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REVIEW

Volcanic impacts on the Holocene vegetation history of Britain and Ireland? A review and meta-analysis of the pollen evidence

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Abstract Volcanic ash layers show that the products of Icelandic volcanism reached Britain and Ireland many times during the Holocene. Historical records suggest that at least one eruption, that of Laki in A.D. 1783, was associated with impacts on vegetation. These results raise the question: did Icelandic volcanism affect the Holocene vegetation history of Britain and Ireland? Several studies have used pollen data to address this issue but no clear consensus has been reached. We re-analyse the palynological data using constrained ordination with various representations of potential volcanic impacts. We find that the palynological evidence for volcanic impacts on vegetation is weak but suggest that this is a case of absence of evidence and is not necessarily evidence of absence of impact. To increase the chances of identifying volcanic impacts, future studies need to maximise temporal resolution, replicate results, and investigate a greater number of tephras in a broader range of locations, including more studies from lake sediments.

Keywords Tephra · Hekla · Volcanic impacts · Palynology · Tephropalynology · Ordination

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Introduction

At the end of the 1980s, two important discoveries were made in the Holocene palaeoenvironmental record of Britain and Ireland. In the Irish bog-oak tree-ring record, Baillie and Munro (1988) found clusters of extremely narrow rings close to the inferred age of the Minoan eruption of Santorini (Thera) and interpreted these as evidence for a major and widespread volcanogenic climatic deterioration, first suggested by frost-rings in Californian Bristlecone Pines (LaMarche and Hirschboek 1984). In northern Scotland meanwhile, Dugmore (1989) reported the first discovery of Holocene Icelandic tephra (volcanic ash) on the British mainland. This finding was swiftly followed by many others throughout the British Isles as palaeoecologists realized the potential of cryptotephrochronology as an accurate, precise and comparatively inexpensive approach to geochronology (Pilcher and Hall 1992, 1996; Dugmore et al. 1995a; Hall and Pilcher 2002). At least 14 Holocene cryptotephras have been found in Britain and 33 in Ireland (Swindles et al. 2011). At the same time as these discoveries, there was increasing scientific curiosity about the environmental impacts of volcanism following the eruptions of Mount St. Helens in 1980 and Pinatubo in 1991, and a more general resurgence in interest in catastrophism (Burgess 1989; Marriner et al.

2010). These developments led to an important trend in palynological research through the 1990 and 2000s—the attempt to use the pollen archive to identify distal volcanic impacts on vegetation (Birks 1994; Buckland et al. 1997). The term *tephropalynology* has been coined for such studies (Edwards 1996; Lowe and Hunt 2001; Edwards et al. 2004).

Blackford et al. (1992) were the first to investigate the palynological record across a volcanic ash layer at high resolution (Table 1). At two peatland sites in Scotland, these authors showed coincidence between the ca. 4300 B.P. eruption of Hekla (Hekla-4: Dugmore et al. 1995b; Pilcher et al. 1995a; Zillén et al. 2002) and a widely-reported decline in *Pinus* pollen. In a subsequent study in northern Ireland, Hall et al. (1994b) found no correlation between the Hekla-4 tephra and changes in *Pinus* pollen, although interpretation was complicated by the uncertain local presence of pine at their study sites (Edwards et al. 1996; Hall et al. 1996). For a tephra layer in Ireland which may be from Hekla-4, Dwyer and Mitchell (1997) suggested possible evidence for volcanic impacts on local, but not regional pollen and non-pollen palynomorph (NPP) taxa, while Hall (2003a) found no evidence of significant changes across other Irish tephras. In Scotland, Charman et al. (1995) noted palynological changes associated with some tephras, but not others, and in Ireland Caseldine et al. (1998) suggested variability in apparent palaeoenvironmental response between the same tephra in different profiles. Overall, this literature does not provide a clear answer to the key questions—did volcanic activity affect the vegetation history of Britain and Ireland during the Holocene?, and if so, how? The aim of this paper is to review and re-analyse this evidence after 20 years of studies in an attempt to assess the strength of the case for volcanic impacts on vegetation and to identify significant practical and methodological issues.

Volcanic impacts on vegetation: what can be expected?

