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Abstract: For the greater part of the last century, anthropogenic palynology has made a sustained contribution to archaeology and to Quaternary science in general, and pollen-analytical papers have appeared in Journal of Archaeological Science since its inception. The present paper focuses selectively upon three areas of anthropogenic palynology, enabling some assessment as to whether the field is advancing: land-use studies, archaeological site study, and modelling. The Discussion also highlights related areas including palynomorph identification and associated proxies. There is little doubt that anthropogenic palynology has contributed to the vitality of pollen analysis in general, and although published research can be replicative or incremental, site- and landscape-based studies offer fresh data for further analysis and modelling. The latter allows the testing of both palynological concepts and inferences and can inform archaeological discovery and imagination. Archaeological site studies are often difficult, but palynology can still offer much to the understanding of occupation sites and the discernment of human behaviour patterns within sites.

***Highlights (for review)**

- Anthropogenic palynology has for long been a major contributor to archaeology.
- Conventional land-use-scale studies continue to produce important new data.
- Archaeological site study remains productive.
- Modelling allows the testing of key ideas about the structure of landscapes.
- Palynomorph identification and associated proxies enable continued advances.

*Revision Notes

Dear Robin,

Please find copies of the referees' reports below. These are annotated **in bold text** to explain the changes we have made to the text.

We hope you now find this satisfactory.

Yours,

Kevin Edwards

**Reviewer #1: Text comments for Edwards et al. paper**

| | |
|---|---|
| Line 189 | 'interactions' should be 'interaction' to agree with 'has' - **Done** |
| Line 212 | 'Tweddle et al.' should be 'Tweddle & Edwards' - **Done** |
| Line 230 | 'Weinstein-Evron, 1987' is not in the bibliography - **Done** |
| Line 233 | '1992' should be '1994'? - **Done** |
| Line 242 | 'though' should be 'through' - **Done** |
| Line 269 | '2008b'should be '2008' - **Done** |
| Line 611 | 'Erlensson' should be 'Erlendsson' - **Done** |

Papers in the bibliography but not in the text – **all attended to**
Weinstein 1981
Sangster & Dale 1961
Sangster & Dale 1964
Plunkett 2009

This is a difficult type of paper to design, as the subject is huge and the space available is limited, therefore selection of examples and approach is inevitable and cannot be anywhere near comprehensive. Since it is 'anthropogenic palynology' however, I would like to see a little more discussion regarding improvements in the identification and interpretation of cultural/indicator pollen types, such as cereal-type for example.
**This has been done with a new paragraph added to the restructured Discussion.**

A useful additional reference in this regard would be

Tweddle JC, Edwards KJ, Fieller NRJ (2005) Multivariate statistical and other approaches for the separation of cereal from wild Poaceae pollen using a large Holocene dataset. Veget Hist Archaeobot 14:15-30.

and possibly also the work of Andersen and Joly.

Although many parts of the world are covered, I would also like to see something in other regions where important work is being done on human-land relationships and history, such as China. A reference such as

Atahan, P., Grice, K. and Dodson, J. 2007: Agriculture and environmental change at Qingpu, Yangtze delta region: a biomarker, stable isotope and palynological approach. The Holocene 17, 507-15.

might give a greater balance.

**We have added two additional paragraphs to the Discussion which broaden the geographical and methodological scope of the paper (e.g. covering cultivars, associated proxies, the Tropics, and genetics).**

Otherwise it is a very interesting paper that obviously uses the previous interests of the authors to illustrate the discussion, but makes some very important points regarding the discipline. The discussion seems rather short for such a wide topic. Could this not be expanded to address more aspects of the subject, and perhaps suggest where advances may be expected in the future, other than in modelling?

**The Discussion has been re-fashioned (see earlier comments). The material in the discussion section seen by the referees has now been partially restructured and some of it has been moved to a concluding section 6 ('Envoi').**

**Reviewer #2:** The paper gives an overview of the contribution of palynology to archaeology by focusing on three areas of research - land-use studies with focus on multiple palynological sites and identification of proxies such as non-pollen palynomorphs; studies of archaeological sites; and modelling approaches. By use of relevant examples, they present the potential of the different approaches for studies in the future, and highlight the development within palynology the recent years which may contribute to important new information for archaeology. The paper gives a good overview, it is well-written and I have only a few minor comments.

Lines 59-66/Table 1: Why not including 'Vegetation History and Archaeobotany' in Table 1? Since this journal has a focus towards archaeology it may be interesting to compare with Journal of Archaeological Science.

**The Table purposely considers only the general Quaternary outlets (with *JAS* as a comparison). As stated in the text, "there are journals for which palynology is a strength or even dominant, most notably *Review of Palaeobotany and Palynology*, *Grana* and *Vegetation History and Archaeobotany*" – and to have included them would have given a very unbalanced view as palynology is a mainstay of all of them.**

Lines 83-86: Is the aim of this sentence to focus on the questions that are raised - from stand scale reconstructions to large-scale reconstructions? Or is it meant to be towards different information given from sites of different sizes? Davis et al. 2014 use the European Pollen Database (relevant to line 98). They use several sites for large-scale vegetation formations, but the sites themselves may be small (and varying). Use another reference if the size of the investigated basin is a point.

**The aim was to communicate that the spatial scale of vegetation reconstruction possible through pollen analysis will vary according to the size of the site under investigation. We have changed the text to more clearly reflect this, adding some citations to papers that consider the effects of basin size on pollen source area. We have removed the reference to Davis et al. 2014, which is no longer relevant in the context of the revisions.**

Lines 161-171 and Fig. 5: Rumex acetosella is present and expands later than around AD 1000 when the coprophilous fungal spores and charcoal increase. Do you have an explanation for this?

**The delayed response in the expansion of *R. acetosella* at Sissarluttoq (i.e. around 100-150 cal yr after the AD 985 *landnám*) is somewhat anomalous for the region as a whole. The lag may reflect the spread of the plant to this site following its introduction at *landnám* at another farmstead nearby (as discussed in Schofield et al 2013). We have developed this argument for the reader at the appropriate point in the text.**

Line 212: Tweedle et al. or Tweedle and Edwards (line 908)? - **Done**
Line 268: Mercuri, 2008 - **Done**

Lines 291-296: I think it is a bit misleading to write that the work connected to the POLLANDCAL network resulted in development of the Landscape Reconstruction Algorithm. Sugita's simulation approach (1994) existed and made the basis for the POLLANDCAL network.

**This is quite correct, that Sugita was working on the LRA before the POLLANDCAL network was established. We have made alterations to the text to clarify that the LRA was not the direct product of POLLANDCAL.**

Figure 9, figure legend: A reference to the original figures - modified from..., should be included.

**Reference to Bunting and Middleton (2009) has been included within the figure caption.**

# Moving forwards? Palynology and the human dimension

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**ABSTRACT**

For the greater part of the last century, anthropogenic palynology has made a sustained contribution to archaeology and to Quaternary science in general, and pollen-analytical papers have appeared in *Journal of Archaeological Science* since its inception. The present paper focuses selectively upon three areas of anthropogenic palynology, enabling some assessment as to whether the field is advancing: land-use studies, archaeological site study, and modelling. The Discussion also highlights related areas including palynomorph identification and associated proxies. There is little doubt that anthropogenic palynology has contributed to the vitality of pollen analysis in general, and although published research can be replicative or incremental, site- and landscape-based studies offer fresh data for further analysis and modelling. The latter allows the testing of both palynological concepts and inferences and can inform archaeological discovery and imagination. Archaeological site

studies are often difficult, but palynology can still offer much to the understanding of occupation sites and the discernment of human behaviour patterns within sites.

*Keywords:* palynology; land-use history; on-site studies; modelling

## 1. Introduction

Since the employment of pollen analysis in human contexts over half a century ago (Firbas, 1937; Iversen, 1941; Fægri, 1944; Godwin, 1944), anthropogenic palynology has made a sustained contribution to archaeology, archaeological science and the wider realms of palaeoecology and Quaternary science (Behre, 1986; Birks et al., 1988; Edwards and MacDonald, 1991; Bell and Walker, 2004; Roberts, 2014). From its first volume, pollen analysis has featured in the pages of *Journal of Archaeological Science* (Dimbleby and Evans 1974; Greig and Turner 1974) – perhaps not a total surprise given that soils palynologist Geoffrey Dimbleby was a first editor – and this has continued. The number of papers containing a sole or substantial pollen content remained relatively constant over the first 20 years of the journal's life and has increased since then (Fig. 1a-b); however, allowance must be made for the increase in the number of all archaeological science articles published over time (Fig. 1c), which itself reflects the health of the field in general. Caveats clearly apply to the use of such data and the mode of extraction (see the caption to Fig. 1), but palynology obviously represents a recognisable component in the journal's profile and, indeed, following Dimbleby, two of the outlet's editors (Kevin Edwards 1983-92, and Chris Hunt 2011-14) have also been palynologists as have other members of the editorial board.

This is not the place to produce an in-depth analysis of the metrics associated with palynological papers within the *Journal of Archaeological Science*. As intimated, palynology is a mainstay of palaeoecology and Quaternary science, and journals covering these fields contain impressive numbers of palynological papers in their own right (Table 1). While many of these articles are concerned with anthropogenic topics, or are of relevance to human activity, that cannot be said to apply to the majority of them. In addition, there are journals for which palynology is a strength or even dominant, most notably *Review of Palaeobotany and Palynology*, *Grana* and *Vegetation History and Archaeobotany*.

We focus selectively upon three areas of anthropogenic palynology which enable us to assess whether the field is advancing. This paper does not claim to be comprehensive and there are areas which are not covered here at all, even if they could have relevance to the practice of humanly-related palynology (e.g. automated pollen counting [Holt and Bennett, 2014], genetics [Parducci et al., 2013], many related proxies [O'Brien et al., 2005; Meadows, 2014], and, of course, dating issues [Whittle et al., 2011]). Similarly, we barely address the issue of microscopic charcoal and fire which have a long and continuing history in palynology (cf. Swain, 1973; Patterson et al., 1987; Bradshaw and Sykes, 2014; Sadori et al., 2015). It does, however, cover key areas which could contribute to priority research questions identified for palaeoecology (Seddon et al., 2014).

## 2. Can traditional land-use employments of palynology still inform and surprise us?

The investigation of the past relationship between vegetation and people has classically involved the study of pollen and associated proxies (e.g. fungal spores, microscopic charcoal) preserved within stratified, waterlogged deposits such as lake mud and peat (Fægri et al., 1989). The spatial scale of the vegetation reconstructions possible through this method are highly dependent upon the size of the pollen site under investigation; put very simply, small diameter sites such as woodland hollows will provide information about fine-scale vegetation patterns immediately around the sampling location, whilst large lakes record the regional picture (cf. Jacobson and Bradshaw 1981; Prentice 1985; Sugita 1994; Bradshaw 2007). The conventional methodological approach has been to make inferences based upon the analysis of a single core that is deemed by the investigator to be representative of changes occurring throughout the landscape in question. Research into multiple pollen profiles spread across the same site (e.g. Edwards, 1983; Waller, 1998), or combining data across a network of locations (e.g. Tipping, 2010; Ledger et al., 2014), whilst time consuming, can offer more precise details about the spatial patterning in vegetation and the impact of prehistoric society on land cover (e.g. Lechterbeck et al., 2014; Woodbridge et al., 2014).

Advances in the modelling and simulation of vegetation using practical tools that incorporate knowledge about pollen production, transport and deposition (e.g. Sugita, 2007a, 2007b; Gaillard et al., 2008), plus the widening availability of an expanding number of large pollen datasets though on-line databases such as the European Pollen Database (http://www.europeanpollendatabase.net/; Fyfe et al., 2009) and Neotoma (http://www.neotomadb.org/), mean that the discipline may grow to rely less upon the 'traditional' field- and laboratory-based empirical studies described above for all its answers (see section 4 below). Nevertheless, conventional pollen analytical investigations still continue to play a key role within the discipline, not least in the empirical testing of models and simulations, the filling of gaps in the spatial and temporal coverage of vegetation histories, refining existing patterns, and challenging ideas and knowledge. This can be exemplified through a brief examination of selected aspects of recent pollen-analytical research from some of the North Atlantic islands colonised by Norse/Viking settlers during the late first millennium AD (Fig. 2).

In the Faroe Islands, pollen-analytical studies have played a crucial role in the re-examination of the timing of first human settlement. On the basis of saga literature and the archaeological record, the initial settlement ('*landnám*') of this island group has normally been ascribed to the arrival of Norse settlers sometime during the early 9$^{th}$ century AD; this being despite evidence to the contrary appearing in another contemporary literary source – *De Mensura Orbis Terrae*, written around AD 825 – in which the Irish monk, Dicuil, stated that anchorites had reached lands fitting the description of the Faroe Islands in advance of the 'northmen pirates' (Tierney, 1967; Dugmore et al., 2005). Jóhansen (1971) was the first to present palynological evidence for a possible pre-Viking presence, though the timing (given as ~AD 600-700) surrounding his discovery of *Avena* (cf. oats) pollen in a profile from 'ancient Celtic fields' disturbed by burrowing puffins on Mykines (Jóhansen, 1979) was later brought into question (e.g. Buckland et al., 1998). Yet the early cultivation of cereals was also subsequently indicated at Eiði on the island of Eysturoy (Hannon et al., 2005) and especially at Hovsdalar, Suðeroy, where optimising methods for the detection of cereal-type pollen grains revealed a pollen curve for *Hordeum*-type (barley) extending back to ~AD 560 (Edwards et al., 2005a, 2005b). Most recently, the discovery of carbonised barley grains appearing in peat ash of anthropogenic origin at Á Sondum on the island of Sandoy, and radiocarbon-dated to the 4-6$^{th}$ centuries AD (Church et al., 2013; Fig. 3), delivers strong archaeological evidence for an early human presence that offers justification for the interpretation arising from the pollen-analytical evidence. This 'process' finds echoes in palynological inferences surrounding the determination of a hunter-gatherer occupation of certain areas within the Northern and Western Isles of Scotland, which, for a long time, had no proven cultural reality (Gregory et al., 2005; Edwards, 2009).

In Iceland – where Norse settlement is dated to around AD 870 – an important landscape-scale question that palynologists have been addressing is the spatial extent of tree birch (*Betula pubescens*) woodland at the time of colonisation and how this became diminished following the arrival of people. Common perception of past woodland coverage in Iceland has been heavily influenced by a comment made by Ari the Wise in the 12th century *Íslendingabok* (Book of the Icelanders) which stated that woodland at the time of *landnám* stretched from the mountains to the seashore (Benediktsson, 1968). This is seemingly borne out by some of the earlier studies (e.g. Einarsson, 1963; Hallsdóttir, 1987) in which pollen diagrams typically demonstrate sharp declines in birch woodland during the 10th century which have been directly linked to clearance. Not unexpectedly perhaps, this seems to be an over-simplification of the picture, and as the number of pollen-analysed sites has expanded, it has become clear that many exposed high altitude and coastal locations have always been very open in character (Erlendsson et al., 2009). Furthermore, whilst human impact at *landnám* did undoubtedly lead to an overall decline in woodland, the rates and patterns of reduction are more variable than was first envisaged. For example, pollen data produced by Lawson et al. (2007) for the inland district of Mývatnssveit shows a steady regional decline in *Betula* pollen over a period of ~400 years following settlement, demonstrating a slow drawdown on the woodland resource, possibly involving active management, rather than the rapid destruction of otherwise valuable birch woodland (Fig. 4). This led the authors to speculate that substantial patches of birch may have survived in many areas long after *landnám*, but are simply not being widely detected because the pattern of sampling has predominantly focused around the farms where human impacts would presumably have been most intense.

