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ORIGINAL ARTICLE

Reconstructing prehistoric land cover and landuse in complex 'blue-green' landscapes

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Abstract

Environmental context is vital when analysing archaeological sites and interpreting past human activity. Pollen, being widely dispersed and readily preserved in wetland sediments, is frequently used to investigate past land cover, especially in wetland-rich 'blue-green' lowland landscapes (landscapes formed in locations where hydrology is an important determinant of natural vegetation, geomorphology and land use, such as river valleys and estuaries; landscapes which are transitional between aquatic-dominated and terrestrial-dominated). Recent developments in quantitative landcover reconstruction from pollen diagrams, such as the Multiple Scenario Approach (MSA), improve interpretations by taking into account variations in pollen production, dispersal, and sedimentary basin properties. We apply the MSA to derive quantitative, spatially-informed land cover reconstructions for four prehistoric periods in a major UK blue-green lowland landscape, the Humberhead Levels. Reconstructed quantified land cover broadly confirms inferences from previous studies, showing the spread of wet woodland and development of raised mires in the middle Holocene, whilst highlighting the spatial complexity of this dynamic blue-green landscape. The reconstruction process highlights gaps in available data and shows, for example, that the complex interplay of freshwater and marine systems in the later Holocene is only partially understood; thus reconstructions can inform the development of future research agendas in this and other blue-green landscapes. The spatially referenced MSA outputs offer a powerful means of enhancing the integration of pollen analysis with other disciplines, including archaeology, and for developing clear hypotheses for future research.

Keywords Land cover reconstruction · Multiple scenario approach · Palynology · Prehistory · Humberhead levels

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Introduction

Reconstruction of the spatial pattern of land cover, and how it changes over time and space, can contribute to a better understanding of the long-term dynamics of interactions between the physical environment and its inhabitants (Bunting et al. 2018). The distribution of different vegetation communities is a major determinant of the nature and spatial patterning of human activity by influencing factors such as resource availability and human mobility through the landscape. Understanding contemporaneous land cover can profoundly affect interpretation of the purpose and arrangement of archaeological sites; for example, whether a stone circle is set in open ground and thus visible from a considerable distance or hidden in dense woodland (Winterbottom and Long 2006). Human activity, in turn, can have a transformative effect on land cover through impacts that are both 'active' (e.g. tree clearing for agriculture) and 'passive' (e.g. grazing pressure of livestock) (Richer and Gearey 2017). Reconstructing the proportions of land cover types and extent and rate of change in land cover associated with these impacts provides insights into the scale and intensity of human presence in the landscape over time.

Sub-fossil pollen analysis is one of the main tools used to investigate past land cover, despite the complexity of interpreting pollen records for past land cover reconstruction. Palynological records are preserved in sedimentary archives, typically wetlands or lakes, and are collected from a single point, although the 'signal' seen within these point records is generated from the deposition of pollen produced by plants distributed across the landscape around the sedimentary body. The amount of pollen produced, and the dispersal properties of those grains, varies between plants, reflecting different reproductive strategies. The amount of pollen any individual plant contributes to the sedimentary record depends on these properties and the position of the plant relative to the sampling point (Moore et al. 1991).

Interpretation of a pollen record from a single sampling point typically takes the form of a 'narrative' about how that site and its surrounding landscape has changed through time. However, it is possible to develop algebraic models of the pollen dispersal and deposition process that can be used to translate pollen records into quantitative estimates of past land cover composition, and to generate reconstructions of the spatial distribution of those plants, by using methods such as the Landscape Reconstruction Algorithm (LRA: Sugita 2007a, b) or the Multiple Scenario Approach (MSA: Bunting and Middleton 2009). These methods can be applied at a range of spatial scales from sub-continental (e.g. Trondman et al. 2015) to landscape (e.g. Farrell et al. 2020). Creating and applying models of complex physical processes to reconstruct past land cover can not only deepen understanding of human-landscape dynamics over time but also improve understanding of the processes that create the records and their strengths and limitations. Studies of pollen dispersal and deposition shed new light on the "pollen's eye view" of past land cover, and on the types of changes in the landscape around a sedimentary basin that may or may not be recorded in the pollen archive over time. Quantitative reconstruction methods encourage the analyst to be explicit about the assumptions being made and, when used thoughtfully, can reveal limitations and gaps in the existing data, whilst also improving understanding of the spatial context of past human activity, thereby helping environmental archaeologists develop explicit hypotheses to guide future research activity.