There is little doubt that volcanoes can have drastic impacts on vegetation. Adjacent to a volcanic source lava, pyroclastic flows and lahars may kill all plant life through a combination of extreme heat, manual breakage and burial (Griggs 1918, 1922). In explosive eruptions, plant life may be killed by the extreme heat and violent winds of a volcanic blast (Griggs 1919; Eggler 1948). Such volcanic impacts and the largely sterile substrates which remain, form the basis of a classic primary succession sequence (Eggler 1941; Fridriksson 1975, 1987; Whittaker et al. 1989, 1992; Grishin et al. 1995). While such volcano-vegetation relationships seem evident in the tephropalynological records from peneproximal sites (Erlendsson et al. 2009) and even further afield (Edwards and Craigie 1998), the zone affected by such proximal impacts is relatively small—generally kilometres to tens of kilometres for Holocene eruptions. A much larger region may be affected by distal impacts through exposure to volcanic ash, volcanic gases, aerosols and volcanically-modified precipitation, and additional volcanic impacts on climate and weather. Tephra may lead to the abrasion of plant surfaces (Griggs 1922; Bjarnason 1991), the inhibition of photosynthesis (Cook et al. 1980; Clarkson and Clarkson 1994) and gas exchange (Eggler 1948), cooling of leaves (Cook et al. 1980), crushing of plant tissues (Eggler 1948; Wilcox 1959; Cook et al. 1980), waterlogging (Vucetich and Pullar 1963; Crowley et al. 1994), release of metals (Smith et al. 1983; De Vleeschouwer et al. 2008), changes to predation (Wilcox 1959) and disease vulnerability (Cook et al. 1980), all resulting in structural changes in plant community composition (Antos and Zobel 1985; Zobel and Antos 1997). As well as tephra, volcanoes may produce large quantities of gases including CO_2, SO_2, HCl and HF (Wilcox 1959; LeGuern et al. 1988; Symonds et al. 1988; Delmelle et al. 2002) which can affect vegetation as dry deposition, acidic precipitation, aerosols and adherents to tephra particles (Rose 1977; Oskarsson 1980; Delmelle et al. 2001). Impacts on plants may include lesions and burnt spots extending to total defoliation and plant death (Parnell and Burke 1990; Clarkson and Clarkson 1994; Delmelle et al. 2002). Vegetation may be further affected through volcanic soil acidification (Delmelle et al. 2001, 2002). The largest volcanic eruptions also have the power to modify climate with stratospheric injection of sulphur leading to formation of aerosols which are generally efficient scatterers, but only weak absorbers of radiation at solar wavelengths, with consequent tropospheric cooling (McCormick et al. 1995). Meteorological and proxy-climate records suggest typical cooling following Holocene eruptions of up to 1–2 °C for up to 5 years (Mass and Schneider 1977; Self et al. 1981; Angell and Korshover 1985; Sear et al. 1987; Scuderi 1990; Zielinski 2000; Gervais and MacDonald 2001). Plants in marginal locations may be affected by this cooling, producing changes in community composition which could (conceivably) be represented in the pollen record. Plants growing close to a thermal threshold may be limited in flowering, or prevented from producing pollen at all for the period of reduced temperatures. Proximally and in the short-term, volcanic eruptions may also lead to increased precipitation and frequent lightning strikes.

The potential for Icelandic volcanism to produce impacts on vegetation in the British Isles is illustrated by the A.D. 1783/84 Laki eruption. Abundant historical evidence records plant damage and death consistent with known impacts of volcanic acids and aerosols, particularly in eastern England and Scotland, with similar accounts from throughout western Europe (Thorarinsson 1981; Sigurdsson 1982; Camuffo and Enzi 1995; Grattan and Charman 1994; Grattan and Gilbertson 1994; Grattan and Pyatt 1994; Grattan et al. 1999). Given the potential of volcanic eruptions to produce impacts on vegetation, the presence of Icelandic tephra from many Holocene eruptions suggests the possibility of volcanic impacts on vegetation in Britain and Ireland which could be represented in the pollen record. The existing research, however, is inconclusive, with apparently contradictory evidence and various authors presenting a range of viewpoints.

Statistical analysis of pollen data

Although the use of quantitative data analysis techniques was advocated in 1994 by Birks, the identification of volcanic impacts in pollen diagrams spanning Holocene tephra layers in Britain and Ireland has been entirely qualitative, being based on observed changes coincident with tephra layers and judgements as to whether any of these exceed natural variability. Here we apply a quantitative approach based on constrained ordination. Pollen percentage summary diagrams from published pollen analyses across tephra layers were digitised and compiled (Fig. 1). Almost all such diagrams are from peatlands.

A detrended canonical correspondence analysis (DCCA) with depth as the sole explanatory variable was used to determine compositional gradient lengths. As these gradients were short (<1 standard deviation), ordination methods based on a linear taxon response are most appropriate. Redundancy analysis (RDA), the constrained form of principal components analysis (PCA), was used in all subsequent analyses. Pollen data were square-root transformed and double centring of samples and variables was applied. In order to statistically account for long-term processes occurring through the full duration of the profiles, depth was treated as a co-variable in all analyses as a surrogate for time. Stratigraphically-constrained Monte Carlo permutation tests (999 permutations) were used to test the significance of the models. All ordinations used Canoco v. 4.53 (Ter Braak and Šmilauer 1997–2004).