The Norse diaspora led not only to the dispersal of people across the North Atlantic but also the deliberate and accidental movement of flora and fauna (cf. Sadler and Skidmore, 1995). Pollen analysis provides a powerful tool for tracing the introduction and spread of non-native plants, and has been used in Greenland to advance the debate regarding what constitutes the 'Old Norse' (anthropochorous) element within the modern flora. One of the most striking features noted by Fredskild (1973, 1988) in his pollen diagrams from Qassiarsuk, south Greenland, is the appearance and expansion of *Rumex acetosella* (sheep's sorrel) after *landnám* (AD 985), leading him to conclude that the species was introduced by the Norse settlers. More recently, palynological studies representing a network of sites around Norse farms located in the former Eastern Settlement of Greenland have allowed the production of a series of maps at regular (100 year) intervals that trace the dispersal of the plant through the wider landscape and confirm its status as a key biostratigraphic marker for settlement (Schofield et al., 2013). The synthesised data do, however, reveal some subtleties. At certain locations (e.g. Sissarluttoq; Fig. 5) the rise in *R. acetosella* pollen following *landnám* is delayed, while in another instance the pollen from the plant is absent. This might indicate that the plant was introduced – presumably from Iceland – at only selected locations from which it subsequently spread rapidly to most of the other farmsteads. The variable abundances of *R. acetosella* pollen depicted at sites on the maps also stimulate debate about what effect any differences in the size, function or role of farms might have had on creating suitable habitats for the plant to flourish.

The impact of Norse colonists across each of the North Atlantic island environments can be recognised through a widely repeatable palynological 'footprint' for human settlement in pollen diagrams (Edwards et al., 2011a). A defining aspect of this signature (Fig. 5) is an increase in dung (coprophilous) fungal spores reflecting the introduction of domesticated grazing animals (primarily sheep, cows and goats) to landscapes as part of the settlement process (cf. Schofield and Edwards, 2011). Since the last major review of Quaternary pollen analysis (Seppä and Bennett, 2003), significant progress has been made with the identification, taphonomy, indicative value and quantification of such non-pollen palynomorphs (NPPs) as part of the wider palynological method, and this has now become an important aspect of investigations into land-use history. In particular, the analysis of fungal spores which are typically present in sample residues alongside pollen, but were for long ignored by palynologists (especially *Sporormiella*-type, *Sordaria*-type and *Podospora*-type), can be demonstrated as a powerful proxy for tracing the past impacts of herbivory (e.g. van Geel et al., 2003; Blackford and Innes, 2006; Cugny et al., 2010; Feeser and O'Connell, 2010; Schofield and Edwards, 2011; Baker et al., 2013). New advances in the extraction and amplification of ancient DNA (aDNA) from sedimentary sequences are likely to proliferate into archaeological science to aid identification of grazing animals (e.g. Giguet-Covex et al., 2014). Applying aDNA to existing sequences with clear pollen and NPP indicators for human management may result in great advances in understanding how people and animals shaped their landscapes.

Human-environment interaction in the Anthropocene has been identified as one of six key themes linked to priority research questions in palaeoecology (Seddon et al. 2014). The case studies presented from the North Atlantic arena demonstrate that traditional studies of land-use history through pollen analysis can continue to play a central role in advancing our understanding of when human activities 'began altering ecosystems at globally relevant scales and how ecosystems responded in these human-mediated landscapes' (ibid. p. 259).

## 3. Palynology of archaeological sites

Archaeological sites present many problems, but also opportunities, for the understanding of past human environments and activities. In northern latitudes at least, soil palynology represents the most frequently adopted approach to the pollen-analytical investigation of archaeological sites. There is an extensive body of published research in the area and it would be invidious not to note Dimbleby's long and substantial contribution (summarized in Dimbleby, 1985) that had its beginnings in soil pollen methodology (Dimbleby, 1957, 1961a, 1961b) and an appreciation of landscape-scale human modification (Dimbleby, 1962). This work has laid a foundation for much subsequent research in a variety of archaeological contexts (e.g. Bakker and Groenman-van Waateringe, 1988; Segerström, 1991; Kelso, 1994; Tipping, 1994; Edwards and Whittington, 1998; Whittington and Edwards, 1999; Groenman-van Waateringe, 2011).

The terrestrial deposits which characterise many archaeological sites are reflective of taphonomic pathways which are far from the relatively well known systems typical of lakes and mires (Tweddle and Edwards, 2010). By their very nature, archaeological sediments are liable to have been disturbed and are typically heterogeneous, combining a mixture of materials from different sources (Greig, 1981). This applies, for example, in the case of artificially accreting soils (plaggens or anthrosols), whose pollen content may be derived from the *in situ* vegetation (crops and weeds rooted in the soil itself), additions of waste (turves, peat, straw, animal dung, etc.) to fields from house or byre, plus the pollen rain from the surrounding vegetation communities and the background airborne component (Groenman-van Waateringe, 1992; Buckland et al., 2009; Donaldson et al., 2009; Ledger et al., 2015; Fig. 6). The environmental conditions under which pollen is preserved on archaeological sites may, in many cases, also be sub-optimal (i.e. drier and less acidic) when compared with the natural depositional contexts favoured for 'conventional' studies (section

2). As a consequence, palynologists working on archaeological sites must contend with pollen depositional biases, and often low total pollen concentrations and poor pollen preservation (Bottema, 1975; Hall, 1981; Hunt, 1994; Weinstein-Evron, 1994; Lebreton et al., 2010), although much methodological work has focused upon understanding these issues (e.g. Sangster and Dale, 1961, 1964; Havinga, 1967; Davidson et al., 1999; Bunting and Tipping 2000; Tipping 2000).

Important taphonomic work has explored the representativeness and reliability of palynomorph assemblages from caves (Weinstein, 1981; Weinstein-Evron, 1994; Coles et al., 1989; Diot, 1991; Genty et al., 2001; Simpson and Hunt, 2009; Fig. 7) and fluvial sites (Brush and Brush, 1972; Fall, 1987; Hunt, 1994). Cave deposits show consistent taphonomic biases where an entrance flora is present (Coles and Gilbertson, 1994) and where animal vectors are prolific (Hunt and Rushworth, 2005), but otherwise, pollen floras in caves reflect closely the pollen rain within a few kilometres of the sampling site. In some parts of the world, including central France, southeastern Spain, peninsular Italy and Libya, a substantial proportion of our understanding of Middle and Late Quaternary vegetation and associated environments, comes from caves. Such geographical areas cannot always furnish suitable long lake and peat bog records and this is an example of how archaeological sites can be useful in plugging significant palynological gaps.

Processes such as suffusion, recycling and bioturbation can relocate material through archaeological deposits and soils, and these processes are a consistent cause for concern for archaeopalynologists. This problem can sometimes be addressed by careful examination of the condition of pollen grains preserved in the sediment. Intrusive or recycled pollen will often be preserved in a visibly different condition to *in situ* organic-walled microfossils. Ultraviolet fluorescence microscopy offers an underused method to assess the stratigraphic integrity of pollen assemblages where mixing is suspected (Hunt, 1998; Yeloff and Hunt, 2005). With the advent of digital image analysis, this technique can be applied systematically with little operator error (Hunt et al., 2007a). Pollen fluoresces in the visible wavelengths under UV illumination. As pollen 'ages' taphonomically, the intensity of fluorescence diminishes and colour progresses from blue, through yellow, to orange, red and finally brown. Recycled material appears less bright and further towards the red end of the spectrum than *in situ* material, whereas intrusive (modern) grains show as blue, and thermally mature (burnt) material as intense light blue (ibid.) (Fig. 8).

It should be stressed that palynology is significantly more than basic pollen and spore analysis. Organic particulates are generated by many natural processes and human activities. Many of these particulates preserve well and are amenable to analysis using the palynofacies technique (Hunt and Coles, 1988). Thus the feeding of crop residues to sheep or goats in a Libyan farmstead led to characteristic palynofacies and pollen assemblages (Hunt et al., 2001) and humanly-set fires within the Great Cave of Niah in Sarawak, Malaysian Borneo, resulted in characteristic thermally-mature amorphous matter, caused by the heating of cave sediments (Hunt et al., 2007b). In Ludden Dene, Halifax, UK, very distinctive coppicing, fire and regeneration cycles are visible in pollen and palynofacies signatures from charcoal-burning hearths (Ibbetson, 2011).

From earlier beginnings (Turner, 1965; Göransson, 1986; Edwards, 1993), there continues to be a productive development of insights and methods (Mercuri, 2008; Waller et al., 2012; Woodbridge et al., 2014) within the palynology of archaeological sites. Yet in a world where traditional activities and land-use patterns are vanishing before the onslaught of globalisation, there is still an urgent need to study ethnopalynological patterns caused by a wide range of actions before these disappear forever. These include aspects of landscape management, and agricultural, industrial and domestic practices.

## 4. Modelling vegetation cover from pollen data

Quantification of vegetation cover from pollen-analytical data has been a long-desired goal of all groups who use such data. The use of pollen to address archaeological questions such as the contextual environmental conditions for a particular site or type of site (e.g. Brown et al., 2011), or the scale of woodland clearance during European prehistory (e.g. Fyfe et al., 2014), requires the ability to transform pollen data into a meaningful quantity beyond the relative abundance of different pollen taxa. This is hampered by several factors, notably the differential production of pollen by different plant species and the varying spatial scale of representation of pollen sequences. In essence, the relationship between pollen proportions and the abundance of the source plants in the vicinity of a particular site is not linear (Sugita et al., 1999).

Approaches to the transformation of pollen to vegetation abundance began in the 1960s (Davis, 1963) and were developed over subsequent decades (Andersen, 1970; Prentice and Parsons, 1983; Prentice, 1985). A resurgence of interest in such approaches was triggered in the early 2000s with the development of the Pollen-Landscape Calibration (POLLANDCAL) network (Gaillard et al., 2008). Significant advances have been made in the transformation of pollen proportions to estimated plant abundance, resulting in the development of a 'Landscape Reconstruction Algorithm' (LRA), as described by Sugita (2007a, 2007b). A major advantage of the LRA is that the spatial scale of representation is formally recognised, and indeed is included within the output of the approach, in what is described as the 'relevant source area of pollen' (RSAP). This is best thought of as the distance at which background pollen loading (the regional pollen rain) is constant between sites in a region, and is formally defined in modern pollen-vegetation studies as the distance beyond which the correlation of pollen to vegetation abundance does not change or improve (Sugita, 2007b).

The modelling approach has been described and discussed at length elsewhere (e.g. Sugita 2007a, 2007b; Gaillard et al., 2008; Sugita et al., 2010; Nielsen and Odgaard, 2010; Fyfe et al., 2013; Marquer et al., 2014), but it marks perhaps one of the most significant advances in the analysis of pollen data in recent decades. The LRA comprises two components (Fig. 9). The REVEALS model estimates taxon abundance within the broad region (50-100 km radius around a site) using pollen count data from sites that are taken to be representative of the regional pollen rain (e.g. large lakes). This regional taxon abundance is then used as one input parameter for the LOVE model, which subtracts the background component to estimate vegetation abundance within the source area of target (smaller) sites that are more representative of local plant communities. The LRA requires not only pollen count data from sites that are regional and local in character, but also estimates of the relative pollen productivity (RPP) of the taxa being quantified (Broström et al., 2008), and figures for the fall speeds of the different pollen types involved. The approach has, to date, been evaluated using modern pollen-vegetation comparisons in both northern Europe and North America (e.g. Hellman et al., 2008; Sugita et al., 2010) and much recent work has been focused on specific assumptions inherent within the models. The global application of this model-based approach is limited by the availability of PPEs (pollen productivity estimates) from regions of interest, and much work is currently in progress or being initiated to develop these parameters from areas beyond northwest Europe and North America, such as southern Africa (Duffin and Bunting, 2008), China (Xu et al., 2014) and Greenland (Bunting et al., 2013).

The output of the LRA is thus an estimate of plant abundances within a broad region, and within a given radius of the target pollen site. Preliminary results of the application of the LRA to pollen data from Exmoor, southwest Britain, provide insights into spatial patterning of upland vegetation (Fig. 10). It is possible to distinguish *Calluna*-, Poaceae- and Cyperaceae-dominated moorland communities and to estimate how much woodland persisted into the medieval period. Results from the REVEALS model have been interpreted to suggest that landscapes were more open in the past than had previously been assumed from pollen proportions alone (Soepboer et al., 2010; Nielsen et al., 2012; Fyfe et al., 2013; Marquer et al., 2014; but see Davis et al., 2015). Application of the full LRA to landscape research is still in its infancy, with few published studies (Nielsen and Odgaard, 2010; Fredh et al., 2012; Cui et al., 2013; Hultberg et al., 2015), none of which specifically target archaeological questions *per se*, and the arrangement of plants *within* the RSAP of a target site (i.e. maps of vegetation cover) cannot yet be determined. One difficulty that still needs to be overcome is that different vegetation patterns may result in the same pollen loading at a particular place in the landscape, leading to problems of equifinality (Caseldine et al., 2008; Bunting and Middleton, 2009).

An alternative, complementary, approach to the LRA has been to tackle the problem in reverse, by starting with hypothetical vegetation arrangements in a landscape (managed within a GIS) and calculating pollen loadings at selected points or locations (Figs. 9, 11). These simulated pollen loadings can then be compared to empirical pollen count data in order to assess the plausibility of hypothetical vegetation arrangements (e.g. Caseldine and Fyfe, 2006; Fyfe, 2006; Stedingk and Fyfe, 2009). This has been formally described as the Multiple Scenario Approach (MSA: Bunting and Middleton, 2009). Through this method, 'swarms' of vegetation arrangements can now be modelled and compared to empirical data, to assess the 'best fit' through a data/model comparison. The MSA still requires PPEs, estimates of the fall speed of pollen and modelling of a sufficiently large landscape so that the background pollen component is included, but it does offer palynologists a means of testing, rejecting and/or validating different landscape scenarios (Tipping et al., 2009).