Land cover reconstructions from these model-based approaches take two forms: quantitative estimates of past land cover composition over time and maps of the distribution of land cover types. The LRA uses pollen counts to generate estimates of the proportions of land cover classes for large regions (conceptualised as 50–200 km radius around a sampling point) or distance-weighted plant abundance around individual sites. Quantitative outputs from multiple sites can then be combined to generate maps of likely land cover at different points in time. The main applications of the LRA to date have been mapping national or sub-continental patterns of land cover change over time using large regional land cover outputs (e.g. Fyfe et al. 2013; Githumbi et al. 2022; Li et al. 2022).

MSA uses both pollen counts and maps of major environmental constraints on land cover such as topography or bedrock geology, and its primary output is in the form of maps of possible spatial arrangements of land cover which could have produced those pollen counts (see ESM 1 for more detail). These maps can then be summarised as quantified proportions of different land cover types. The main application of the MSA in the literature to date is in the reconstruction of changing patterns of land cover in landscapes of archaeological interest (e.g. Bunting et al. 2022; Farrell et al. 2020). Presenting land cover reconstructions as maps is a visually effective communication tool, but a single map implies a delineated, defined, stable landscape structure and a 'representative visualisation' of the past (McCoy and Ladefoged 2009; Richer and Gearey 2017). These outputs are actually better considered as data visualisations, with inherent uncertainties associated with both quality and resolution of input data and with the equifinality of pollen records (since ecologically and visually distinct arrangements of plants can produce the same pollen signals; Bunting and Middleton 2009). Developing representations that show a range of possibilities, or otherwise clearly incorporate the uncertainty and equifinality of the pollen record, is an ongoing challenge, but crucial if the accidental misuse or over-interpretation of mapped outputs is to be avoided.

Heterogenous, wetland-rich lowland 'blue-green' landscapes, spaces in which vegetation and geomorphology are strongly influenced by hydrology across the whole landscape such as estuaries, river deltas or coastal wetland complexes, were important areas for human settlement throughout prehistory and continue to be so due to the richness and diversity of resources available (Menotti and O'Sullivan 2012). Today, these landscapes are often the focus of economic and social concern as they face increased flood risk due to both climate change and sea-level rise, threatening both settlement and food production. Blue-green landscapes are well suited for exploration using land cover reconstruction approaches because their many wetland elements such as bogs, fens, marshes and floodplains preserve palynological records, whilst strong spatial patterning in land cover is exhibited between dryland and wetland systems. In this paper, we use the term "dryland" to refer to any part of the landscape which is not inundated at any point in the year and where the vegetation has a fully terrestrial character. Pollen records in these landscapes mostly come from locations with deep deposits of wetland sediment – providing long detailed records – whilst land cover-modifying human activity mostly occurred on dryland "islands" and at the wetland-dryland margin, usually at some distance from the sediment core locations. Consequently, signals of dryland environments and activities (e.g. arable cultivation) in the pollen record are diluted and blurred by wetland plants growing closer to the sampling location (e.g. Binney et al. 2005; Bunting 2008; Waller et al. 2017). Model-based approaches can help to tease out these low-level signals or quantify their uncertainties more effectively (e.g. Farrell et al. 2020). More broadly, reconstructing the past trajectories of change in such landscapes gives insight into the feedbacks and processes acting upon and within them, and contributes to the development of effective and appropriate land management strategies (e.g. Waller and Kirby 2021).

This paper presents the results of applying the MSA to existing pollen records from a blue-green landscape, the Humberhead Levels (HHL).

Its aims are:

1. To reconstruct past land cover for four time windows in the Humberhead Levels during the late Mesolithic (4750–4250 BCE), middle Neolithic (3350–2850 BCE), early Bronze Age (2350–1850 BCE), and Iron Age (800–300 BCE).
2. To evaluate the impact of MSA model inputs on the reconstruction outputs of land cover in blue-green landscapes and identify the main sources of uncertainty.
3. To make recommendations of future research priorities in the HHL, and for the application of the MSA in other blue-green landscapes.

