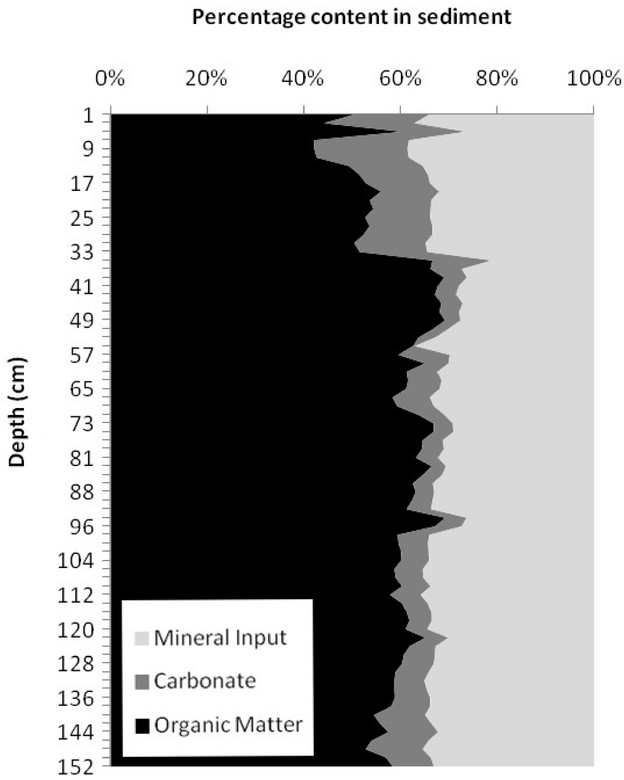

Figure 3. Loss-on-ignition (LOI) profile for Rockforest Lough.

3.2. Chronology

SCPs, produced from fossil fuel combustion and preserved in lake sediments, provide a historical record of atmospheric pollutant deposition. SCP concentration profiles are consistent and often regionally characteristic such that the main profile features can be used for sediment dating. The Rockforest SCP record began at 13 cm (Figure 4). SCP numbers were low initially, likely due to low levels of industrialisation in the region. A rapid increase and sub-surface peak appeared at 8 cm and 7 cm respectively. Based on mean dates from Irish SCP profiles [42], these features were assigned to the 1880s, 1960s and 1981 respectively (Table 1). A second rapid increase at 4 cm was assigned to 1985, when Moneypoint Power Station, *c.* 50 km to the south-west, was commissioned. The filtration of samples may have selectively removed SCPs generated by oil combustion, which are usually smaller than those from coal [34]. However, as the nearest power station is primarily coal-fired and the main profile features described by Rose et al. [42] were observed, selective removal does not appear to have been a significant issue.

The chronology is well-constrained in the upper metre but less so below as fewer dates were obtainable (Table 1). The model excluded an anomalously old date from bulked organic material at 72–74 cm (Figure 5). Sediment accumulation was relatively constant in the upper metre (0.7 mm year^{-1}) but considerably lower below (0.1 mm year^{-1}). Pollen analysis was confined to the upper 112 cm due to increased uncertainty in the chronology below the AMS date at 104–107 cm.

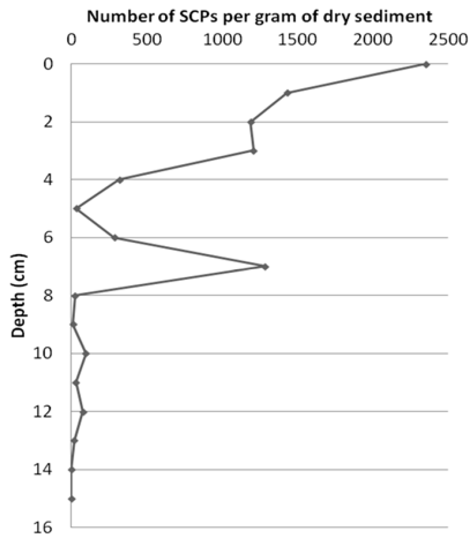

Figure 4. Spheroidal Carbonaceous Particle (SCP) concentration profile for Rockforest Lough.

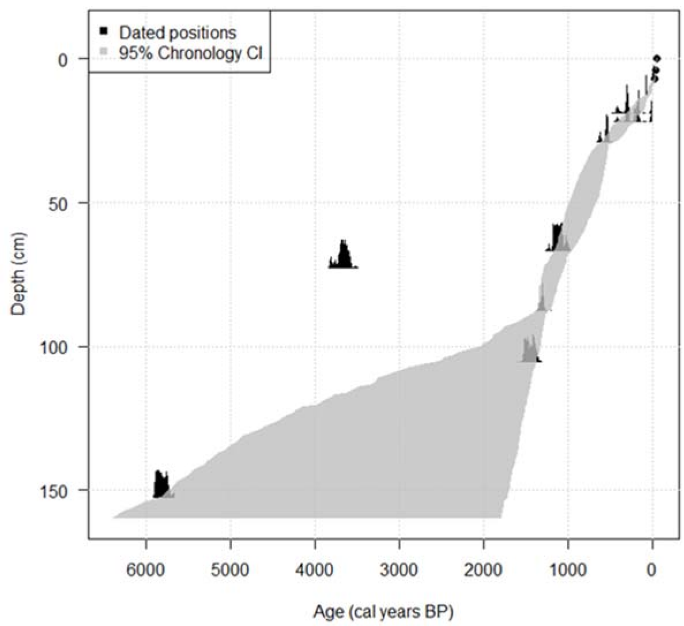

Figure 5. Bchron age-depth model for Rockforest Lough based on dates given in Table 1.