Both the spatial and temporal scale of pollen data is of critical importance in accurately modelling past vegetation. As described above, the LRA first models regional vegetation (using REVEALS) within a radius of 50-100 km around the pollen site, and then moves on to consider the 'local' vegetation (using LOVE). The spatial scale of 'local' vegetation is dependent on a range of factors, including the size of the sampling site, and the physical arrangement of plants in the landscape (Bunting et al., 2004). It is important that the scales chosen for vegetation reconstruction match the hypothesised impact of people in the landscape: for instance, small-scale ephemeral woodland clearance is unlikely to be distinguished in a regional analysis. The temporal scale of vegetation disturbance is also important. Much recent work around the impact of early Neolithic peoples (e.g. Whittle et al., 2011; Whitehouse et al., 2014) has emphasised the short biographies of monument complexes. Unless pollen sequences are sufficiently temporally resolved (through high-resolution pollen analysis; cf. Turner and Peglar, 1988; Innes et al., 2004; Edwards et al., 2008) and precisely dated, modelling work is unlikely to be helpful in detailing the impact of short-lived 'events' in the archaeological record. The LRA also necessitates a shift in the sampling framework for landscape reconstruction. It is insufficient to have a narrow focus on a small number of pollen sites which have local pollen source areas, as modelling of the wider regional vegetation is also essential. Sugita et al. (2010) have demonstrated that groups of small sites can be used to derive a regional average for vegetation cover, but few regions across Europe, or indeed beyond, possess dense networks of sites which are either sufficiently well resolved or with appropriately detailed chronologies to allow such an approach to be successful at this time.

Where does this currently leave us, with respect to using a pollen modelling approach to advance archaeological knowledge? Caseldine et al. (2008) and Fyfe et al. (2010) considered the role of such research in integrated projects and the usefulness of the output. They were at pains to stress that the output is a virtual reconstruction of the past that can be considered plausible, whether derived from pollen data (e.g. the LRA) or tested against it (the MSA). Whilst the term 'landscape' has been used here, the output of either the MSA or the LRA is not a landscape reconstruction, but might be better described as a pseudo-landscape, a partial and credible representation of a fraction of the lived experience of communities who had a mutual relationship with the plants around them. Within the constraints of model robustness and data availability, the modelling approach allows us to reject, if necessary, fundamental ideas about the structure of prehistoric or historical landscapes; the recognition of the extent of openness across northwest Europe through application of the REVEALS model is an excellent example of this which should lead to reconsiderations of the structure of Mesolithic environments and interactions (Nielsen et al., 2012; Fyfe et al., 2013; Marquer et al., 2014).

Visualisation of plausible pseudo-landscapes, particularly of contrasting vegetation arrangements that might produce a similar pollen loading at a single site (e.g. Winterbottom and Long, 2006), may play an important part in the 'thinking through', or (re-)interpretation of archaeological site data, and thus become part of a new interpretive toolset.

## 5. Discussion

There is no doubting that anthropogenic palynology has contributed great vitality to the science of pollen analysis. Although published research can be replicative or incremental, it remains the case that site- and landscape-based studies continually offer fresh data for further analysis and modelling.

The future of palynological analysis on archaeological sites is promising, albeit a difficult and frequently frustrating exercise. Palynology can offer much to the understanding of occupation sites, both in terms of the wider vegetational and environmental contexts and in discerning patterns of human behaviour within sites. As stated earlier, scale is of key importance in any modelling work that attempts to address human-environment relationships. If archaeological site palynology is going to share in this aspect of the field (and sharing is not necessarily mandatory for advancement of the sub-discipline), then the up- and down-scaling of models may represent a fertile area of development (cf. Mercuri et al. 2015, p. 4). On- and off-site palynology will undoubtedly continue to play a major role within integrated multi-proxy analyses, and the advances that can be gained from the application of a suite of complementary methods that already include NPPs, traditional archaeobotany and micromorphology, are likely to expand out to include innovative new approaches such as biomarkers (Linseele et al., 2013), sedimentary geochemistry (e.g. D'Anjou et al., 2012) and aDNA (Giguet-Covex et al., 2014).

The analysis of NPPs has now become routine within many palynological studies and further advances should be anticipated. Baker et al. (2013) note that certain coprophilous fungal spores (notably *Sporormiella*-type) can now be regarded as clear bioindicators for the presence of grazing animals within the landscape, but some doubt remains about other ‘coprophilous’ types which are often interpreted in the same manner. An empirical link between the numbers of coprophilous fungal spores preserved in peats and lake muds, and livestock numbers/densities, still needs to be established (Raper and Bush, 2009), while further testing is required to confirm the extent to which different NPPs can be linked specifically to the dung of certain animals or groups of herbivores (e.g. Richardson, 2001).

Although there is exhaustive high-quality monographic documentation of economically-useful plants in some tropical regions (for instance Herrera and Urrego, 1996), global coverage is uneven. In island SE Asia for example, the range of subsistence plants is vast and many either produce totally undiagnostic pollen (e.g. *Oryza* [rice]), or are reproduced vegetatively and do not flower (e.g. many *Dioscorea* spp. [yams]), or generate pollen which does not preserve (cf. *Musa* spp. [bananas]). One avenue of research in this case might be to investigate the weed floras and ancillary plants associated with cultivation systems. Monocultures are typical in conventional Western farming, but are unknown within many tropical systems, where complex polycultures, often involving many perennial plants, are practised. In some cases, long-established forms of arboriculture/forest management produce economically useful plants (Hunt and Rabett, 2014). Many of these systems are threatened by logging and mineral extraction and investigation is urgently necessary to identify their palynological signature.

When it comes to the identification of key subsistence plants within anthropogenically-modified plant communities, then palynology is unlikely to be as precise as macrofossil analysis (Birks and Birks, 2000; Dickson and Dickson, 2000; Bosi et al., 2015). The determination of Cerealia pollen grains especially remains a contested topic (Edwards and Hirons, 1984; Göransson, 1986; Edwards, 1989; Poska and Saarse, 2006; Behre, 2007; Brown, 2007; Tinner et al., 2007), but there is no doubting that the recording of cereal-type pollen grains has raised many questions, some of which have been verified by archaeobotany (Church et al., 2013; Edwards, 2014; Henriksen, 2014). Pollen genetics may eventually assist in resolving debates and uncertainties, as well as revealing new research horizons. Meanwhile, just as it has done since the early days of palynology (Firbas, 1937; Grohne, 1957; Beug, 1961, 2004; Andersen and Bertelsen, 1972**.** Andersen, 1979; Köhler and Lange,1979), advances in the identification of cereal – morphological, statistical and methodological – continue (Edwards and McIntosh, 1988; Edwards et al., 2005b; Tweddle et al., 2005; Joly et al., 2007; López-Merino et al., 2015), while approaches being developed for Poaceae differentiation may also assist in this (Mander et al., 2013, 2014).

Moving beyond cereals, uncovering evidence for the cultivation of plants through pollen analysis continues to prove difficult in many cases due to the restricted level of taxonomic precision which can be achieved through routine counting using a transmitted-light microscope. A fundamental problem is the separation of the pollen of crop plants from that of other species within the same genus or family where these include several taxa that inhabit different natural and cultural environments (the Fabaceae being a case in point). In addition, of those cultivated plants which can be confidently identified (e.g. *Fagopyrum* [buckwheats], *Linum usitatissimum* [flax], *Vicia faba* [broad bean]), many are low pollen producers (Behre, 1981) and this further reduces their visibility in the palynological record. Recent advances have been made, however, with the detection of woodland management techniques. For example, modern pollen-vegetation studies in British woodlands have demonstrated that pollen production for *Corylus avellana* (hazel) is significantly higher in the early years after coppicing (as has long been surmised), yet flowering of *Alnus glutinosa* (alder) and *Tilia cordata* (lime) is supressed under the same conditions (Waller et al., 2012). In the tropical Americas, methodological developments in the concentration of pollen of important cultigens (e.g. *Mahinot esculenta* [manioc], *Ipomoea batatas* [sweet potato] and *Zea mays* [maize]) have made recognition of cultivation more reliable. Large pollen types (>53 microns) that are typical of cultivars are separated from the rest of the pollen sample using an additional sieving stage (Whitney et al., 2012), and then identified through rapid scanning of the coarser fraction, whilst the fine fraction is counted as usual. Major advances in the identification of pre-Columbian agriculture in the Amazonian basin have resulted through the enhanced ability to identify the key crops from a combined palynological and phytolith approach, from both archaeological sites and adjacent wetlands (Mayle and Iriate, 2014; Whitney et al., 2014).

## 6. Envoi

As we approach the centenary of Lennart von Post's public demonstration of the utility of pollen analysis (von Post, 1916; Manten, 1967), it is instructive to reflect upon several key issues of relevance to anthropogenic palynology as much as to the parent discipline. Once the field equipment and basic laboratory infrastructure are in place, it is a relatively low-cost science, dependent largely on associated fieldwork funding. By the same token, its best practitioners need to be highly skilled as taxonomists and as ecologists in the widest sense (embracing plant, human and landscape ecology). Apart from obvious collaborations with archaeologists and those working in allied environmental disciplines, palynologists, increasingly, must either be adept at, or able to join forces with statisticians and modellers. If they have not come up through the ranks of empirically-based palynology, such valued co-workers may not be especially knowledgeable concerning the strengths and weaknesses of palaeoecology, and this puts the onus on the palynologist to be especially vigilant and not to become unreasonably transported by the 'wonders' of ungrounded data manipulation.

Back in 1967, limnologist Ed Deevey observed (p. 65):

> Von Post's simple idea, that a series of changes in pollen proportions in accumulating peat was a four-dimensional look at vegetation, must rank with the double helix as one of the most productive suggestions of modern times.

It seems to us that there has been no diminution in the quantity, nor, arguably, the quality of output within the field. We may have concerns about the ability of palynologists and research colleagues to be fully cognizant with the explosion of literature, but these may be the perpetual worries of middle- and late-career academics.

The archaeologist Stig Welinder (1988, p. 129) commented somewhat forlornly that:

> Pollen analysis is a science fascinatingly devoid of epistemological theory compared to modern archaeology.

– but we would adopt a more positive perspective. After all, the purpose of archaeological science might be seen as the use of science to inform archaeological enquiry, and this is most usefully based in reality, however determined, prior to the use of derived information in the service of advanced conjecture, theory, quantification or modelling. For its part, palynological modelling, anthropogenic or otherwise, provides a fresh lens through which to view and test both palynological concepts and inferences and, by extension, to inform archaeological discovery and imagination.

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We are delighted to share in this celebration of Richard Klein's contributions to this journal and the discipline of archaeology. Such studies as *Quaternary Extinctions: a Prehistoric Revolution* (1989), *The Human Career: Human Biological and Cultural Origins* (1999) and *The Dawn of Human Culture* (2002) speak to us as palaeoecologists as much as they speak to archaeological science and to archaeology more broadly. We are also happy to acknowledge the support of two anonymous referees.

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**Figure captions**

Fig. 1. Data relating to palynological publications (n = 211) contained in *Journal of Archaeological Science*, 1974-2014. Data were extracted using the advanced search facility within the Elsevier home page of the journal, searching for ‘pollen’ or ‘palynology’ within title, abstract or keywords of articles, review articles and short communications: (a) number of palynological papers within the journal per annum; (b) total number of papers within the journal per annum; (c) palynological papers as a percentage of total papers within the journal per annum.

Fig. 2. Map showing countries mentioned in the text (with the exception of Sarawak).

Fig. 3. The site of Á Sondum, Faroe Islands, is located beneath the grass-roofed building at the bottom right of the picture (photograph by K.J. Edwards). The lower diagram shows calibrated $^{14}C$ dates for archaeological contexts from Á Sondum compared to the time of appearance of *Hordeum*-type pollen from Hov (see text and Church et al., 2013 for further details). A – lower peat ash patch; B – upper peat ash patch; C – longhouse external midden; D –longhouse central hearth; E – *Hordeum*-type pollen percentages from the site of Hov (pollen sum c. 500 total land pollen (TLP); F – *Hordeum*-type pollen percentages from Hov, optimised pollen sum estimated at c. 1500 TLP.

Fig. 4. *Betula pubescens* (downy birch) growing on lava fields close to Mývatn, northeast Iceland (photo by K.J. Edwards). The graph on the right shows pollen percentage data for *B. pubescens* from Helluvaðstjörn, with confidence intervals at the 2σ level (see text and Lawson et al., 2007 for further details).

Fig. 5. Photograph at the top of the diagram shows a Norse building at Sissarluttoq, Eastern Settlement, Greenland (photo K.J. Edwards). The palynological spectra (selected taxa only) in the lower diagram span the time of Norse settlement (*landnám*) and come from lake mud contained in a small pond beside the ruins at Sissarluttoq. The introduction of people and domesticated animals into a pristine environment around AD 1000 (SSQ-1/2 zone boundary) resulted in a reduction in pollen from shrubs (e.g. *Salix*) and grazing-sensitive herbs (e.g. Apiaceae), and an expansion in anthropochores (e.g. Lactuceae), apophytes (e.g. *Rumex*

*acetosella*), coprophilous fungal spores (HdV-55A, -113 and -368), and microscopic charcoal. The reverse pattern can be seen following abandonment of the site around AD 1400 (SSQ-3/4 boundary). For the full dataset and discussion, see Edwards et al. (2011b).

Fig. 6. Anthropogenically enhanced plaggen soils can yield useful pollen data, demonstrated here using pollen sites in Greenland (Atikilleq, Vatnahverfi; Ledger et al., 2015) and the UK (Village Bay, Hirta, St Kilda; Donaldson et al., 2009). (a) coastal section at Atikilleq where the plaggen deposit could be traced over a distance of ∼20 m (photo by J.E. Schofield); (b) the sampled section at Atikilleq comprising basal natural soil, plaggen (organic-rich sandy soil containing charcoal and charred bone fragments, ~21 cm thickness) and a surface capping of sandy soil and turf (photo by J.E. Schofield); (c) summary pollen spectra from Atikilleq indicating relatively high concentrations of pollen (dominated by Poaceae, Cyperaceae and *Ranunculus acris*-type) from the start of woodland reduction (*landnám*); (d) Consumption Dyke formed from field-gathered boulders and stones (constructed AD 1830) in Village Bay underlain by plaggen soils (soil profile 8 was in the centre of the picture, photo by C. Deacon); (e) soil profile 8, Village Bay (72 cm depth, photo by C. Deacon); (f) summary diagram from the Village Bay profiles showing the occurrence of some of the main pollen types (% TLP, upper scale beneath diagram) and total pollen concentration (grains $cm^{-3}$ wet sediment, lower scale).

Fig. 7. Part of the West Mouth of the Great Cave of Niah, Sarawak, taken from the rockfall in the southern passage in 2008 (photograph by C.O. Hunt). The pollen sample transect (line diagram) is in the Archaeological Reserve to the far side of the cave mouth, just beyond the shelter at that side of the cave. Percentage pollen fallout for major ecological groups per year on a transect running inside the cave from the entrance zone (data from Hunt and Rushworth, 2005) show that the main source for pollen in the first 25 m of the transect is airfall, with assemblages closely mirroring those from taphonomic samples in the forests outside the cave. The influence of bat and bird vectors on pollen assemblages beyond 25 m into the transect, where swiftlet nests and bat roosts are abundant, can be seen in the high percentages of mangrove pollen and low frequencies of open-ground taxa.