Study area

The Humberhead Levels (Fig. 1) in eastern England (UK) are an excellent example of a 'blue-green' landscape. Once an extensive wetland-dryland complex, the area today mostly consists of agricultural land of significant economic and food production value with remnant wetlands only in protected areas (e.g. the Humberhead Peatlands National Nature Reserve which includes the Special Areas of Conservation (SACs) and Sites of Special Scientific Interest (SSSIs) of Thorne, Goole and Crowle Moors and Hatfield Moors; Potteric Carr Nature Reserve) within a heavily modified and managed hydrological system (van de Noort and Ellis 2000). Human activity has extensively altered the landscape through drainage and wetland reclamation over the last two thousand years (Jones 1995; Whitehouse 2004; Gaunt 2012). Many pollen-analytical studies have been carried out in the area (see Figs. 1 and 2), from locations with deep wetland sediments formed across river floodplains or raised peatlands, but these have only been combined and considered using narrative methods. This study uses a quantitative reconstruction approach to synthesise available records, reconstruct past land cover and wetland distribution, and assess how well pollen records from "blue" contexts reflect the spatial patterning of a blue-green landscape, particularly of human activities centred in "green" locations.

Since the beginning of the Holocene (9700 BCE), the interplay between relative sea-level (RSL) change coupled with tidal and sedimentary dynamics has been the dominant control on the nature and distribution of different wetland types across the HHL (Best et al. 2022). During the Mesolithic (ca. 9600–4000 cal BCE), rates of RSL rise of ca. 4 mm yr^{-1} resulted in rapid estuarine expansion, floodplain alluviation and peat formation. Later in the Holocene, during the Bronze Age (ca. 2400–800 cal BCE), estuarine conditions reached their maximum extent with widespread fen wetlands in the river valleys and intertidal wetlands along the estuary margins (Long et al. 1998; Metcalfe et al. 2000). From the late Bronze Age and into the Iron Age, the rate of RSL rise slowed to c.1 mm yr^{-1}, resulting in a shift towards local factors such as sediment supply and human-induced woodland clearance becoming the key drivers of landscape development (Hamilton et al. 2019; Best et al. 2022). During this time, extensive wetland development took place across the HHL, with estuarine infilling occurring in the river valleys as the increased sediment input from catchment erosion (Buckland and Sadler 1985) outpaced the rate of RSL rise.

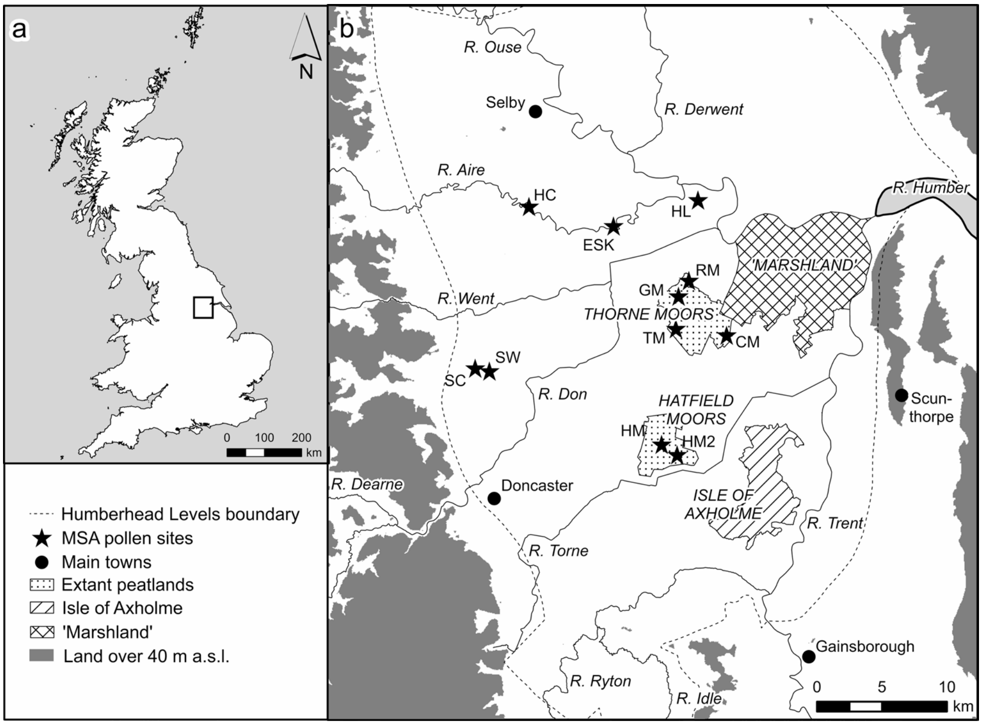
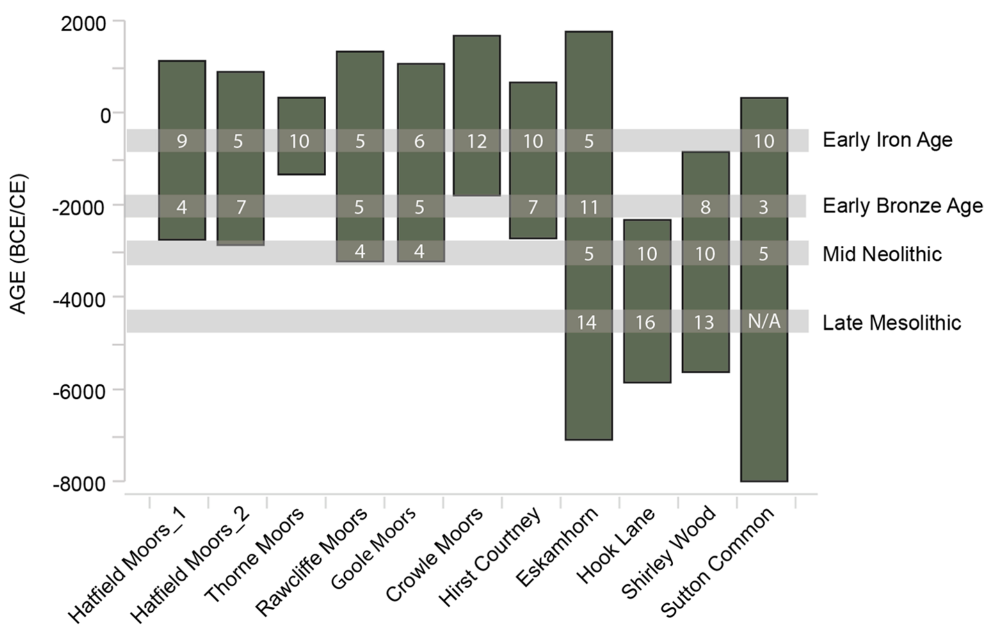