Table 1. Spheroidal Carbonaceous Particle (SCP) and Accelerator Mass Spectrometer (AMS) dates from Rockforest Lough.

Core	Depth (cm)	Laboratory Reference	Sample Description	^{14}C Year BP [1]	Calendric Age (AD)	IntCal 2.5% (cal Year BP)	IntCal 50% (cal Year BP)	IntCal 97.5% (cal Year BP)
			SCPs					
RFB	4	-	2nd rapid increase	-	1985	−9	−37	−35
RFB	7	-	Sub-surface peak	-	1981 ± 2	−36	−30	−24
RFB	8	-	Rapid increase	-	1965 ± 5	−2	0	2
RFB	13	-	Start of record	-	1885 ± 5	92	10	108
			Macrofossils					
RFB	19	Beta-247933	Wood	240 ± 40	-	2	284	423
RFB	22	Beta-247934	Plant material	230 ± 40	-	2	264	418
RFB	29	Beta-247935	Wood	520 ± 40	-	508	538	631
RFB	66–68	Beta-252787	Plant material	1180 ± 40	-	989	1107	1229
RFC	72–74	Beta-252788	Organic material	3410 ± 50	-	3511	3662	3819
RFC	88	Beta-253480	Plant material	1380 ± 40	-	1198	1300	1359
RFC	104–107	Beta-252790	Plant material	1540 ± 40	-	1347	1438	1522
RFC	153	Beta-252791	*Pinus* wood	5050 ± 40	-	5676	5814	5898

[1] AMS dates are quoted with a standard deviation of 2σ (95% confidence limit).

3.3. Pollen and Macrofossil Stratigraphy

Figure 6 spans from *c.* 1600 cal BP/AD 350 to the present; 68 terrestrial taxa were recorded. Pollen preservation was sub-optimal with frequencies of 10.3–29.1% indeterminate grains. These were included in the pollen sum to reduce overrepresentation of *Pinus*. Arboreal pollen (AP) dominates throughout, ranging from 54.6–73.0%. The *Pinus* signal is consistently high, peaking at the base of the profile (51.3%) and never falling below 38.2%. *Corylus* is frequent throughout. *Betula*, *Alnus, Quercus* and *Ulmus* are present at lower frequencies. *Fagus* appears in the upper half, becoming consistently present at 24 cm. Poaceae dominate the non-arboreal pollen, increasing gradually from 3.5–10.3%.

No *Pinus* stomata were found. Macrofossils were scarce but a *Pinus* needle and *Pinus* wood fragment were found at 66 and 153 cm respectively.