Fig. 8. Fluorescence micrographs and intensity value graphs (red, green and blue light, relative to a greyscale from 0 [no light] to 256) for pollen and spores from the basal peats on

Dooncarton Mountain, Co. Mayo, Ireland (Hunt et al. 2007). (a) image of two *Corylus* grains, the upper being recycled and showing a typical dull orange colour, the lower showing the brighter yellow colours typical *of in-situ* material; (b) intensity analysis of *in-situ Corylus* grain shown in (a); (c) intensity analysis of recycled *Corylus* grain shown in (a). Note that all three colour bands show lower intensity; (d) image of thermally mature (burnt) *Polypodium* grain showing the very bright pale blue fluorescence typical of burned material; (e) intensity analysis of the thermally mature *Polypodium* grain shown in (d). Note that the blue band shows high intensity, but that there is virtually no fluorescence in the red wavelengths. (For greater clarity, see the on-line colour version).

Fig. 9. Schematic diagrams illustrating the key inputs and modelling programmes used within the Landscape Reconstruction Approach (LRA) and the Multiple Scenario Approach (MSA) modified from Bunting and Middleton (2009). Both modelling approaches draw on pollen productivity estimates (PPEs) and fall speed of pollen, and use the same pollen dispersal and deposition models. The LRA requires raw pollen counts as input data; the MSA requires raw pollen count data for evaluation of simulated pollen proportions.

Fig. 10. LRA-based estimates of local vegetation cover within the NSAP (necessary source area of pollen) of sixteen sites (designated by abbreviations) on Exmoor (indicative photograph by Ralph M. Fyfe) for the time period 1500-1000 cal BP. For each site, the regional vegetation is estimated in REVEALS using the other 15 sites, followed by estimating local vegetation for that site using LOVE. The error bars represent 2σ confidence limits.

Fig, 11. A simulation of broad vegetation zones on Exmoor (upper panel). Zones are differentiated based on a combination of elevation and slope, and follow archaeological interpretations of the early medieval period (Rippon et al., 2006); vegetation is kept simple, with only five taxa. Forty-nine sets of simulated pollen loadings have been generated from within the inset box, and are illustrated in the lower panel. Full details of the simulation can be found in Fyfe (2006). (For greater clarity, see the on-line colour version).

**Table 1**

**Table 1.** Numbers of palynological papers appearing in selected journals since their dates of release.

| **Journal** | **Period covered** | **Number of palynological papers*** | **Mean number of palynological papers per annum**** |
|---|---|---|---|
| *The Holocene* | 1991-2014 | 627 | 26.13 |
| *Quaternary Science Reviews* | 1982-2014 | 608 | 18.42 |
| *Quaternary International* | 1989-2014 | 476 | 18.31 |
| *Palaeogeography, Palaeoclimatology, Palaeoecology* | 1965-2014 | 792 | 15.84 |
| *Journal of Quaternary Science* | 1986-2014 | 398 | 13.72 |
| *Quaternary Research* | 1970-2014 | 606 | 13.47 |
| *Boreas* | 1972-2014 | 336 | 7.81 |
| *Journal of Archaeological Science* | 1974-2014 | 211 | 5.15 |

* Based on the words ‘pollen’ or ‘palynology’ appearing within the title, abstract or keywords of articles, review articles and short communications, where these are ascertainable within the relevant search engines of the journal home pages. There is likely to be uncertainty in these figures.

** These figures are not normalized for annual journal length.

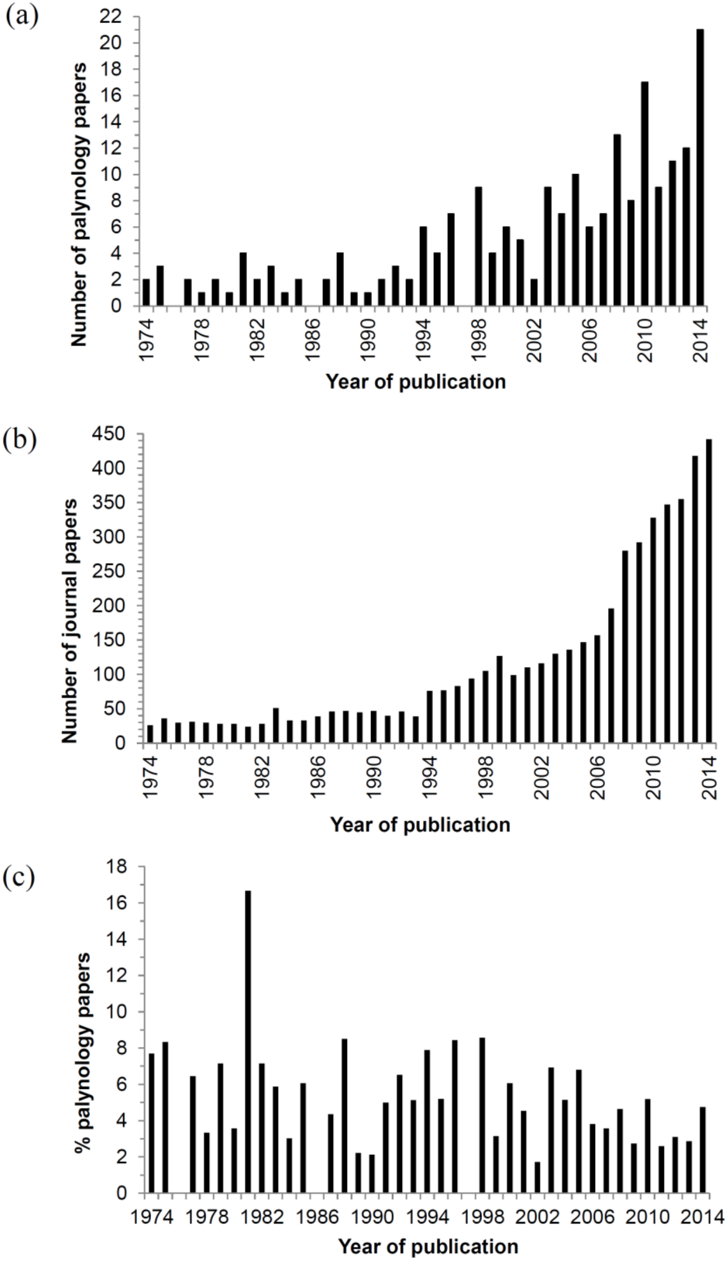
(a)
Number of palynology papers
Year of publication
(b)
Number of journal papers
Year of publication
(c)
% palynology papers
Year of publication

Figure 2 colour

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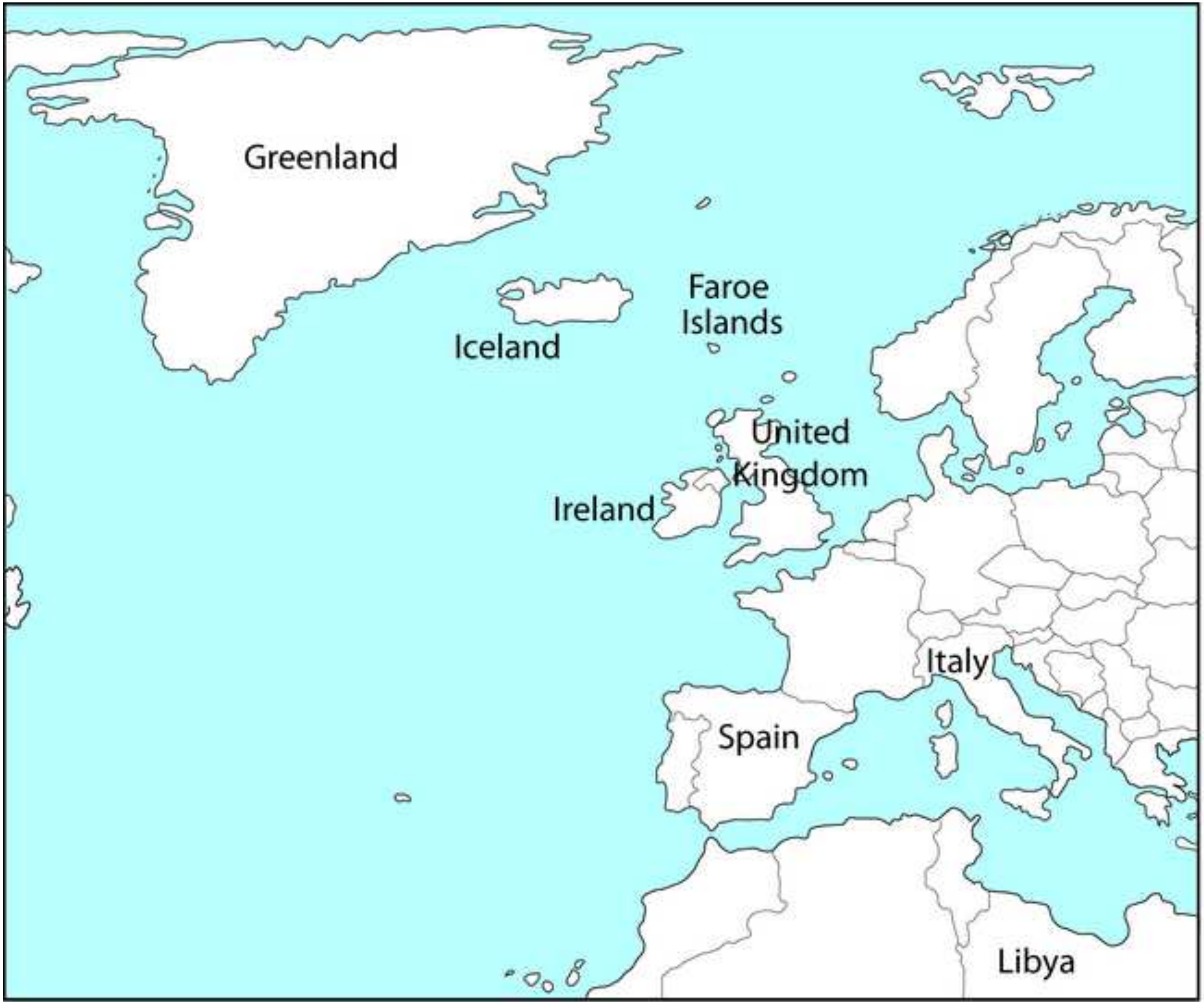

Figure 2 greyscale
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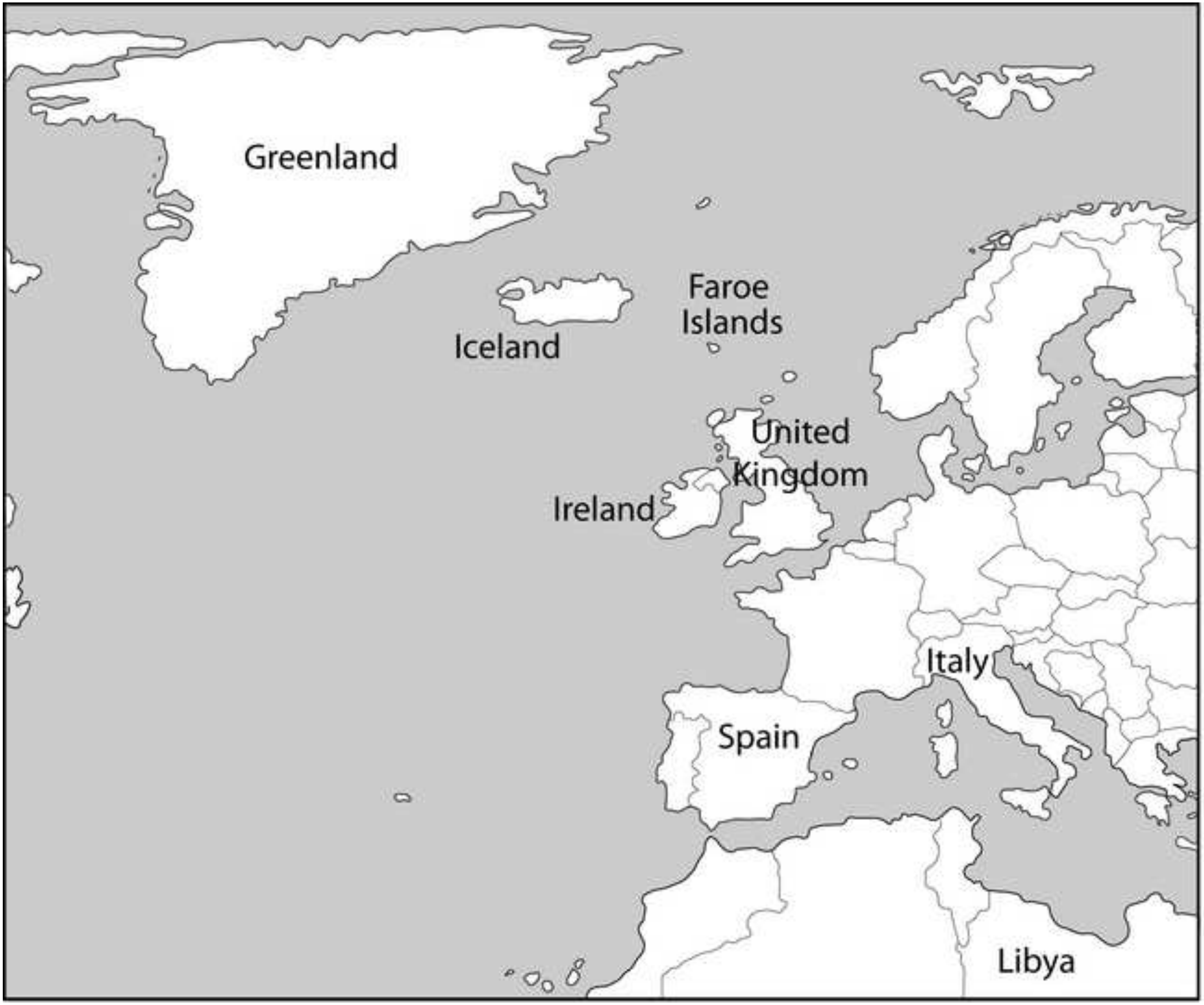