Previous studies have taken a variety of approaches to the representation of a volcanic impact in an ordination of palaeoecological data. We tested four contrasting models:

i. The simplest model considers the difference between the pollen assemblages prior to and following emplacement of the tephra layer, modelled in Canoco as a before (0) and after (1) dummy variable with the division placed at the peak tephra concentration. This approach makes the assumption of a lasting impact with no recovery within the period spanned by the profile. This will only be valid where recovery takes longer than the remaining period of the profile, or where the impact leads to a permanent vegetation change.

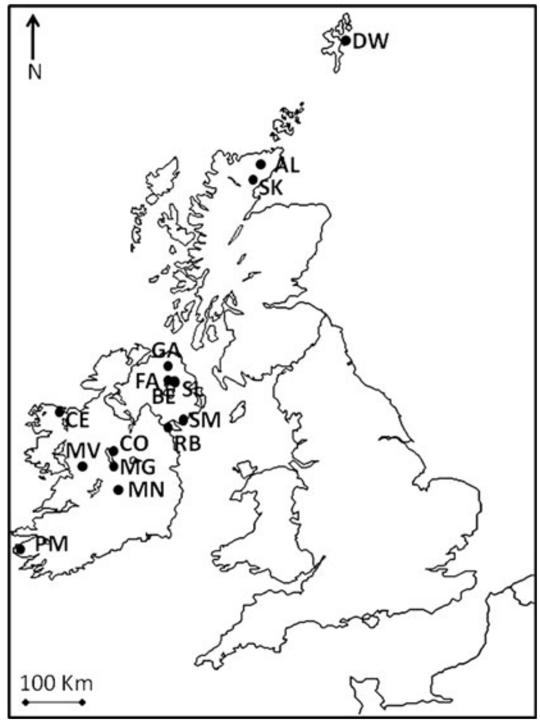

Fig. 1 Tephropalynological study sites in Britain and Ireland included in this study. Site codes: *DW* Dallican Water, *AL* Altnabreac and Loch Lèir, *SK* Strath of Kildonan, *GA* Garry Bog, *FA* Fallahogy, *BE* Ballyscullion East, *SL* Sluggan Bog, *SM* Slieve Meelbeg, *RB* Redbog, *CE* Croaghaun East, *CO* Corlea, *MG* Mongan Bog, *MV* Moneyveagh Bog, *MN* Monaincha Bog, *PM* Portmagee Bog. Iceland is ~500 km NW of the NW corner of this map

ii. A more sophisticated method is to model the onset and recovery from a volcanic impact. Lotter and Birks (1993) proposed an approach based on an exponential decay curve. The variable (x) is assigned a value of 0 below the tephra, a value of 100 at the tephra peak decreasing as exp $x^{-\alpha t}$ above the tephra where α is the decay coefficient and t is the sample time after the tephra peak. The model thereby assumes an impact starting with the tephra peak and declining rapidly with time. Lotter and Birks (1993) used a value of $\alpha = 0.5$. We varied α between 0.1 and 0.7, but this did not change the (non-) significance of the results. Results are reported using $\alpha = 0.5$ for comparison with previous studies. Where evidence of impacts is found in multiple profiles, varying this coefficient might be a useful approach to examine differences in the duration of impact.

iii. The above model assumes an instantaneous start to a volcanic impact which, while perhaps valid for the