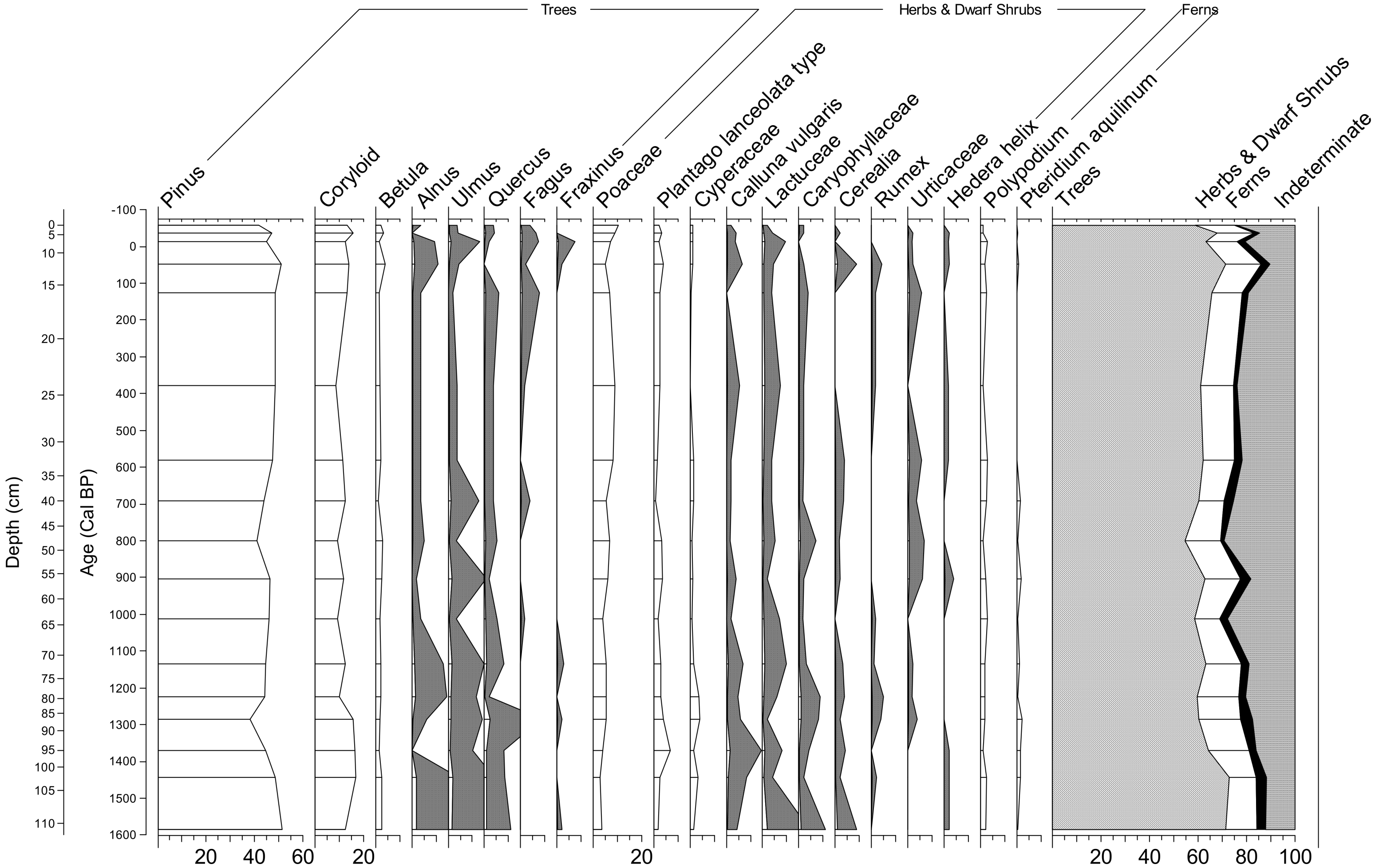

Figure 6. Percentage pollen diagram of selected taxa from Rockforest Lough (shading = Exaggeration × 10).

4. Discussion

The pollen profile is relatively static. It opens with relatively high AP frequencies (71%) from *c.* 1600–1450 cal BP/AD 350–500 (Figure 6). *Pinus* dominated, indicating an open woodland structure as *P. sylvestris* cannot tolerate heavy shade from other trees [7]. *Alnus* may represent regional pollen as *Alnus* macrofossils were not recorded at Gortlecka [20] and it is rare in the Burren today [26]. This period of high AP frequencies may represent the Late Iron Age Lull (LIAL), when declining farming activity resulted in widespread woodland regeneration. The LIAL appears in other pollen profiles from the area, at Lios Lairthín Mór and Molly's Lough (Figure 1), from *c.* 1950–1450 cal BP/AD 0–500, typically followed by declining AP indicating a resumption of human activity and woodland clearance [43,44]. Indeed, AP declined at Rockforest during the early medieval period *c.* 1450–1300 cal BP/AD 500–650. *Pinus* fell to its lowest frequency, 38.2%, *c.* 1300 cal BP/AD 650 but still dominated the AP.

For the remainder of the early medieval period, and until *c.* 800 cal BP/AD 1150, little change was observed overall. A *P. sylvestris* needle found in the sediment at 66 cm demonstrates that *Pinus* was locally present at 1110 cal BP/AD 840. From *c.* 800–50 cal BP/AD 1150–1900, AP and *Pinus* rose gradually. Mineral input increased abruptly at 600 cal BP/AD 1350, which may reflect intensified human activity in the lake catchment. However, this was not apparent in the pollen profile as AP and *Pinus* continued to rise. The non-native *Fagus* peaks *c.* 125 cal BP/AD 1825. Between *c.* 50 cal BP/AD 1900 and the present, mineral input and Poaceae reach maximum values, indicating intensive human activity and grassland expansion, while AP and *Pinus* decrease. The overall rise in Poaceae from 1600 cal BP/AD 350 to the present indicates the gradual opening up of the woodland and expansion of open grassland. The Cerealia signal, though discontinuous, indicates arable farming.

While palaeoecological methods are most effective in elucidating woodland history [45], archaeological and historical sources are essential in data interpretation [46]. The archaeology within a 1 km radius of Rockforest Lough includes a *fulacht fia* (putative cooking pit), earthwork, ringfort (residence or farmstead generally dating to AD 500–1000) and tower house (fortified house generally dating to AD 1400–1600) [47].

Rockforest is referenced in historical sources, which refer to both woodland cover and human activities. The ancient name of Rockforest Wood was *Coill Ó Flanchada*. The Wars of Thomond affected County Clare in the 12th–14th century. A strategically important pass, *Bealach an Fhiodhfail*, once the main route from Clare to Galway, now the Corofin to Gort road, went through the wood [48] (Figure 2). A battle was fought at the entrance to the wood to contest the pass in 1311 and a defeated force fled through it in 1314 [49]. The Annals of the Four Masters recorded that in 1599 Red Hugh O'Donnell's army massed at the "eastern extremity" of the wood and marched "through the centre of *Coill Ó Flanchada*, through *Bealach an Fhiodhfail*" [50]. In 1655, the Down Survey showed that the only timber woods in this barony (Inchiquin) lay in this parish (Kilkeedy), occurring in nearly every townland in the parish. Covering 850 ha, they likely formed one of the county's largest woods [51]. Henry Pelham's Grand Jury Map of County Clare (1787) depicts woodland at Rockforest but little in the surrounding landscape. Rockforest House was built in the late 18th century [52]; its estate included a grain silo, ice house and walled garden [53]. By 1808, over 30 ha of rocky soil of poor agricultural value had been planted with *Acer*, *Alnus*, *Betula*, *Fagus*, *Fraxinus*, *Larix*, *Picea*, *Pinus pinaster*, *Pinus sylvestris*, *Quercus*, *Ulmus* and other species [54]. A "finely planted demesne" extended almost a mile along the road [53]. The first (1840) and second (1899) editions of the Ordnance Survey six inch maps depict the area as wooded [14]. Selective felling and scrub clearance was undertaken in the 20th century (J. Cunningham, pers. comm.). Though fragmentary in nature, the available historical sources imply continuous presence of woodland cover at Rockforest despite ongoing human activity. However, historical sources are generally dated with a high level of certainty, while dating of palaeoecological data must be inferred from the age-depth model, making it prone to inherent errors; these data should be compared cautiously.