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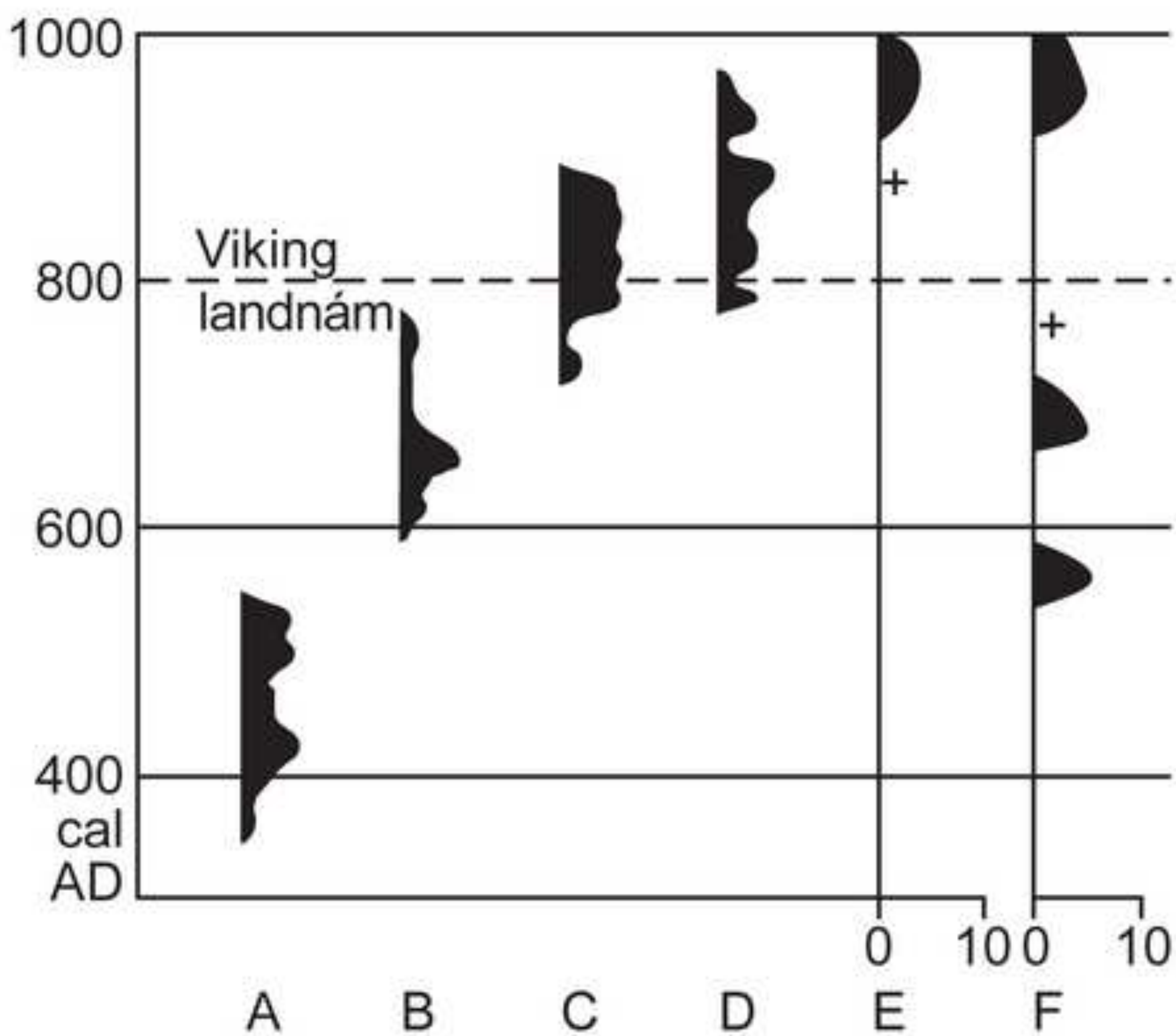

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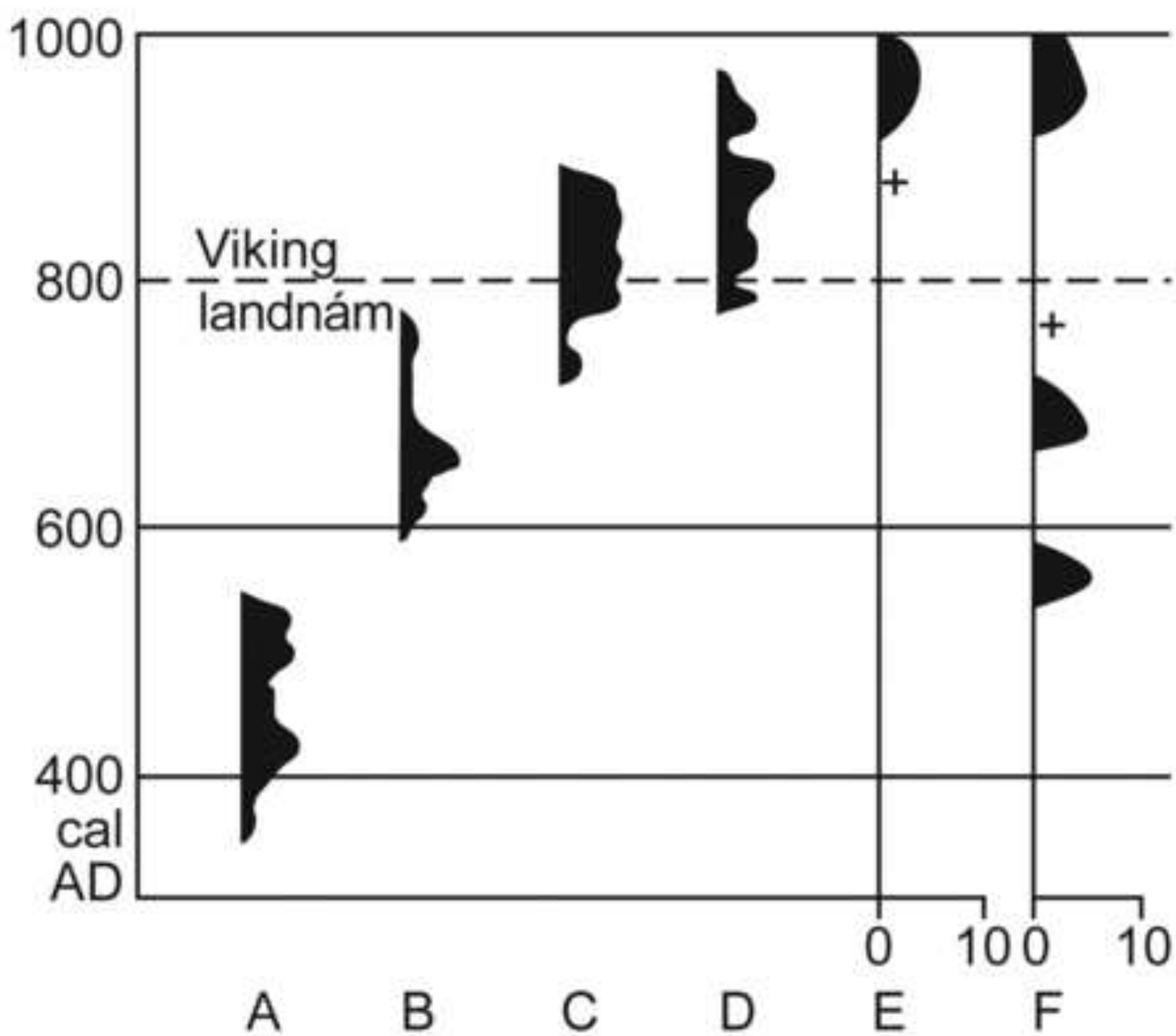

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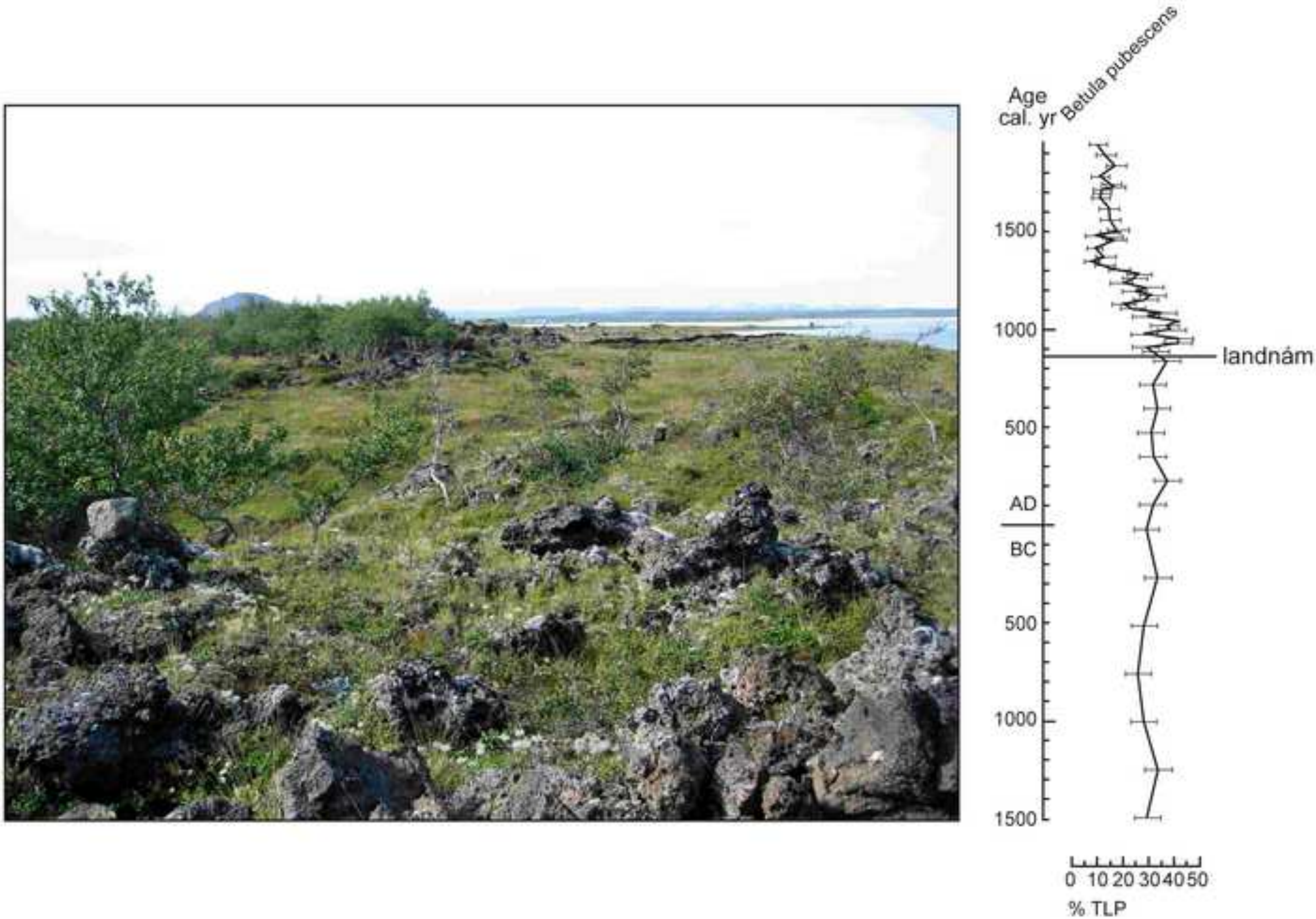

Figure 4 greyscale

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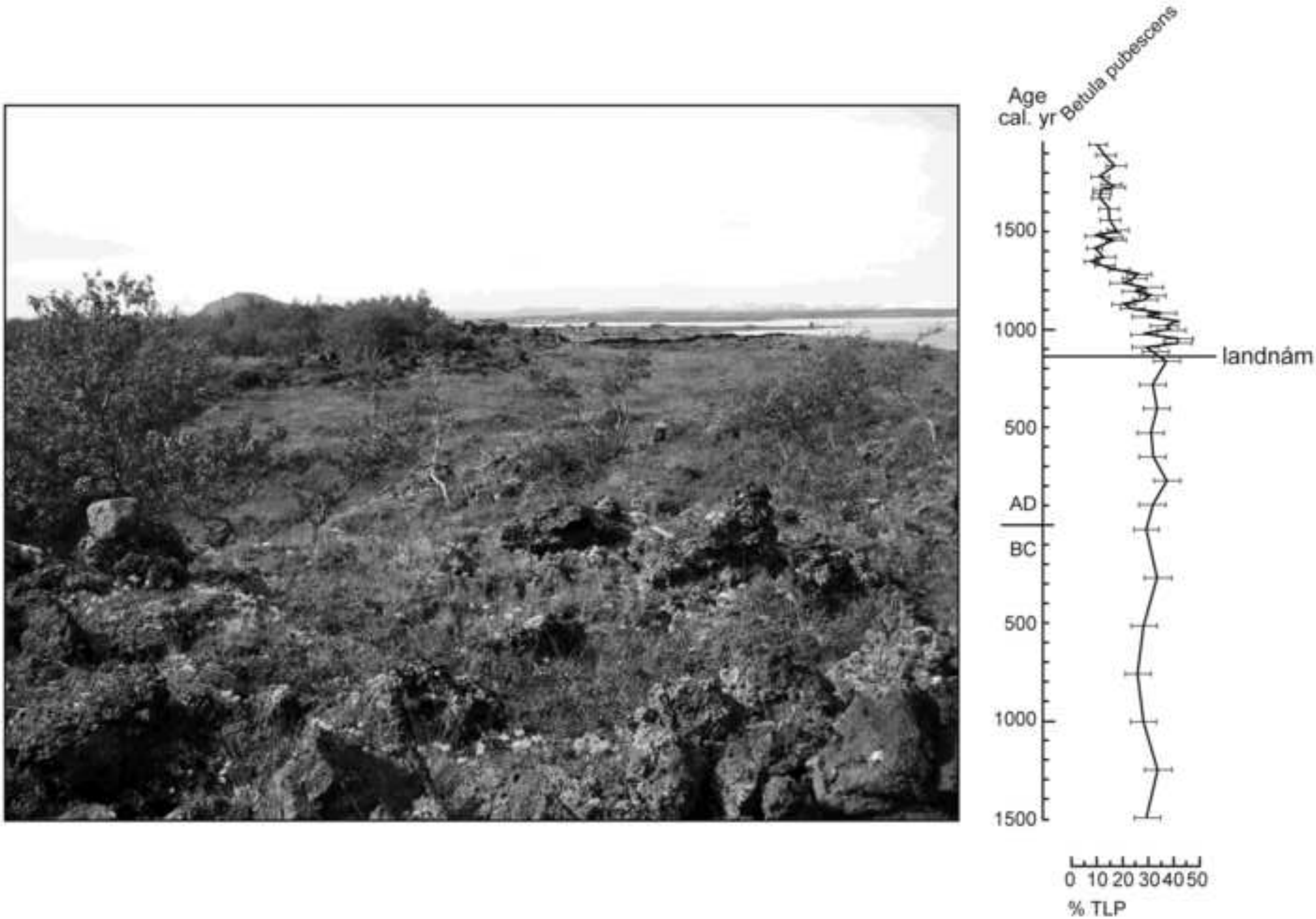