Fig. 1 **a** Location of the study area (boxed) within the UK. **b** The area where the Multiple Scenario Approach was applied (using a 50 × 50 m^2 grid). Stars and lettered site codes indicate the location of pollen records used within this study. The full details of the records can be found in ESM 3. The boundary used to delimit the Humberhead Levels is that of the HHL National Character Area defined by Natural England (2014). The Isle of Axholme is defined by the 5 m contour, and the area known as 'Marshland' is delimited by the Ancient Parish Boundaries of Whitgift, Adlingfleet and Luddington (Southall and Burton 2004). Site names: Hatfield Moors 1 (HM1), Hatfield Moors 2 (HM2) Thorne Moors (TM), Rawcliffe Moors (RM), Goole Moors (GM), Crowle Moors (CM), Hirst Courtney (HC), Eskamhorn (ESK), Hook Lane (HL), Shirley Wood (SW), Sutton Common / Hampole Beck (SC)

Fig. 2 Time span covered by the available pollen records in the study region. The four 500-year time windows investigated are highlighted with horizontal grey bars and the number of samples used from each site are given in white text. Note that not enough samples were available within the Late Mesolithic window for Sutton Common, so this site was not included in the reconstruction for this time window (site details are provided in ESM 3)



Human activity in the context of these changes is evident within the extensive archaeological record that has been documented across the region (van de Noort and Davies 1993), although the information for early prehistory is likely to be incomplete as contemporaneous river-edge landscapes are now buried under deep floodplain deposits, and are therefore unlikely to be discovered. Interspersed across the landscape are numerous dryland islands and wetland-dryland margins that were the focus of relatively intense and frequent human activity compared to the interiors of wetlands (van de Noort and Ellis 2000). The largest of these islands is the Isle of Axholme, which rises to 30 m OD (ordnance datum), and is located toward the eastern edge of the Levels.

Materials and methods

This study aims to reconstruct changes in the spatial distribution and overall abundance of land cover types in the HHL during defined archaeological periods. Four 500-year time windows were chosen that represent key archaeological time periods and include a number of pollen records (details below): the late Mesolithic (4750–4250 BCE), middle Neolithic (3350–2850 BCE), early Bronze Age (2350–1850 BCE), and Iron Age (800–300 BCE) (see ESM 1 for details). The MSA is an appropriate means of reconstruction for this study due to its ability to provide both spatially explicit and quantified land cover reconstructions within an equifinal context (see Bunting et al. 2018; Farrell and Bunting 2018). The MSA was implemented using LandPolFlow and associated software packages (Middleton unpublished; Bunting and Middleton 2005; Bunting et al. 2018).