The continuously elevated AP signal and the available historical sources both suggest that Rockforest has a long history of woodland cover. This contrasts, however, with patterns seen in contemporaneous Irish pollen profiles. Prior to the Great Famine of 1845, Ireland's population reached almost nine million, causing severe land-use pressure. Poorer land was cleared for agriculture over much of Ireland [55]. In the Burren, AP frequencies were just 4% from 250–100 cal BP/AD 1700–1850 at Cappanawalla (Figure 1) [56]. Firewood was so scarce that *Pteridium aquilinum* and *Dryas octopetala* were used [57]. The dissimilarity may relate to the management of the Rockforest Estate. Nationally, the woodland resource steadily diminished until the 20th century, excepting woodland remnants within estates [58,59]. Rockforest appears to be one such estate.

Pinus pollen is usually abundantly produced and well-dispersed and so is generally overrepresented in the pollen rain [60]. A 'critical pollen percentage' of 20% was proposed [5] and later revised to 5% to indicate local presence of *P. sylvestris* [61]. However, analyses of fossil stomata provided unambiguous evidence of local presence of *P. sylvestris* when *Pinus* pollen frequencies were as low as 2.8% [62] and 0.4% [63]. From a study of modern pollen deposition in the Rockforest area, McGeever and Mitchell [64] concluded that a *Pinus* pollen value of 5% indicated local presence of *P. sylvestris* in this area. The *Pinus* curve from Rockforest Lough is consistently high, never less than 38.2%, and greatly exceeds the critical pollen percentages. This strongly suggests that *P. sylvestris* was locally present and was a significant component of the vegetation.

Furthermore, macrofossil evidence demonstrates local presence of *P. sylvestris* around Rockforest Lough during the Neolithic at 5810 cal BP/3860 BC and the early medieval period at 1110 cal BP/AD 840. The latter is significant as the species was presumed to have become extinct in Ireland during that period [6]. The latest unambiguous Irish specimen was a preserved stump from Clonsast Bog, which was directly dated to 1550 ± 140 cal BP/AD 400 [21]. The later Rockforest macrofossil (1110 ± 120 cal BP/AD 840) is contemporaneous with the last recorded *Pinus* macrofossils from Gortlecka (1050 ± 160 cal BP/AD 900) [20], which is located 3.3 km west of Rockforest Lough (Figure 1). Watts expressed concern that the date appeared too young but this new evidence strongly indicates that Watts' date was accurate and *Pinus* persisted in the Burren after its assumed disappearance from midland raised bogs.

The later Rockforest macrofossil coincides with a *Pinus* pollen frequency of 45%. Subsequently, the *Pinus* signal remains high, dominating the AP to the present. Though *Pinus* had been planted on the Rockforest Estate by 1808 [54], its pollen was previously strongly represented. Rockforest Wood, which is located 500 m upwind of the coring site and matches the vegetation type recorded in the pollen profile, is the likely source of this *Pinus* signal. The *P. sylvestris* population at Rockforest appears to have persisted through the late Holocene to the present.

These findings are also supported by those of McGeever and Mitchell's [64] analysis of a radiocarbon-dated terrestrial core from Aughrim Swamp, which is located 650 m north-east of the Rockforest Lough coring site (Figure 1). Pollen preservation was good throughout the pollen profile, which extends from the present to 1600 cal BP/AD 350. A continuous *Pinus* signal was observed. Although a decline began *c.* 1550 cal BP/AD 400, reaching minimum values of *c.* 8% of total terrestrial pollen (TTP) *c.* 1350 cal BP/AD 600, the *Pinus* signal recovered quickly, reaching sustained levels of *c.* 15–25% of TTP, before declining to *c.* 5% at the top of the core. It is likely that Rockforest Lough (8 ha) mainly samples extralocal pollen from a pollen source area of 300–800 m [29], while the small wetland of Aughrim Swamp (0.4 ha) mainly samples local pollen, making it more sensitive to localised vegetation change [65]. The upper halves of undated cores from Rinn na Mona [20] and the Carron Depression [66] (Figure 1) also show continuous *Pinus* signals during the period of supposed extirpation, with frequencies of *c.* 3% and up to *c.* 7% of TTP respectively. While this may indicate that *P. sylvestris* at Rockforest dispersed pollen to these sites or that other localised stands were present, the frequencies in question are rather low in relation to the critical pollen percentage. Macrofossil data were not presented for these sites.

Floristically similar pinewoods existed on limestone pavement elsewhere in Ireland at various times during the Holocene but are no longer extant. Pollen and macrofossil evidence suggest that open woodland composed of *Pinus*, *Ulmus*, *Corylus* and *Betula* existed at Gortlecka (Figure 1) in the early Holocene [20]. Fine spatial resolution pollen analysis indicates that woodland rich in *Pinus*, *Corylus*, *Quercus* and *Ulmus* at Reenadinna, County Kerry developed into *Taxus* woodland *c.* 5730 cal BP/3780 BC [67]. Fine spatial resolution pollen analysis also suggests that open, species-rich woodland dominated by *Pinus* and *Corylus*, with *Calluna* and *Succisa*, existed at Cappanawalla (Figure 1) in the north-west Burren uplands from *c.* 3450–2450 cal BP/1500–500 BC. *Pinus* appeared to have been extirpated there *c.* 500 BC due to clearance by humans, followed by an expansion in grassland [56]. Pinewoods on limestone are present today at Rockvale in the Burren, Castletaylor and Coole Park in County Galway and Keel Bridge and Ballykine in County Mayo but most appear to have originated from introduced *P. sylvestris* [30]. Pinewoods on limestone no longer occur in Britain but pollen and macrofossil evidence indicate that they once existed at Malham, northern England [68]. They are extant and widespread in Fennoscandia [23,69].