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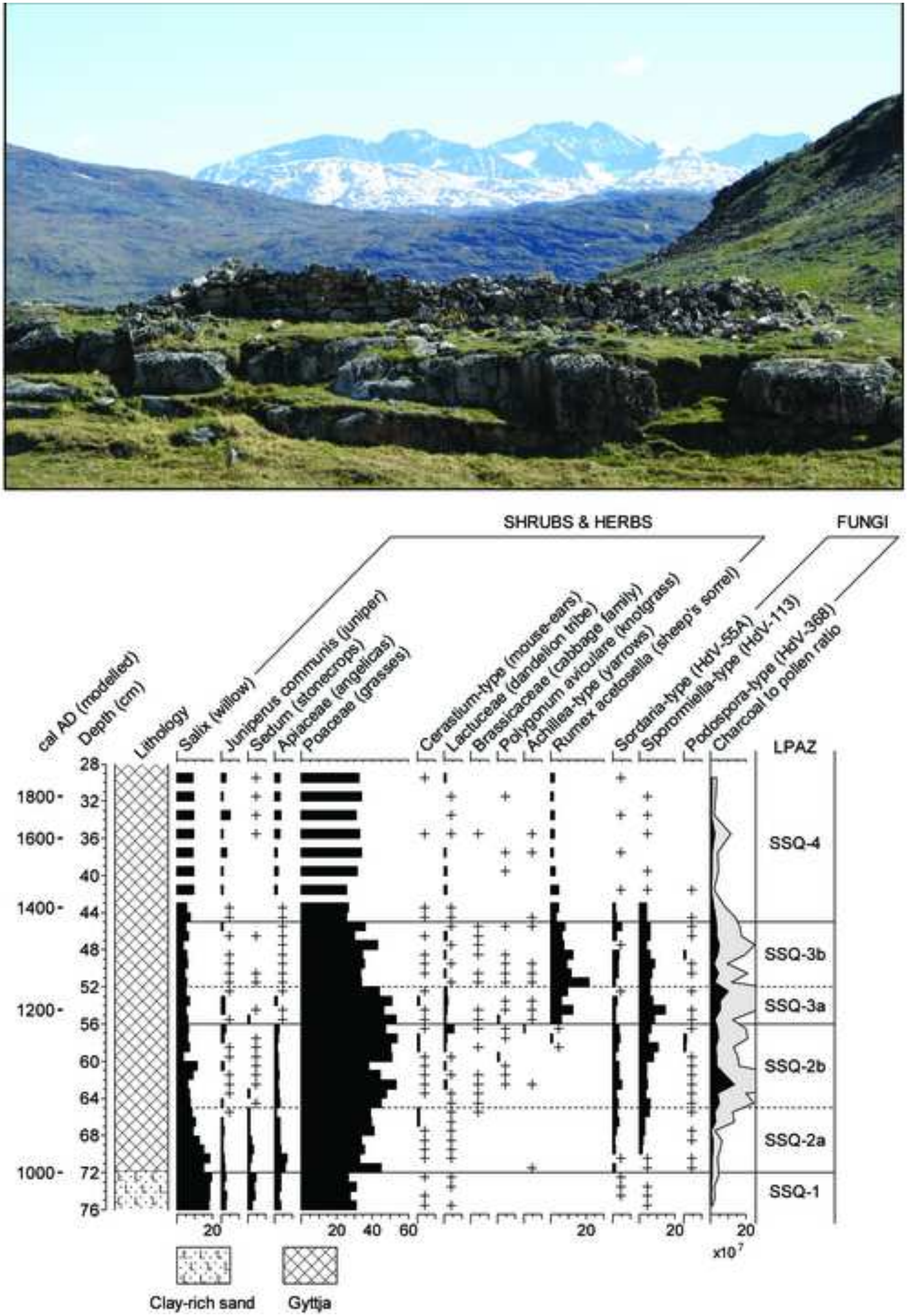

Figure 5 greyscale

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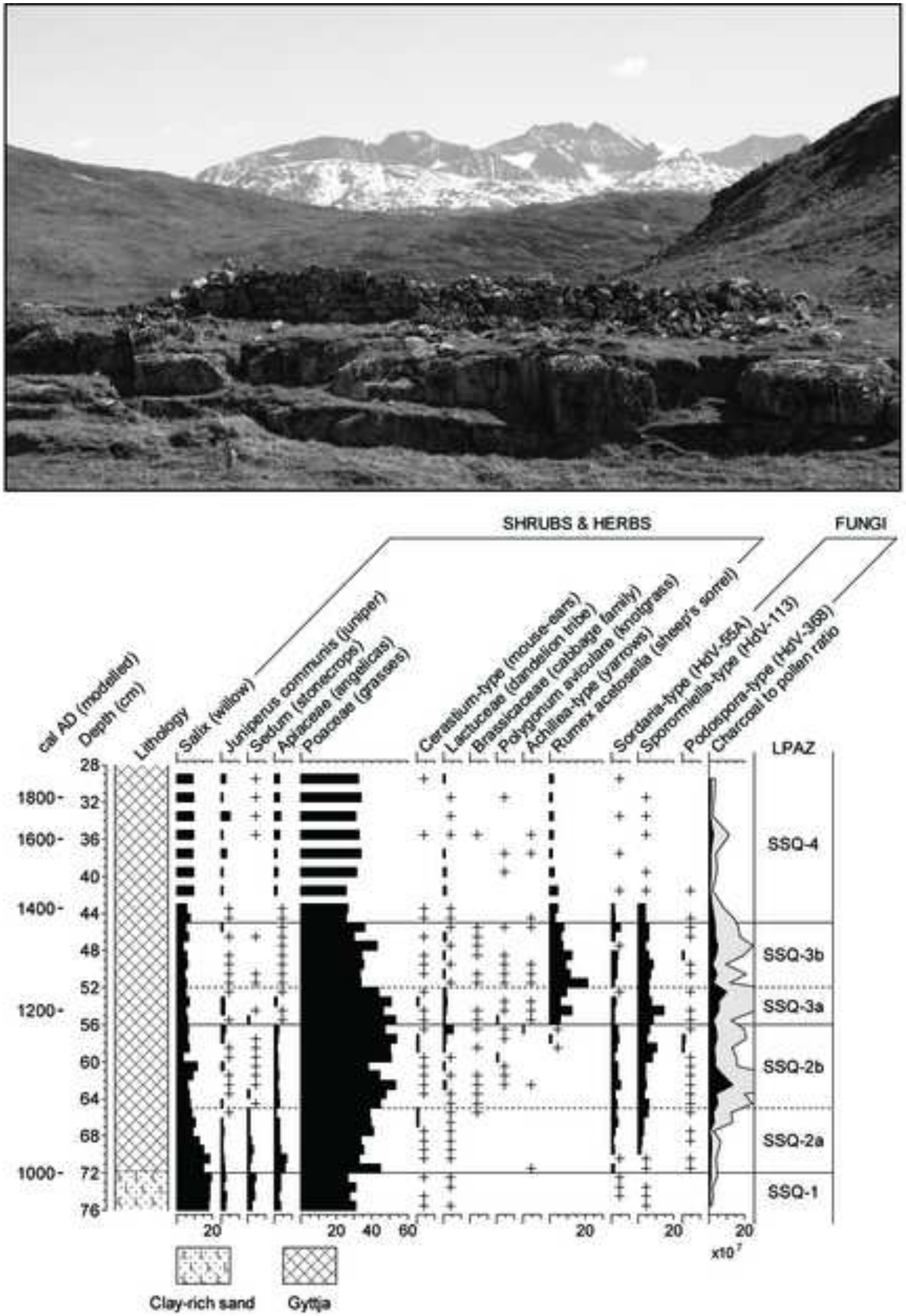

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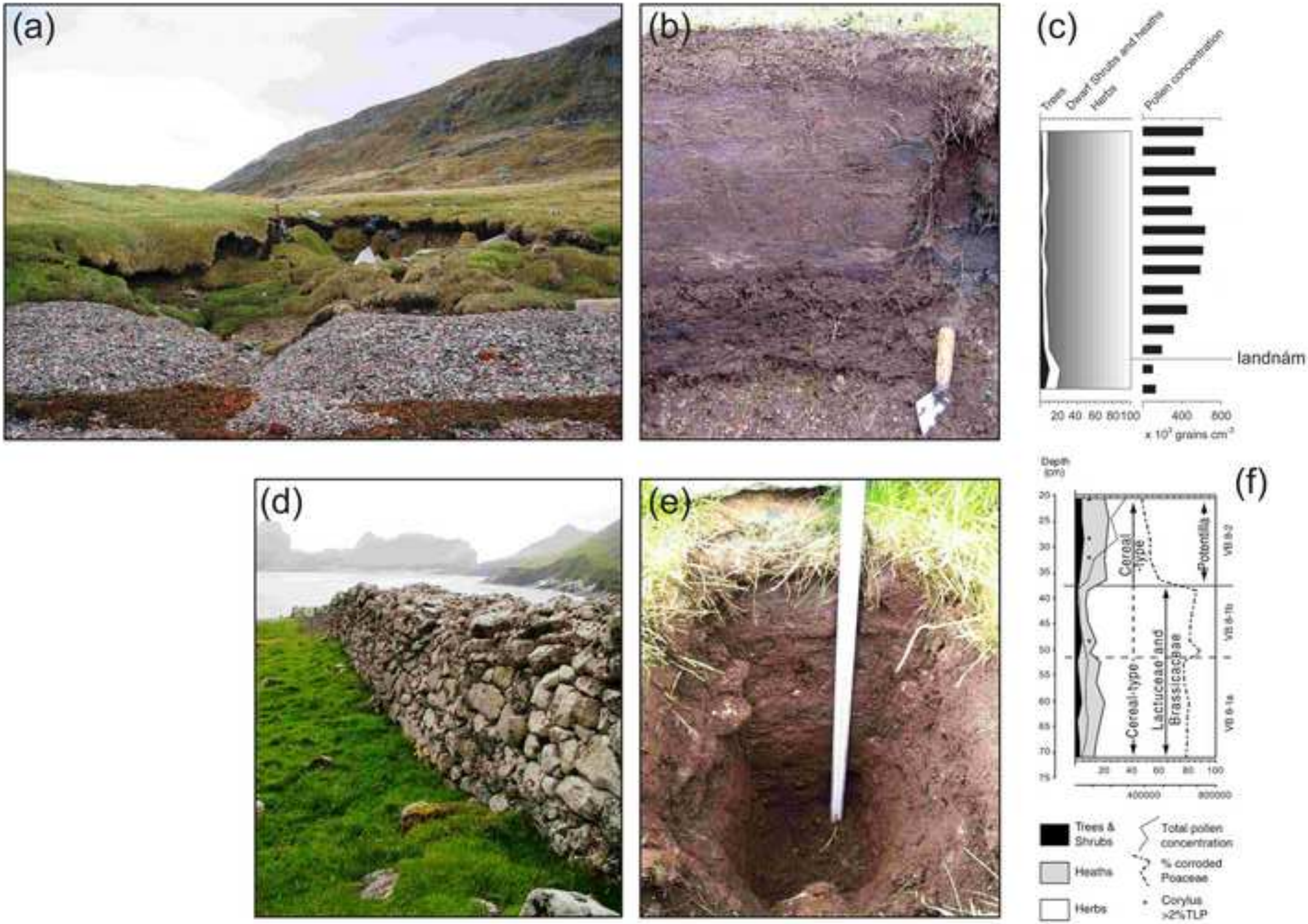

**Figure 6 greyscale**

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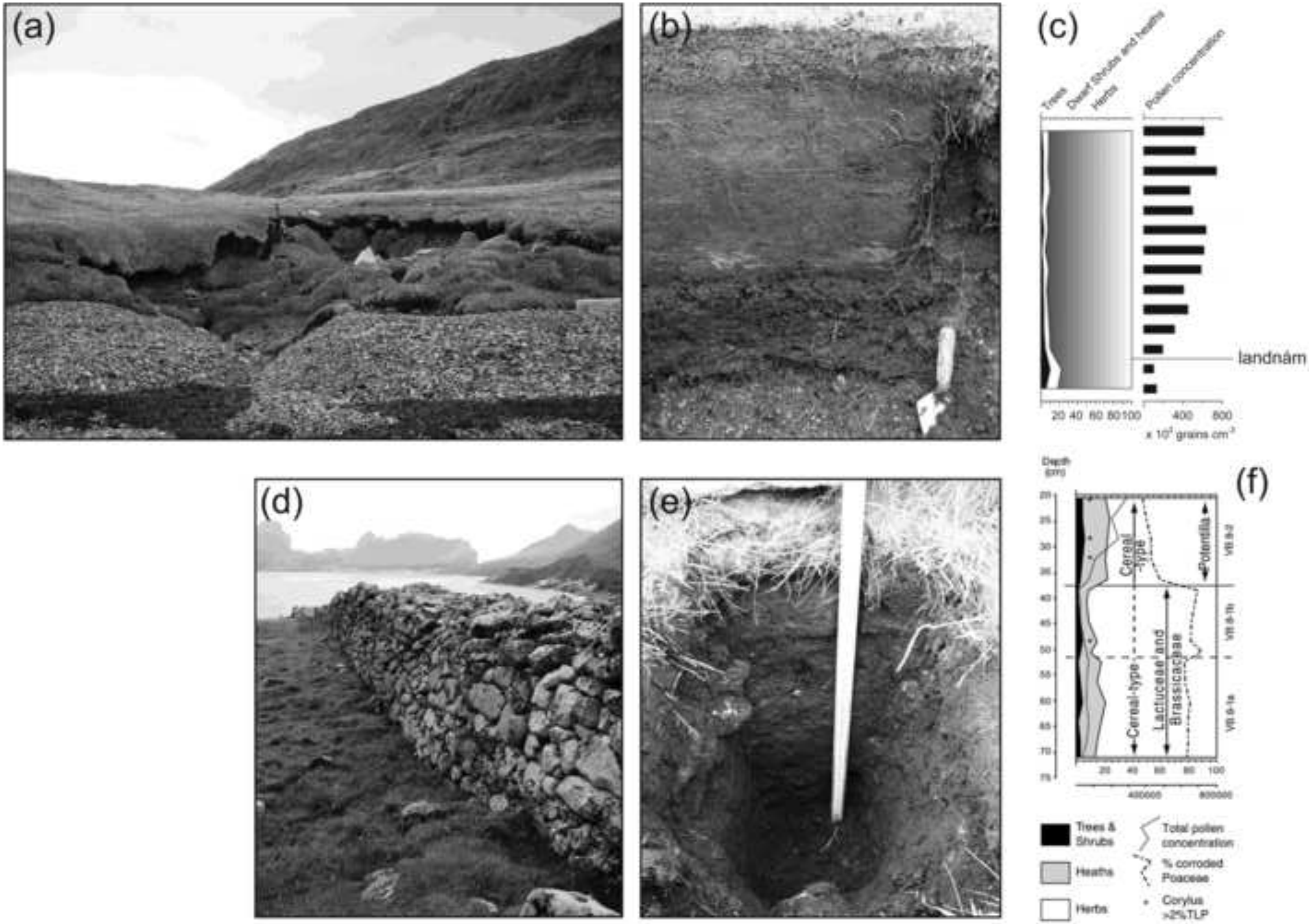