Table 1 Key details of tephropalynological profiles from Britain and Ireland

Authors	Site/profile	Dating approach	Duration of record (years; to nearest 100)	Sampling resolution (mm)	Approx. temp. resol. (years; to nearest 10)	Tephra identification approach	Tephra
Bennett et al. (1992)	Dallican Water	^{14}C	~8,500	40–80	~30	WD-EPMA	Probable Saksunarvatn
							Hekla-4?
							Uncertain
Charman et al. (1995)	Strath of Kildonan K1	Regional pollen record	400 Year?	10	~40?	–	Uncertain
Charman et al. (1995)	Strath of Kildonan K2	Regional pollen record	400 Year?	10	~40?	Based on inferred age	Possible Hekla-4
Charman et al. (1995)	Strath of Kildonan K3	Regional pollen record	400 Year?	10	~40?	–	Uncertain
Hall (1998)	Garry Bog	By reference to historically dated tephras	~800	10	~10–20	WD-EPMA	Hekla 1510
							Öræfajökull 1362
Hall (2003a)	Fallahogy	^{14}C dated tephras	~500	10	~10	WD-EPMA	Lairg-A
							Lairg-B
Hall (2003a)	Sluggan Bog	^{14}C	~1,100	10	~10	–	Uncertain
						WD-EPMA	Lairg-A
							Lairg-B
Hall (2003b)[b]	Portmagee Bog	^{14}C dated tephra	~1,000	20	~60	WD-EPMA	Hekla 1104
Hall (2003b)[b]	Moneyveagh Bog	Historically dated tephras	~1,000	10	~20	WD-EPMA	Hekla 1104
							Öræfajökull 1362
Hall (2003b)[b,c]	Monaincha Bog	Historically dated tephras	~900	10	~20	WD-EPMA	Hekla 1104
Hall et al. (1994b)	Garry Bog	^{14}C dated tephra	~300	5	~10	WD-EPMA	Hekla-4
Hall et al. (1994b)	Sluggan Bog	^{14}C	~300	5	~10	WD-EPMA	Hekla-4
Blackford et al. (1992)	Altnabreac	^{14}C dating in nearby core	~300	1–4	~5–30	WD-EPMA in nearby core	Hekla-4
Blackford et al. (1992)	Loch Lèir	^{14}C dating in nearby core	~200	1–4	~5–20	WD-EPMA in nearby core	Hekla-4
Dwyer and Mitchell (1997)	Croaghaun East	^{14}C	~1,400	50	~70	WD-EPMA	Hekla-4?[a]
Caseldine et al. (1998)	Corlea I	^{14}C dating in nearby cores	~800	20–80	~10	ED-EPMA in nearby core and probable date	Hekla-4?
Caseldine et al. (1998)	Corlea II	Single ^{14}C date and analogy to other dates from nearby	~1,000	20	~10	ED-EPMA	Hekla-4?
Caseldine et al. (1998)	Corlea V	^{14}C dating in nearby cores	~1,000	10–40	~10	ED-EPMA in nearby core and probable date	Hekla-4?
Hall et al. (1994a)[b]	Slieve Meelbeg	^{14}C dated tephra	100?	10	~10	WD-EPMA	Hekla-4
Hall et al. (1993)	Sluggan Bog	^{14}C (?)	~700	10	~20	WD-EPMA	c. A.D. 860 t
							c. A.D. 1088 t.
Hall et al. (1993)	Fallahogy	^{14}C dated tephra (?)	~600	10–20	~10–20	Appearance and inferred age	c. A.D. 860 t
							c. A.D. 1088 t.

Table 1 continued

Authors	Site/profile	Dating approach	Duration of record (years; to nearest 100)	Sampling resolution (mm)	Approx. temp. resol. (years; to nearest 10)	Tephra identification approach	Tephra
Hall et al. (1993)	Ballyscullion East	^{14}C dated tephra (?)	~500	10–20	~20–40	Appearance and inferred age	c. A.D. 860 t c. A.D. 1088 t
Weir (1995)	Redbog	^{14}C	~6,500	10–40	~20–90	–	Unknown
						WD-EPMA and inferred age	Hekla-4?
Hall and Mauquoy (2005)	Mongan Bog	Historically-dated tephras	~1,500	10	~20	WD-EPMA	Hekla 1947 c. A.D. 1600 t Hekla 1104

All dates are historical or calibrated radiocarbon years based on the chronology in the original paper. For Bennett et al. (1992) new calibration was carried out with CALIB6.0 based on the IntCal09 data (Reimer et al. 2009). Due to the limited dating evidence, the estimated duration and temporal resolution of several records should be regarded as highly approximate. Sampling resolution reflects the combination of the thickness of each sampled depth and, where samples are non-contiguous, the gap between samples

WD-EPMA wavelength-dispersive electron probe microanalysis, *ED-EPMA* energy-dispersive electron probe microanalysis

[a] Described as twin tephra layers, but in the absence of a tephra concentration profile and EPMA data for both it is impossible to be sure these are not simply two peaks of the same tephra

[b] These studies were not focused on identifying possible volcanic impacts but are included here for completeness

[c] One further site studied by this author is not included here as the tephra layer lies in the lowermost sample

context in which it was first proposed (diatoms in lacustrine sediments), is arguably not appropriate for pollen in peat profiles. The issue is one of taphonomy—Clymo and Mackay (1987) and Rowley and Rowley (1956) have experimentally demonstrated substantial post-depositional movement of pollen through peat profiles. If a volcanic event caused a short-lived increase in pollen deposition of a taxon we would expect some of that additional pollen to be transported into the under- and over-lying peat. An alternative volcanic impact model therefore takes account of this taphonomic dimension using an exponential decay curve as above, but with x declining similarly both above and below the tephra peak.

iv. A final approach contrasts with the above models. Instead of using a conceptual construct, the tephra concentration profile is used as the explanatory variable (Eastwood et al. 2002). This approach has been used in some palaeolimnological studies as volcanic impacts may be directly due to the presence of tephra in the lake (Barker et al. 2000). In the data analysed in this study the concentration profile represents the post-depositional taphonomy of tephra shards (Payne and Gehrels 2010) and there is no probable intrinsic reason for it to be related to the pattern and timing of any volcanic impact on vegetation. However, if the taphonomy of tephra shards and pollen grains were equivalent (see discussion below) then the tephra concentration profile might be a useful indicator of how a short-lived change in pollen deposition would be represented (Hall and Pilcher 2002).