These findings provoke the question of why *P. sylvestris* could have survived at Rockforest, in contrast to the decline and extirpation observed elsewhere. Climate is the main determinant of large-scale forest composition but edaphic factors, succession and human disturbance become increasingly important at the local scale [8]. The Burren's patchy, shallow soils suffer periodic drought and low phosphorus and nitrogen availability [70]. *P. sylvestris* tolerates these stresses, giving it a competitive advantage [5]. During its decline in Ireland, *Pinus* was replaced by blanket peat in the uplands and *Alnus* in the lowlands, probably due to a climatic shift to wetter conditions [6]. In the karstic Burren lowlands, blanket peat did not develop and *Alnus* is not thought to have been a significant component of the Holocene vegetation [20,26]. Fine spatial resolution pollen and charcoal analyses have shown that late outposts of *Pinus* in Counties Sligo and Kerry died out *c.* 1800 cal BP/AD 150 and 1700 cal BP/AD 250 respectively, likely due to human activity including woodland clearance using fire [45,71–74]. The aforementioned dated pine stump (1550 $\pm$ 140 cal BP/AD 400) from Clonsast Bog came from a layer of stumps found on a recurrence surface [21] i.e., an abrupt stratigraphic transition from highly humified peat to unhumified peat, indicating increased surface wetness caused by a climatic shift to wetter conditions [75]. Waterlogging is unlikely to have been significant at Rockforest Wood due to the karstic hydrology of limestone pavement. While substantial deforestation occurred in the Burren and *Pinus* declines there have been attributed to human activity [56,76], the pollen data and historical sources suggest that Rockforest was an exception to this pattern. The area was subject to continued human activity but the level of disturbance does not appear to have been sufficient to eradicate *P. sylvestris*.

5. Conclusions

The absence of a *Pinus* decline strongly indicates that a relict population of *P. sylvestris* persisted at Rockforest from at least 1600 cal BP/AD 350 to the present (Figure 6). This is supported by the presence of a *P. sylvestris* macrofossil dated to 1110 cal BP/AD 840, which demonstrates that *Pinus* was locally present. The widely accepted hypothesis that *P. sylvestris* became extinct in Ireland is therefore rejected.

Existing research on the postglacial dynamics of *Pinus* in Ireland should be re-evaluated in light of these findings. When *Pinus* pollen was recorded during the period of presumed extinction in Ireland, authors questioned the validity of dating analyses [20] or invoked redeposition or long distance transport [66]. Localised survival of *Pinus* should be considered as a potential source of such a signal, at least in the Burren. A review of the postglacial dynamics of *Pinus* in Ireland is recommended, incorporating relevant studies completed since those of Bradshaw and Browne [6] and Bennett [5] and utilising Geographic Information Systems.

Further site-specific research and conservation measures are needed. Research on the genetics of *P. sylvestris* at Rockforest is ongoing (C. Kelleher, unpublished). Data on the number of individuals, age structure and spatial extent of this population are urgently required to determine its conservation status. *P. sylvestris* has been placed on the waiting list of the Irish Red Data List, pending further research to enable assessment [77]. Based on our current understanding of the distribution of native

P. sylvestris in Ireland as being limited to a single known location, it could be assessed as critically endangered i.e., facing an extremely high risk of extinction in the wild. The insect fauna should be studied to determine whether any pine-dependent species, many of which are considered extinct in Ireland [78–80], occur there.

On the basis of the evidence presented, we argue that Rockforest Wood is Ireland's only known native *P. sylvestris* population. At a longitude of 8°57′ W, Rockforest Wood appears to be the western limit of the global native range of *P. sylvestris*, previously thought to be the north-west Iberian Peninsula at *c.* 8° W [3,16]. This population is of high conservation value but its rarity increases its extinction risk. Furthermore, reintroduced *P. sylvestris* in the vicinity may threaten the genetic integrity of the genepool. Rockforest Wood is located within a protected area but, given the scarcity of *P. sylvestris* regeneration, should be carefully managed and monitored. While ex-situ conservation is recommended, any seed-sourcing for native woodland restoration must be compatible with the long-term viability of the population in-situ. Coordinated action between conservation and forestry agencies will be required to ensure the continued survival of native *P. sylvestris* at Rockforest and to develop opportunities for the restoration of native pinewoods in Ireland.

Author Contributions: F.J.G.M. and S.W. conceived the research idea. J.R.R., F.J.G.M. and B.S.S. conducted coring. J.R.R. and B.S.S. collected the data. J.R.R. and F.J.G.M. analysed the data. J.R.R. wrote the paper. All authors contributed to revisions.

Funding: This work was funded by an Irish Research Council Government of Ireland Postgraduate Scholarship (RS/2005/180). The Society of Irish Foresters funded the article processing charge.

Acknowledgments: We thank Emma Glanville (National Parks and Wildlife Service) and Joseph Cunningham for site access and information and Richard Bradshaw, Daniel Kelly and the anonymous reviewers for their comments on the manuscript.

Conflicts of Interest: The authors declare no conflict of interest. The funding sponsors had no role in the study design; collection, analysis, or interpretation of data; writing of the paper, or the decision to publish the results.