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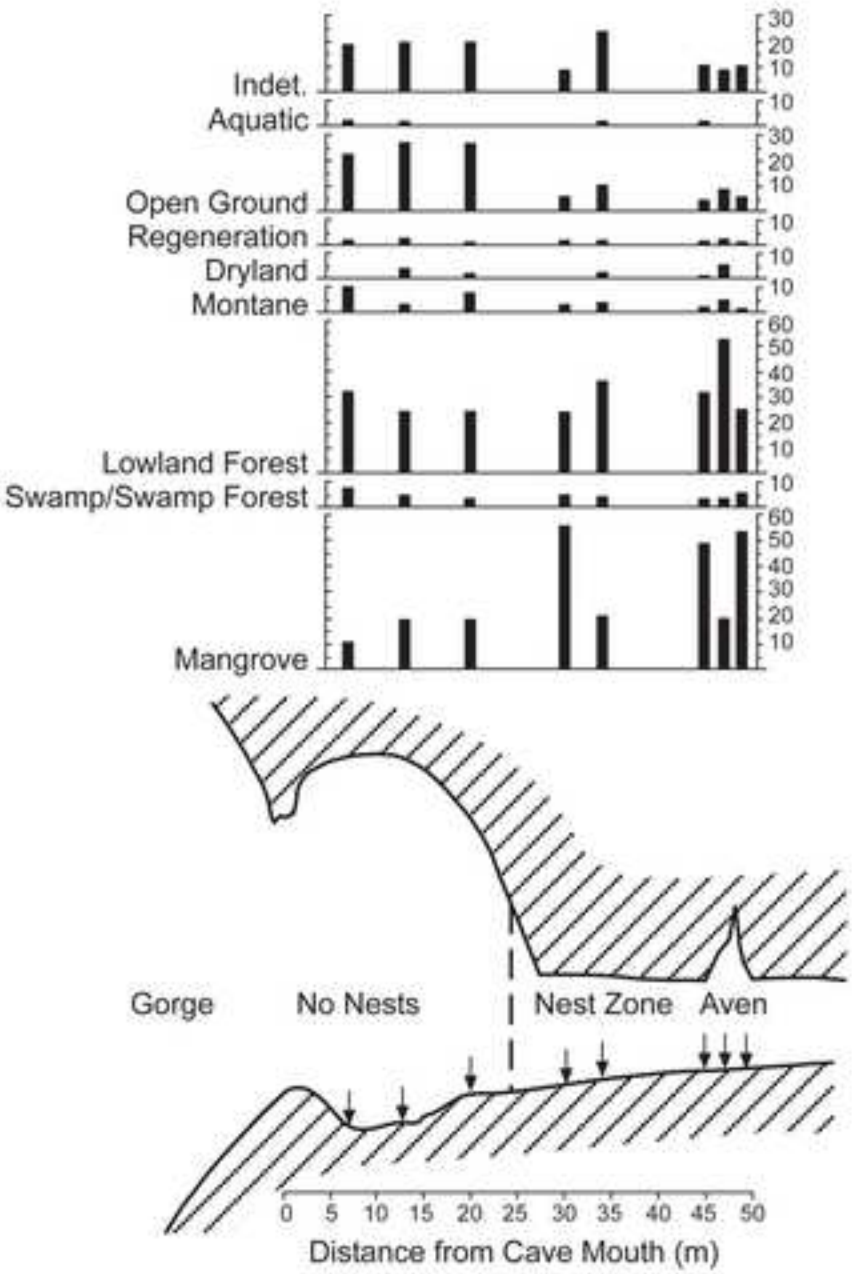

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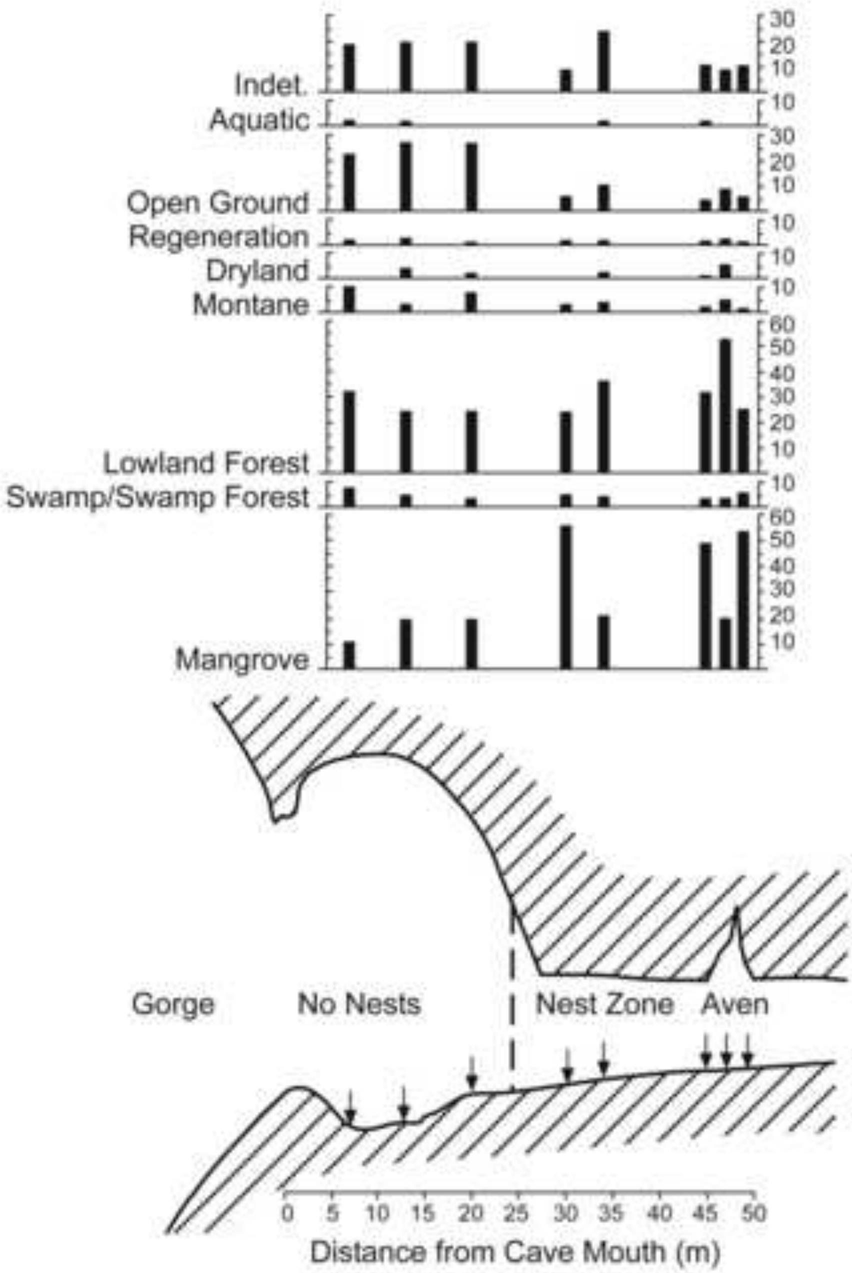

Figure 8 colour

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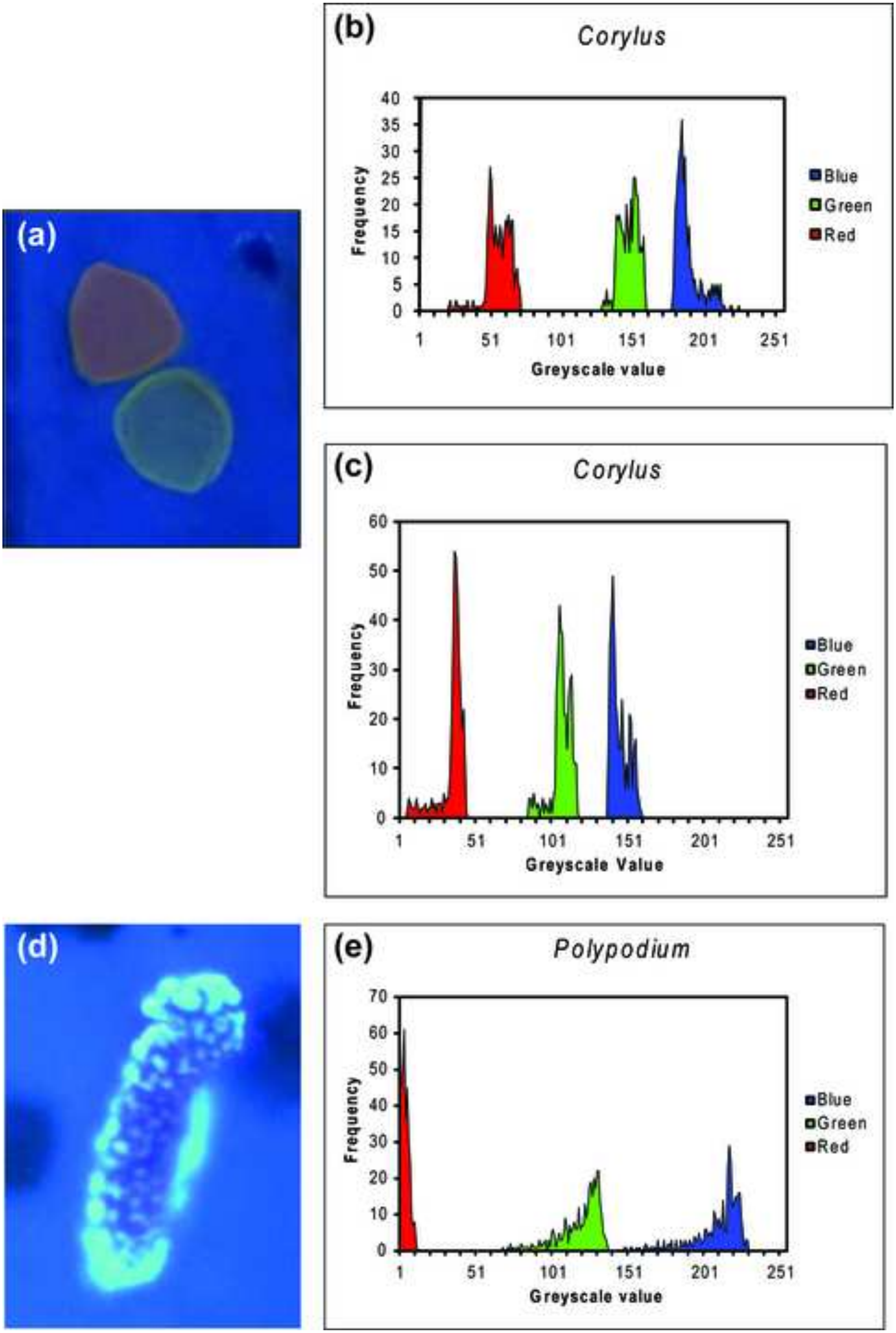

Figure 8 greyscale

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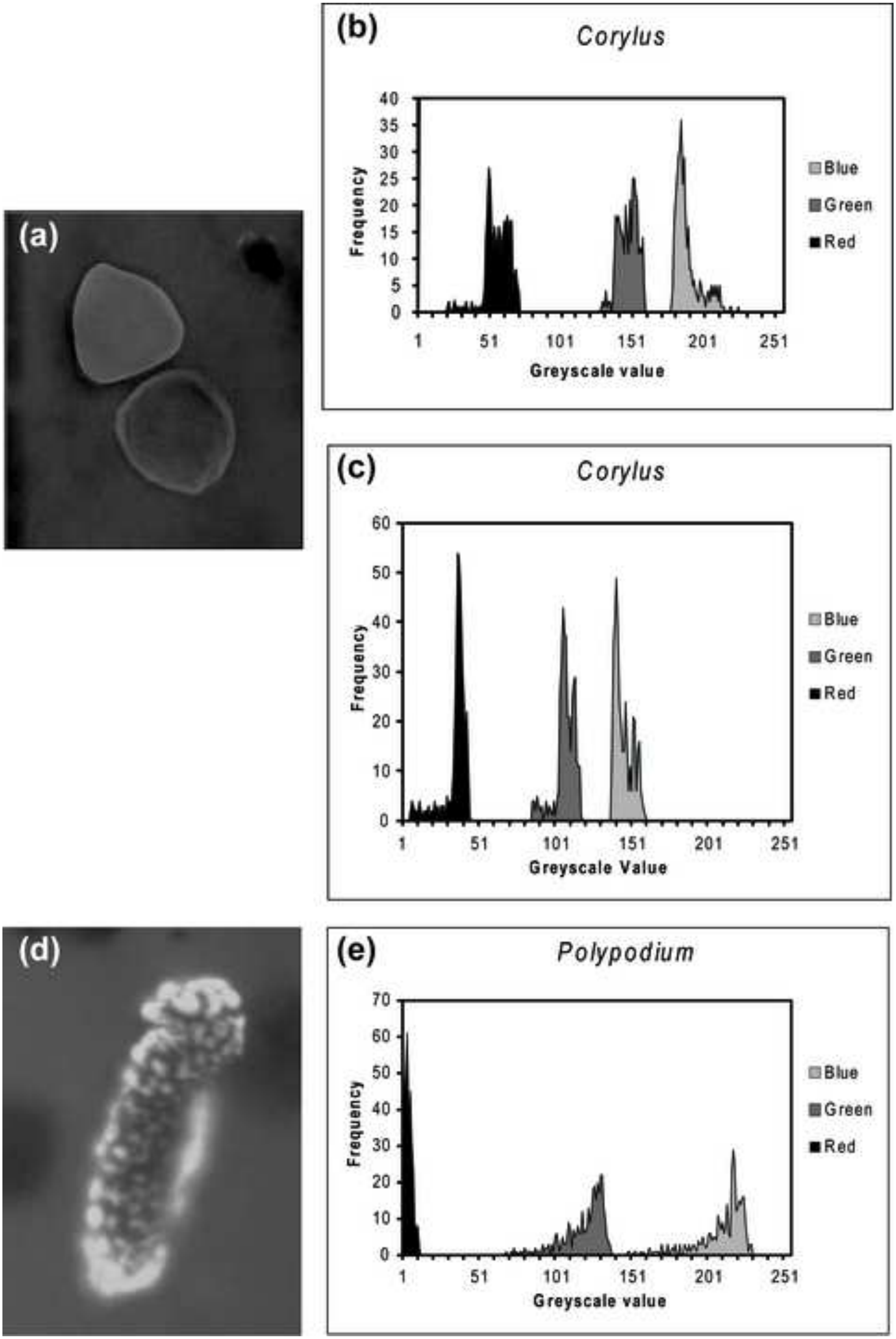