All these models simulate the pattern of a volcanic impact, but they do not make fixed assumptions about the mode of impact; they are applicable to both direct and indirect forcing mechanisms. All models were tested for all datasets with the exception of tephra concentration profiles which were not available for some profiles. Where more than one tephra was present in a sequence, all were incorporated in a single analysis. We included the full length of the published profiles, hence spanning differing time periods in different records (Table 1). Analyses make no correction for taxonomic resolution and are necessarily based only on major pollen types for most profiles.

Discussion of results

Limitations of the evidence

Before discussing the results of our analyses, brief consideration is given to the limitations of the available evidence. The published pollen diagrams include differing numbers of taxa: while some include a large proportion (for example 55 taxa in Weir 1995), others are much more selective (for example 19 taxa in the Slieve Meelbeg site of Hall et al. 1994a). The taxonomic resolution varies with some differentiating taxa grouped by other authors (such as Gramineae/Cerealia) and studies present different selections of 'important' taxa, in the case of Dwyer and Mitchell (1997) including some NPPs (non pollen palynomorphs). The digitisation process is likely to introduce both minor systematic offsets and small random errors into the data, particularly with records of rare taxa marked with a '+' symbol in pollen diagrams, which have generally been recorded as zero. Sampling resolution and profile length also vary between studies and are likely to affect our ability to identify any volcanic impacts. Several of the studies we analyse were not primarily focused on the identification of volcanic impacts and pollen diagrams have been constructed in the light of the research questions of primary interest for the study.

Despite such acknowledged limitations, we believe that the results are adequate to address the fundamental question of whether there is sound palynological evidence for volcanic impacts on vegetation history. To consider the issue of whether exclusion of rare taxa affects results, we compared more- and less-detailed versions of the records for Hekla-4 at Loch Lèir and Sluggan Bog. No changes were found in the significance of the results. Even summary diagrams which include relatively limited numbers of taxa typically encompass the vast majority of all pollen grains. Differences in the published studies would render it difficult to assess the spatial extent of any volcanic impacts, but as our primary question is whether there is *any* robust evidence for volcanic impacts, such differences are not critical to our study.

Data analysis

Volcanic impact models explain a significant proportion of variance in four profiles (Table 2): the Croaghaun East site of Dwyer and Mitchell (1997), the Portmagee site of Hall (2003b), the Dallican Water site of Bennett et al. (1992) and the Altnabreac site of Blackford et al. (1992).

In the case of Croaghaun East, Dwyer and Mitchell (1997) present separate pollen diagrams for regional and local taxa, the latter including some non-pollen palynomorphs such as the testate amoeba *Amphitrema flavum* (*Archerella flavum*). Analyses were conducted on each of these records separately and on a combined record incorporating both 'regional' and 'local' taxa as defined in the original paper. Significant relationships were identified in all three of these datasets using the simplest 'before/after' model only. The largest proportion of variance was explained in the regional data, with differences between the assemblages above and below the tephras largely accounted for by much reduced *Pinus* and increased *Fraxinus* above the twin tephras. In the local record, differences include increased Cyperaceae*, Narthecium ossifragum, Sphagnum* and NPPs type 16 and 28 above the tephras. The changes are both pronounced and coincident with the tephras, but there is no return towards prior conditions in the subsequent ca. 400 years of the record, and non-significant results are obtained when using models which assume a recovery. The authors suggest that their record might represent volcanic impacts but we believe this is unlikely. The profile is of relatively low temporal resolution (c. 70 years between samples) and modern ecological studies do not suggest that distal volcanic effects may lead to such a lasting impact, although this is perhaps possible if the temporary impacts allow an invasive succession. We suggest that this result may be more probably attributable to some broadly coincident non-volcanic environmental change, in this case perhaps a longer-term change to wetter climatic conditions. For Portmagee, the 'before/after' model explained around a third of total variance with moderate significance ($P = 0.03$). The changes detected in the ordinations are a reduction in *Corylus* and an increase in Gramineae (Poaceae) up the core. These changes are both distinct and coincident with the tephra layer, although there is no subsequent return to prior conditions and sampling resolution is low. Other models did not produce a significant result. A human impact is a possible alternative explanation, with *Corylus*-dominated woodland being replaced by grassland.