References

1. Willis, K.J.; Birks, H.J.B. What is natural? The need for a long-term perspective in biodiversity conservation. *Science* **2006**, *314*, 1261–1265. [CrossRef] [PubMed]
2. Davies, A.L.; Columbo, S.; Hanley, N. Improving the application of long-term ecology in conservation and land management. *J. Appl. Ecol.* **2013**, *51*, 63–70. [CrossRef]
3. Willis, K.J.; Bennett, K.D.; Birks, H.J.B. The late Quaternary dynamics of pines in Europe. In *Ecology and Biogeography of Pinus*; Richardson, D.M., Ed.; Cambridge University Press: Cambridge, UK, 1998; pp. 107–121, ISBN 0521551765.
4. Huntley, B.; Birks, H.J.B. *An Atlas of Past and Present Pollen Maps for Europe 0-13,000 Years Ago*; Cambridge University Press: Cambridge, UK, 1983; ISBN 0521237351.
5. Bennett, K.D. The post-glacial history of *Pinus sylvestris* in the British Isles. *Quat. Sci. Rev.* **1984**, *3*, 133–155. [CrossRef]
6. Bradshaw, R.H.W.; Browne, P. Changing patterns in the postglacial distribution of *Pinus sylvestris* in Ireland. *J. Biogeogr.* **1987**, *14*, 237–248. [CrossRef]
7. Carlisle, A.; Brown, A.H.F. Biological flora of the British Isles: *Pinus sylvestris* L. *J. Ecol.* **1968**, *56*, 269–307. [CrossRef]
8. Huntley, B. European post-glacial forests: Compositional changes in response to climatic change. *J. Veg. Sci.* **1990**, *1*, 507–518. [CrossRef]
9. Froyd, C.A.; Bennett, K.D. Long-term ecology of native pinewood communities in East Glen Affric, Scotland. *Forestry* **2006**, *79*, 279–291. [CrossRef]
10. Birks, H.J.B. Holocene isochrone maps and patterns of tree-spreading in the British Isles. *J. Biogeogr.* **1989**, *16*, 503–540. [CrossRef]
11. Lageard, J.G.A.; Chambers, F.M.; Thomas, P.A. Climatic significance of the marginalization of Scots pine (*Pinus sylvestris* L.) *c.* 2508 BC at White Moss, south Cheshire, UK. *Holocene* **1999**, *9*, 321–331. [CrossRef]

12. Smith, A.G.; Pilcher, J.R. Radiocarbon dates and vegetational history of the British Isles. *New Phytol.* **1973**, *72*, 903–914. [CrossRef]
13. Eronen, M.; Huttunen, P. Radiocarbon-dated sub-fossil pines from Finnish Lapland. *Geogr. Ann. A* **1987**, *69*, 297–304. [CrossRef]
14. Roche, J.R. The Vegetation Ecology and Native Status of Scots Pine (Pinus sylvestris L.) in Ireland. Ph.D. Thesis, Trinity College Dublin, Dublin, Ireland, 2010.
15. Gear, A.J.; Huntley, B. Rapid changes in the range limits of Scots pine 4000 years ago. *Science* **1991**, *251*, 544–547. [CrossRef] [PubMed]
16. Jalas, J.; Suominen, J. *Atlas Florae Europaeae, 2. Gymnospermae*; Cambridge University Press: Cambridge, UK, 1973; ISBN 9519108017.
17. Le Maitre, D.C. Pines in cultivation: A global view. In *Ecology and Biogeography of Pinus*; Richardson, D.M., Ed.; Cambridge University Press: Cambridge, UK, 1998; pp. 407–431, ISBN 0521551765.
18. Lust, N.; Geudens, G.; Olsthoorn, A.F.M. Scots pine in Belgium and the Netherlands. *Investig. Agrar. Sist. Recur. For.* **2000**, *9*, 213–231. [CrossRef]
19. Mirov, N.T. *The Genus Pinus*; Ronald Press: New York, NY, USA, 1967.
20. Watts, W.A. The Holocene vegetation of the Burren, western Ireland. In *Lake Sediments and Environmental History*; Haworth, E.Y., Lund, J.W.G., Eds.; Leicester University Press: Leicester, UK, 1984; pp. 359–376, ISBN 9780816613649.
21. McAulay, I.R.; Watts, W.A. Dublin radiocarbon dates. *Radiocarbon* **1961**, *3*, 26–38. [CrossRef]
22. McCracken, E. *Irish Woods since Tudor Times*; David & Charles: Newton Abbot, UK, 1971; ISBN 9780715350089.
23. Roche, J.R.; Mitchell, F.J.G.; Waldren, S.; Bjørndalen, J.E. Are Ireland's reintroduced *Pinus sylvestris* forests floristically analogous to their native counterparts in north-west Europe? *Biol. Environ.* **2015**, *115*, 97–114. [CrossRef]
24. Cross, J.R.; Collins, K.D. *Management Guidelines for Ireland's Native Woodlands*; National Parks & Wildlife Service, Forest Service: Dublin, Ireland, 2017; ISBN 9781902696782.
25. Malone, S.; O'Connell, C. *Ireland's Peatland Conservation Action Plan 2020-Halting the Loss of Peatland Biodiversity*; Irish Peatland Conservation Council: Rathangan, Ireland, 2009; ISBN 1874189277.
26. Webb, D.A.; Scannell, M.J.P. *Flora of Connemara and the Burren*; Royal Dublin Society, Cambridge University Press: Cambridge, UK, 1983; ISBN 052123395X.
27. O'Connell, J.W.; Korff, A. (Eds.) *The Book of the Burren*; Tír Eolas: Kinvara, Ireland, 1991; ISBN 187382100X.
28. Long-Term Climate Averages for Ireland 1981–2010. Available online: http://edepositireland.ie/handle/2262/74915 (accessed on 18 April 2018).
29. Sugita, S. Pollen representation of vegetation in Quaternary sediments-theory and method in patchy vegetation. *J. Ecol.* **1994**, *82*, 881–897. [CrossRef]
30. Roche, J.R.; Mitchell, F.J.G.; Waldren, S. Plant community ecology of *Pinus sylvestris*, an extirpated species reintroduced to Ireland. *Biodivers. Conserv.* **2009**, *18*, 2185–2203. [CrossRef]
31. National Inventory of Architectural Heritage. Available online: www.buildingsofireland.ie/cgi-bin/displayimage.cgi?id=3536&size=f&type=a1 (accessed on 1 April 2018).
32. Livingstone, D.A. A lightweight piston sampler for lake deposits. *Ecology* **1955**, *36*, 137–139. [CrossRef]
33. Grimshaw, H.M. Analysis of soils. In *Chemical Analysis of Ecological Materials*; Allen, S.E., Ed.; Blackwell Scientific: Oxford, UK, 1989; pp. 7–45, ISBN 0632003219.
34. Rose, N.L. A method for the extraction of carbonaceous particles from lake sediment. *J. Paleolimnol.* **1990**, *3*, 45–53. [CrossRef]
35. Rose, N.L. A note on further refinements to a procedure for the extraction of carbonaceous fly-ash particles from sediments. *J. Paleolimnol.* **1994**, *11*, 201–204. [CrossRef]
36. Haslett, J.; Parnell, A. A simple monotone process with application to radiocarbon-dated depth chronologies. *J. R. Stat. Soc.* **2008**, *57C*, 399–418. [CrossRef]
37. Moore, P.D.; Webb, J.A.; Collinson, M.E. *Pollen Analysis*; Blackwell Scientific: Oxford, UK, 1991; ISBN 0865428956.
38. Stockmarr, J. Tablets with spores used in absolute pollen analysis. *Pollen et Spores* **1971**, *13*, 615–621.
39. Beug, H.J. *Leitfaden der Pollenbestimmung Für Mitteleuropa und Angrenzende Gebiete*; Pfeil: München, Germany, 2004; ISBN 3899370430.