Figure 9
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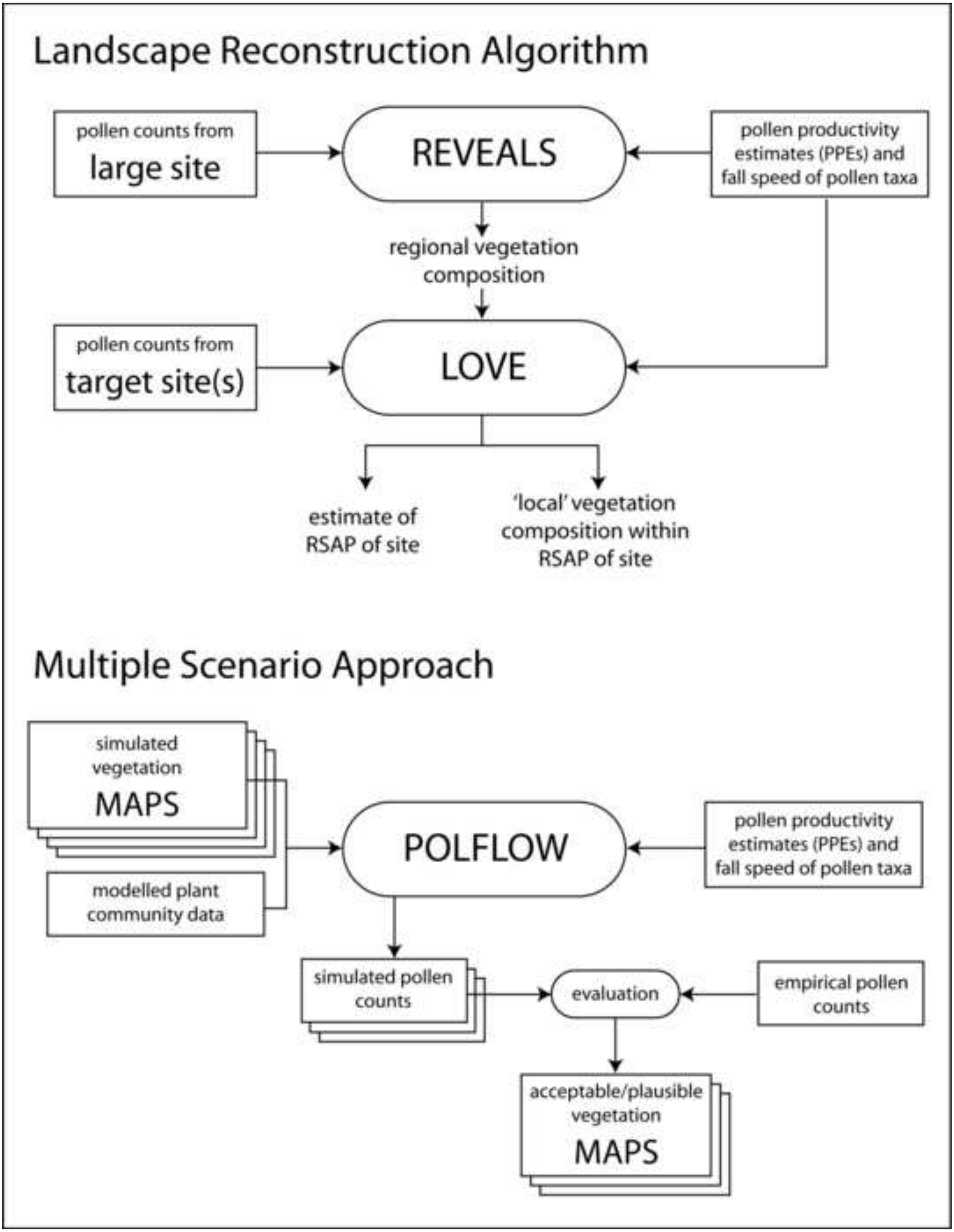

**Figure 10 colour**

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**Figure 10 greyscale**

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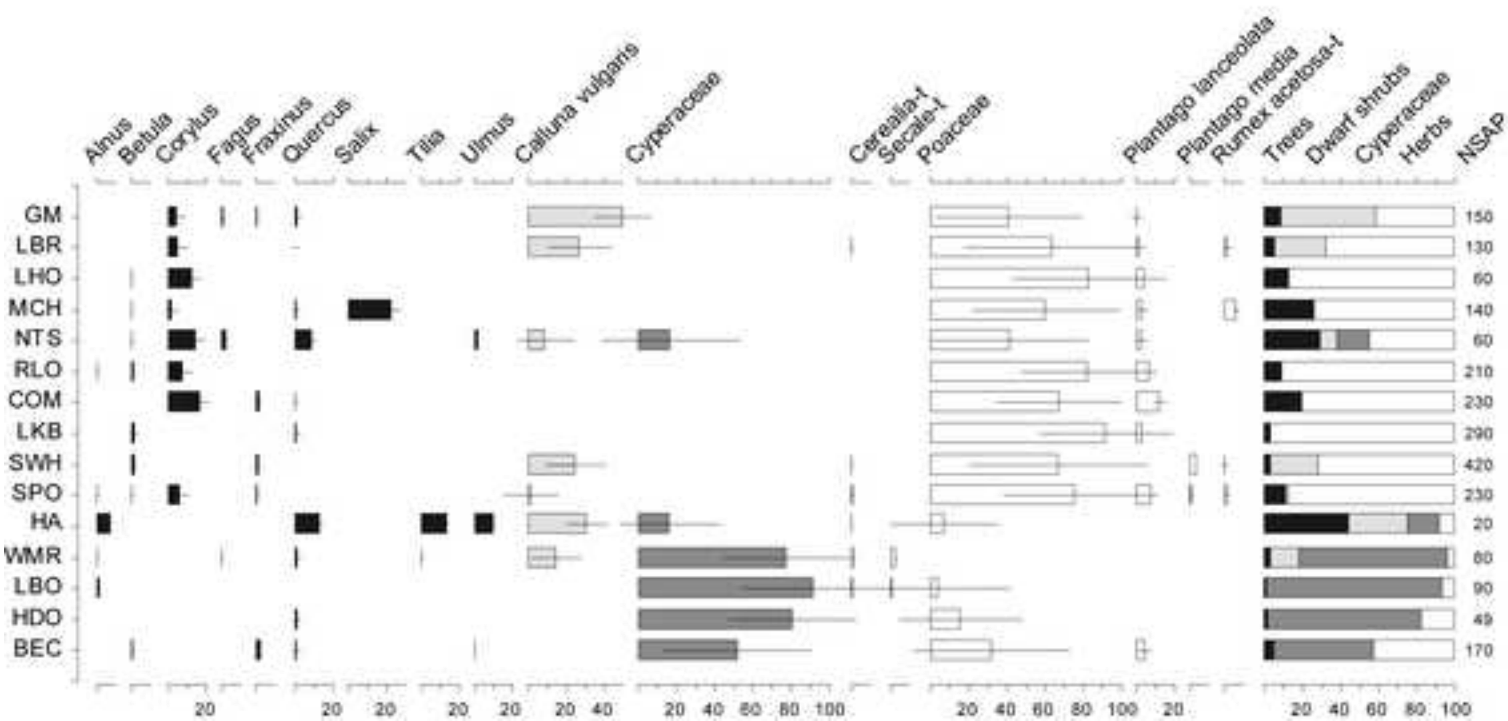

Figure 11 colour

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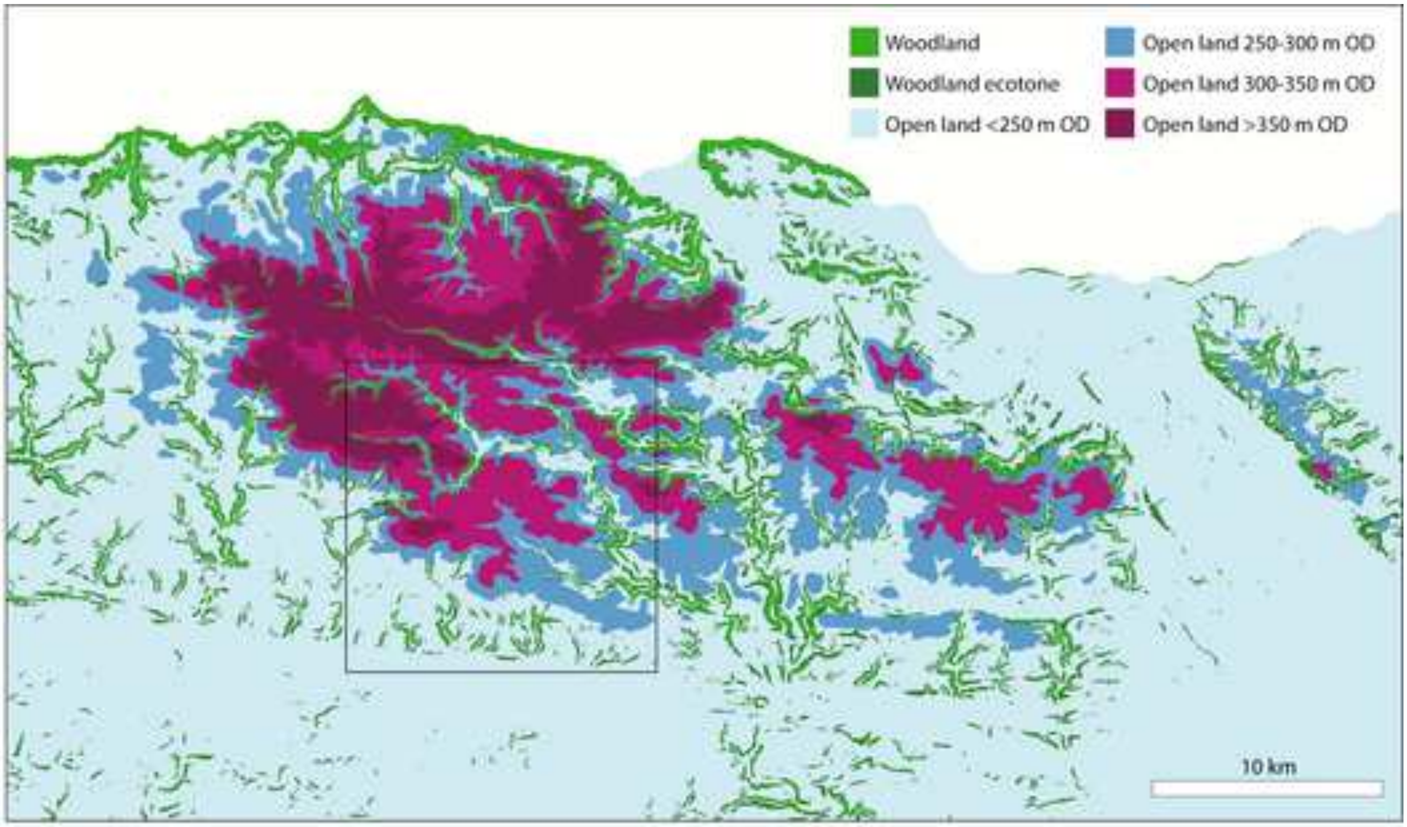


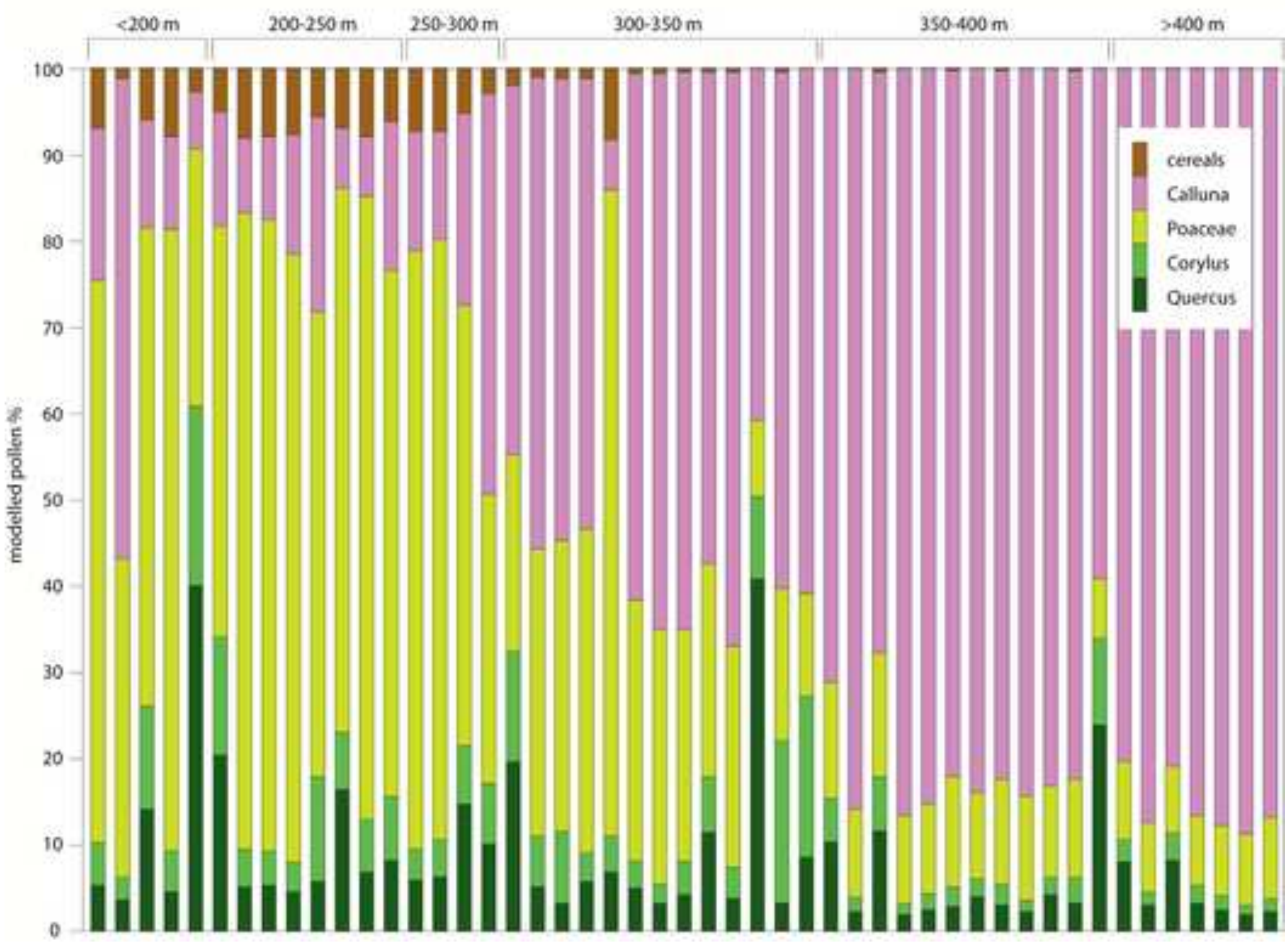

Figure 11 greyscale

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