For Altnabreac, three models explain significant variance: tephra concentration, simple exponential decay and the 'peaked' double exponential decay model, of which the latter explains the most variance. In this case the significant result is driven by a substantial peak in *Sphagnum* coincident with the tephra peak—if this taxon is removed, all analyses for each model lose significance. Other notable changes broadly coincident with the tephra include reduced *Pinus* and an increase in Cyperaceae pollen.

For Dallican Water a moderate proportion of variance is explained with reasonable significance ($P = 0.02$) by the 'before/after' model. In this profile there are three distinct tephra peaks, the lowest (704 cm) probably representing the early Holocene Saksunarvatn tephra. The upper two peaks (524 and 504 cm) are found relatively close to each other and may be either two distinct tephra layers or one layer with complex distribution. Probably at least one of these tephras is Hekla-4. The early Holocene tephra lies close to a zone boundary and coincides with many changes including a decline in *Salix* and the first detection of *Quercus* and *Ulmus* pollen. The 524 cm tephra coincides with a minor peak in *Salix* and marks the onset of a short-lived phase until the 504 cm tephra including a peak in Cyperaceae. There is little distinct change around 504 cm,

Table 2 Results of RDA using four models (i–iv) of volcanic impact as an explanatory variable with depth as a co-variable

Data	Percent variance explained and *P* value			
	(i) Before/after	(ii) Exp. decay	(iii) Peaked	(iv) Conc.
Weir (1995) Redbog II	ns	ns	ns	–
Hall et al. (1993) Fallahogy	ns	ns	ns	–
Hall et al. (1993) Sluggan Bog	ns	ns	ns	–
Hall et al. (1993) Ballyscullion East	ns	ns	ns	–
Hall and Mauquoy (2005) Mongan Bog	ns	ns	ns	–
Hall (1998) Garry Bog	ns	ns	ns	–
Bennett et al. (1992) Dallican Water	10.7 ($P = 0.02$)	ns	ns	ns
Blackford et al. (1992) Altnabreac	ns	23.3 ($P = 0.02$)	32.0 ($P = 0.02$)	19.7 ($P = 0.02$)
Blackford et al. (1992) Loch Lèir	ns	ns	ns	ns
Caseldine et al. (1998) Corlea I	ns	ns	ns	ns
Caseldine et al. (1998) Corlea II	ns	ns	ns	ns
Caseldine et al. (1998) Corlea V	ns	ns	ns	ns
Charman et al. (1995) K1	ns	ns	ns	ns
Charman et al. (1995) K2	ns	ns	ns	ns
Charman et al. (1995) K3	ns	ns	ns	ns
Dwyer and Mitchell (1997) Croaghaun East	31.4 ($P = 0.02$)	ns	ns	–
Regional	13.2 ($P = 0.04$)	ns	ns	–
Local	18.9 ($P = 0.02$)	ns	ns	–
Combined				
Hall et al. (1994b) Garry Bog	ns	ns	ns	–
Hall et al. (1994b) Sluggan Bog	ns	ns	ns	–
Hall et al. (1994a) Slieve Meelbeg	ns	ns	ns	ns
Hall (2003a) Fallahogy	ns	ns	ns	–
Hall (2003a) Sluggan Bog	ns	ns	ns	–
Hall (2003b) Portmagee Bog	29.2 ($P = 0.03$)	ns	ns	–
Hall (2003b) Moneyveagh Bog	ns	ns	ns	–
Hall (2003b) Monaincha Bog	ns	ns	ns	–

The percentage variance explained and *P* values determined by stratigraphically-constrained permutation tests (999 permutations). No individual tests are significant if applying a Bonferroni correction for multiple-comparisons

ns not significant, *exp* exponential, *conc* concentration

but above this peak and the zone boundary at 476 cm there is much less tree pollen. We suggest that the most likely explanation for the significant result is that the 'before/after' variable captures long-term vegetation changes including the early Holocene establishment of trees in an ameliorating climate and mid-Holocene loss of woodland due to human activity. We see little reason to suspect volcanic impacts on the vegetation.