40. Reille, M. *Pollen et Spores d'Europe et d'Afrique du Nord*; Laboratoire de Botanique Historique et Palynologie: Marseille, France, 1992; ISBN 2950717535.
41. Grimm, E.C. *TILIA and TILIAGRAPH Software Package*; Illinois State Museum: Springfield, IL, USA, 1991.
42. Rose, N.L.; Harlock, S.; Appleby, P.G.; Battarbee, R.W. Dating of recent lake sediments in the United Kingdom and Ireland using spheroidal carbonaceous particle (SCP) concentration profiles. *Holocene* **1995**, *5*, 328–335. [CrossRef]
43. Jeličić, L.; O'Connell, M. History of vegetation and land use from 3200 B.P. to the present in the north-west Burren, a karstic region of western Ireland. *Veg. Hist. Archaeobot.* **1992**, *1*, 119–140. [CrossRef]
44. Lamb, H.; Thompson, A. Unusual mid-Holocene abundance of *Ulmus* in western Ireland-human impact in the absence of a pathogen? *Holocene* **2005**, *15*, 447–452. [CrossRef]
45. Mitchell, F.J.G. The vegetational history of the Killarney oakwoods, SW Ireland: Evidence from fine spatial-resolution pollen analysis. *J. Ecol.* **1988**, *76*, 415–436. [CrossRef]
46. Van Geel, B.; Middeldorp, A.A. Vegetational history of Carbury Bog (Co. Kildare, Ireland) during the last 850 years and a test of the temperature indicator value of 2H/1H measurements of peat samples in relation to historical sources and meteorological data. *New Phytol.* **1988**, *109*, 377–392. [CrossRef]
47. National Monuments Service Sites and Monuments Record. Available online: http://webgis.archaeology.ie/historicenvironment (accessed on 1 April 2018).
48. Frost, J. *The History and Topography of the County of Clare, from the Earliest Times to the Beginning of the 18th Century*; Sealey, Byers and Walter: Dublin, Ireland, 1893.
49. MacCraith, S.M.R. *Caithréim Thoirdhealbhaigh*; Irish Texts Society: London, UK, 1929.
50. O'Donovan, J. *Annals of the Kingdom of Ireland by the Four Masters, from the Earliest Period to the Year 1616*; Hodges and Smith: Dublin, Ireland, 1851.
51. Westropp, T.J. The forests of the counties of the Lower Shannon Valley. *Proc. R. Ir. Acad.* **1909**, *27C*, 270–300.
52. Weir, H. *Historical Genealogical Architectural Notes on Some Houses of Clare*; Ballinakella Press: Whitegate, UK, 1999; ISBN 094653828X.
53. Lewis, S. *County Clare: A History and Topography*, 2nd ed.; Clasp Press: Ennis, Ireland, 1837.
54. Dutton, H. *Statistical Survey of the County of Clare*; Graisberry and Campbell: Dublin, Ireland, 1808.
55. Cole, E.E.; Mitchell, F.J.G. Human impact on the Irish landscape during the late Holocene inferred from palynological studies at three peatland sites. *Holocene* **2003**, *13*, 507–515. [CrossRef]
56. Feeser, I.; O'Connell, M. Fresh insights into long-term changes in flora, vegetation, land use and soil erosion in the karstic environment of the Burren, western Ireland. *J. Ecol.* **2009**, *97*, 1083–1100. [CrossRef]
57. Foot, F.J. On the distribution of plants in the Burren, County of Clare. *Proc. R. Ir. Acad.* **1864**, *24*, 143–160.
58. Hickie, D. *Native Trees & Forests of Ireland*; Gill & Macmillan: Dublin, Ireland, 2002; ISBN 0717134113.
59. Everett, N. *The Woods of Ireland. A History, 700–1800*; Four Courts Press: Dublin, Ireland, 2014; ISBN 9781846825910.
60. Broström, A.; Nielsen, A.B.; Gaillard, M.J.; Hjelle, K.; Mazier, F.; Binney, H.; Bunting, J.; Fyfe, R.; Meltsov, V.; Poska, A.; et al. Pollen productivity estimates of key European plant taxa for quantitative reconstruction of past vegetation: A review. *Veg. Hist. Archaeobot.* **2008**, *17*, 461–478. [CrossRef]
61. Bennett, K.D. Post-glacial dynamics of pine (*Pinus sylvestris* L.) and pinewoods in Scotland. In *Our Pinewood Heritage*; Aldhous, J.R., Ed.; Forestry Commission, Royal Society for the Protection of Birds, Scottish Natural Heritage: Inverness, UK, 1995; pp. 23–39, ISBN 0855383259.
62. Fossitt, J.A. Late-glacial and Holocene vegetation history of western Donegal, Ireland. *Biol. Environ.* **1994**, *94*, 1–31.
63. Froyd, C.A. Fossil stomata reveal early pine presence in Scotland: Implications for postglacial colonization analyses. *Ecology* **2005**, *86*, 579–586. [CrossRef]
64. McGeever, A.H.; Mitchell, F.J.G. Re-defining the natural range of Scots Pine (*Pinus sylvestris* L.): A newly discovered microrefugium in western Ireland. *J. Biogeog.* **2016**, *43*, 2199–2208. [CrossRef]
65. Jacobson, G.L.; Bradshaw, R.H.W. The selection of sites for paleovegetational studies. *Q. Res.* **1981**, *16*, 80–96. [CrossRef]
66. Crabtree, K. Evidence for the Burren's forest cover. In *Archaeological Aspects of Woodland Ecology. Symposia of the Association for Environmental Archaeology No. 2*; Bell, M., Limbrey, S., Eds.; British Archaeological Reports; BAR International Series 146: Oxford, UK, 1982; pp. 105–113.