There is no significant relationship in all the other records, including some such as Strath of Kildonan-K1 (Charman et al. 1995) and Loch Lèir (Blackford et al. 1992) which have been suggested to show pollen changes at the time of tephra deposition. In Strath of Kildonan-K1, the tephra profile is rather diffuse, with the most distinct changes (replacement of Coryloid by Cyperaceae pollen) occurring below the tephra peak and therefore not identified as being related to tephra deposition in our analyses. At Loch Lèir, although there is a rise in Cyperaceae and decline in *Pinus* broadly coincident with the tephra layer, larger changes in these taxa are slightly offset (c. 10 mm) from the tephra peak, although tephra mobility in the upper part of a peat profile is a possibility (Payne and Blackford 2005). We suggest that these records do not provide strong evidence for volcanic impacts.

Pinus decline

The original discussion of putative volcanic impacts by Blackford et al. (1992), and subsequent publications, centred on the possibility of a causal relationship between the decline in *Pinus* pollen and the Hekla-4 eruption. A mid-Holocene *Pinus* decline has been widely reported from pollen and macrofossil studies in Britain and Ireland. Earlier research suggested that this event was widespread across Britain, and quite sudden—with *Pinus* forests replaced by blanket bog around 4000 B.P. (Bennett 1984). Increasingly, the weight of evidence suggests diversity in both the age and abruptness of this event (e.g. Birks 1975; Bridge et al. 1990; Charman 1994; Pilcher et al. 1995b; Anderson et al. 1998; Lageard et al. 1999; Tipping et al. 2008). At Loch Lèir the data of Blackford et al. (1992) show a two-stage decline in *Pinus* with the larger changes above the tephra peak. Only in the Altnabreac profile is the *Pinus* decline almost exactly synchronous with the peak concentration of Hekla-4 tephra and there is a clear decline in *Pinus* percentage in the sample(s) above the tephra peak. If volcanism caused a change in *Pinus* pollen production in Britain and Ireland, it would have impacted upon those individuals, or stands of pine, that were already close to a survival threshold. Other trees may have been more robust, while still others may have already declined prior to the Hekla-4 event as a response to a longer-term trend towards wetter conditions (as at Garry Bog; Hall et al. 1994b) or a cessation in the existence of unusually dry bog surfaces (Gear and Huntley 1991). The possibility of an impact of volcanism on *Pinus* growth in the region of the Altnabreac site cannot be excluded, but evidence for a more regional volcanically-induced decline in *Pinus* is weak.

Evidence of absence or absence of evidence?

Overall this analysis of palynological data provides very limited support for vegetation change consistent with a possible volcanic impact coincident with tephra deposition. The most convincing evidence is from the Altnabreac site (Blackford et al. 1992) where there is a distinct peak in *Sphagnum* coincident with the tephra layer. *Sphagnum* might be expected to increase in abundance in response to a cooler climate or increased local moisture but to be deleteriously affected by acidity, the physical impact of tephra or leached metals (Ferguson et al. 1978; Ferguson and Lee 1980; Gorham et al. 1984; Lee et al. 1987). It must be cautioned that this is a change in one taxon at one site and should not be over-interpreted. Although the palynological evidence for volcanic impacts overall is weak, absence of evidence is not necessarily evidence of absence and these results should not be taken to exclude the possibility of volcanic impacts on vegetation.

Volcanic impacts and critical loads

In discussions of possible drivers for putative volcanic impacts in the pollen record, Grattan and Gilbertson (1994) and Grattan et al. (1999) proposed an approach based on the use of critical loads—levels of pollution exposure below which impacts are not known to occur (Nilsson and Grennfelt 1988) and currently set at an effective rainfall pH of 4.4 for UK peatland soils (UK National Focal Centre 2004). Grattan et al. (1999) used extrapolated tephra concentrations in Ireland to state that 'If it is accepted that, at this distance from eruption source, the volume of adsorbed volatiles approached the mass of the [Hekla-4] tephra (Oskarsson 1980), then no less than 50 times the annual critical load for the Irish sediments may have been deposited in one very brief period of time', implying ecological impacts which might be detectable in the pollen record. In Grattan and Gilbertson (1994) the reference is to a more modest '20 times the annual critical load'. This reasoning is problematic. Firstly, exceedance of a critical load represents the potential for damage to occur but is not a quantitative estimate of damage (UK National Focal Centre 2004), and certainly not an indication of damage which would be detectable using the relatively insensitive tool of palynology. Critical loads are based on studies of impacts of long-term chronic pollution exposure—a quite different case from the exposure of an unpolluted ecosystem to a brief pollution episode. The critical load is an equilibrium concept and gives no information on the timescales for damage (UK National Focal Centre 2004). Although a deposition event 'fifty times the critical load' might be associated with ecological impacts, the use of critical loads is largely inappropriate in this context.

To address the impact of such brief pollution episodes, specific experiments are required. Payne and Blackford (2005) tested the deposition scenario proposed by Grattan et al. (1999) for peatlands in Ireland and found no detectable changes in peatland plant communities. When this scenario was re-scaled to match the maximum tephra deposition found in northern Scotland, significant impacts were noted. This suggests an important but overlooked point: the scale of tephra deposition in Scotland is frequently much greater than that in Ireland and if impacts are in any way related to tephra-loading, then it is possible for the impacts in these two areas to be quite distinct. However, there is also an issue with the assumption that tephra mass is equal to acid mass as used by Grattan et al. (1999), which appears to be based on a misreading of Oskarsson (1980). Oskarsson stated that 'the mass distribution of soluble fluorine … approaches the mass distribution of the tephra at longer distances', *not* that the mass of fluorine approaches that of tephra. In the most distal sample analysed, leached fluorine mass is only 0.1 % of tephra mass (Oskarsson 1980, Table 4). The Oskarsson paper therefore suggests that the fluorine mass is much less than is assumed by Grattan et al. (1999) and provides no information at all on acidity *per se*. Although Grattan et al. proposed this model as a first approximation, both the scale of acid-loading and the use of a critical loads approach to assess the impacts of that loading are questionable.

The nature of tephropalynological evidence and recommendations for future research

A tephropalynological approach to the study of past volcanic impacts on vegetation has a number of limitations. The most critical of these is the fundamental inability to identify cause-effect relationships. Changes in pollen concentration or relative abundance coincident with a tephra layer may represent volcanically-induced change, but it is impossible to exclude the possibility of coincident non-volcanic changes such as human impacts. The case for volcanic causation is strengthened if changes are found in multiple profiles and these are consistent with changes observed following recent eruptions. As the magnitude and duration of climate change needed to produce palynologically detectable vegetation change is considerably greater than the climatic impact of most Holocene eruptions, the pollen record is more likely to reveal the direct impact of volcanic products on vegetation than volcanic impacts on climate (Grattan and Charman 1994; Grattan et al. 1999). Given that impacts are generally short-lived, very high resolution would be needed to detect any changes. Typically, this would involve millimetre-scale sampling, and/or the selection of sites with very high accumulation rates.

Linking changes in vegetation to volcanic activity in tephropalynology relies on the comparison of pollen and tephra profiles. Both pollen and tephra move vertically through sediments—tephras are not simple homogenous layers but rather zones of high tephra concentration with sometimes complex three dimensional configurations (Dugmore and Newton 1992; Dugmore et al. 1996; Payne and Gehrels 2010), while similar processes also act on pollen (Clymo and Mackay 1987; Rowley and Rowley 1956). In peatlands, particles with different morphologies and densities may undergo differential taphonomy at three stages: (i) trapping by different vegetation types; (ii) initial post-depositional movement through the living vegetation and acrotelm peat; (iii) longer-term post-depositional movement as the vegetation and acrotelm peat decompose and enter the catotelm. The construction and presentation of tephra profiles is essential in tephropalynological studies. Studies in lakes would provide an interesting contrast to the current studies largely restricted to peatlands, but would bring a different suite of taphonomic problems, such as allochthonous sediments, differential sinking and sediment focusing (cf. Thompson et al. 1986; Boygle 1999; Edwards and Whittington 2001).

A disproportionate number of the existing studies have concentrated on the Hekla-4 eruption. We suggest that a wider range of eruptions should be investigated. It may be the most substantial tephra layer in the region, but the Hekla-4 eruption also occurred at the same time as a pre-existing period of environmental change, thus making impacts harder to identify (Hall 2003a). A particularly useful target would be the 1783 Laki eruption, for which there is abundant historical evidence for impacts on vegetation: are these represented in the pollen record? The chronology of such studies would not be straightforward, as Laki tephra has not been found in the British Isles and so the tephropalynological approach cannot be applied; very precise dating by other means would be required [early conifer planting might provide useful age markers (cf. Linnard 1971)]. The Laki eruption is, however, atypical of Holocene Icelandic eruptions and so other events should also be investigated. A wider range of sites should also be investigated, particularly in northeast Scotland and the Northern Isles as the areas closest to the Icelandic volcanoes and with the most substantial tephra layers (Bennett et al. 1992; Dugmore et al. 1995a, b).

The 2010 Eyjafjöll eruption has highlighted the susceptibility of modern European life to tephra deposition, even though it was not associated with widespread ecological impacts and was relatively small (Davies et al. 2010). The Laki historical records and evidence from large eruptions around the world suggest that eruptions may be associated with widely dispersed ecological impacts, with implications for agriculture, conservation and ecosystem services such as carbon sequestration (Gauci et al. 2008). Palynological efforts to identify such impacts in the Holocene remain worthwhile, even if previous results have been overwhelmingly negative. Well-designed studies are necessary to address these questions.

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