67. Mitchell, F.J.G. The history and vegetation dynamics of a yew wood (*Taxus baccata* L.) in S.W. Ireland. *New Phytol.* **1990**, *115*, 573–577. [CrossRef]
68. Peterken, G.F. *Woodland Conservation and Management*; Chapman & Hall: London, UK, 1981; ISBN 0412128209.
69. Bjørndalen, J.E. Some synchorological aspects of basiphilous pine forests in Fennoscandia. *Vegetatio* **1985**, *59*, 211–224. [CrossRef]
70. Jeffrey, D.W. Grasslands and heath: A review and hypothesis to explain the distribution of Burren plant communities. *Biol. Environ.* **2003**, *103*, 111–123. [CrossRef]
71. Dodson, J.R.; Bradshaw, R.H.W. A history of vegetation and fire, 6600 BP to present, County Sligo, Western Ireland. *Boreas* **1987**, *16*, 113–123. [CrossRef]
72. Little, D.J.; Mitchell, F.J.G.; von Engelbrechten, S.; Farrell, E.P. Assessment of the impact of past disturbance and prehistoric *Pinus sylvestris* on vegetation dynamics and soil development in Uragh Wood, SW Ireland. *Holocene* **1996**, *6*, 90–99. [CrossRef]
73. Ghilardi, B.; O'Connell, M. Fine-resolution pollen-analytical study of Holocene woodland dynamics and land use in north Sligo, Ireland. *Boreas* **2013**, *42*, 623–649. [CrossRef]
74. Watts, W.A. Contemporary accounts of the Killarney woods 1580–1870. *Ir. Geogr.* **1984**, *17*, 1–13. [CrossRef]
75. Allaby, M. *A Dictionary of Ecology*, 4th ed.; Oxford University Press: Oxford, UK, 2010.
76. Feeser, I.; O'Connell, M. Late Holocene land-use and vegetation dynamics in an upland karst based on pollen and coprophilous fungal spore analyses: An example from the Burren, western Ireland. *Veg. Hist. Archaeobot.* **2010**, *19*, 409–426. [CrossRef]
77. Wyse Jackson, M.; FitzPatrick, Ú.; Cole, E.; Jebb, M.; McFerran, D.; Sheehy Skeffington, M.; Wright, M. *Ireland Red List No. 10: Vascular Plants*; National Parks & Wildlife Service: Dublin, Ireland, 2016; ISSN 2009-2016.
78. Speight, M.C.D. The extinction of indigenous *Pinus sylvestris* in Ireland: Relevant faunal data. *Ir. Nat. J.* **1985**, *21*, 449–453.
79. Reilly, E. An ever closing gap? Modern ecological and palaeoecological contributions towards understanding the Irish postglacial insect fauna. In *Mind the Gap. Postglacial Colonization of Ireland*; Davenport, J.L., Sleeman, D.P., Woodman, P.C., Eds.; Irish Naturalists' Journal: Belfast, UK, 2008; pp. 63–71.
80. Whitehouse, N. The Holocene British and Irish ancient forest fossil beetle fauna: Implications for forest history, biodiversity and faunal colonization. *Q. Sci. Rev.* **2006**, *25*, 1755–1789. [CrossRef]