We use the term *'scenario'* to refer to a single possible map of past land cover generated by the software and refer to the total range of scenarios produced by a single LandPolFlow run as a *'swarm'*. A *'run'* of the analysis is controlled by a script (see ESM 1 for example) which informs how the software constructs landscape scenarios and specifies the parameter space for a '*scenario swarm*'. To choose between scenarios, a '*total fit*' score is used (the sum of all individual fit scores calculated between a given scenario's simulated pollen assemblages and the actual pollen assemblages from the time window; see below), and all scenarios achieving a 'good fit' with the pollen targets are referred to as the '*good fit swarm*'. '*Good fit*' scenarios are defined as those where the average fit score (as explained below) per site is below 25. A set of replicated scenarios based on one specific combination of model parameters is known as a '*family*' (members of a 'family' differ only due to the random placement of landscape elements). '*Fit*' is defined via a statistical measure of difference between the pollen assemblage from a sedimentary sequence (the '*target*' assemblage) and the simulated pollen signal for the same location under a particular scenario. '*Total fit*' is the sum of fit scores for all pollen assemblage locations included in the analysis for a particular time window. We calculated the fit scores using the squared chord distance (scd) used in other palaeoecological reconstruction approaches such as the Modern Analog Technique (Overpeck et al. 1985), which gives values between 0 (indicating identical assemblages) and 200 (where assemblages have no taxa in common). Wahl (2004) has shown that values of 25 or below indicate a good match between pollen assemblages from similar vegetation communities, therefore this is the value we chose to use to define a good fit between the simulated and empirical pollen assemblage at each individual site. A detailed explanation of the methods used in this study are presented as ESM 1. The results section entitled 'Iron Age Land Cover Reconstruction' provides a step-by-step example of the workflow for the Iron Age time window.

Step 1: selecting pollen records from the study region

Eleven pollen records covering at least one of the required time windows were identified from the literature for use within the MSA (Fig. 2). Radiocarbon chronologies were re-modelled in OxCal using IntCal13 to standardise the records and group pollen assemblages into the chosen time windows (see ESM 2 for individual age models and a description of the chronological methods). The 500-year bins were selected to allow the inclusion of a sufficient number of pollen records. To be included in a time window, each pollen record had to contain at least three samples within that time window, ensuring a minimum base pollen sum of 900 grains, reducing counting uncertainty. An important source of uncertainty when comparing time windows is that the available pollen records sample different sedimentary environments and landscape units in different time windows. In the late Mesolithic, for example, mire formation was beginning in the central area of the HHL now covered by Hatfield Moors (Chapman and Gearey 2013), most likely as small fen pools among wet woodland, and pollen records are representative of these environments, whilst by the Iron Age the pollen assemblages mainly come from extensive raised mire complexes. Consequently, each reconstruction is triangulated against a different set of sampling sites (Fig. 2) with differing spatial sensitivities.

Step 2: choosing which land cover elements to reconstruct (taxa, communities)

Taxon selection was based on abundance in the pollen dataset, the value of the taxon as an indicator of particular vegetation communities, and the availability of dispersal and deposition model parameters, notably Relative Pollen Productivity and fall speed (Mazier et al. 2012). The 15 most abundant taxa in the pollen dataset were included in the reconstructions (Table 1) and selection criteria are explained in more detail in ESM 1.

Table 1 The ecological community compositions used with the multiple scenarios approach reconstruction

Pollen taxon	Community composition (%)																	
	Wet woodland 1	Limeash	Birch	Pasture	Oakwood	Hazel	Cropland	Mire	Marsh	Wet woodland 2	Limewood	Pine wood	Limeash 2	Managed woods	Wetgrass	Reedbed	Disturbed ground	Fallspeed (m/s)	Relative Pollen Productivity
Quercus		15			50					8				15				.035	5.83
Corylus avellana-type	2.5				25	50				8			15	15				.025	1.99
Alnus glutinosa	25									25								.021	9.07
Betula	2.5		30							2.5								.024	3.69
Tilia		60									30		60	15				.032	0.80
Poaceae				70				20	30						70	30	15	.035	1.00
Plantago lanceolata				3													3	.029	2.02
Rumex acetosa-type				3													3	.018	1.455
Salix	3									3								.022	1.41
Cerealia-type							70											.060	1.63
Secale cereale							20											.060	3.02
Fraxinus excelsior		15											15					.022	1.03
Cyperaceae								15	50						15	15		.035	.887
Calluna vulgaris								20								5		.038	1.233
Pinus sylvestris												50						.031	5.96

The communities comprise specific taxa in varying abundances derived from ecological literature (Rackham 1980; Rodwell 1991) and are expressed as percentage land cover measured by vertical projection. pollen dispersal and deposition model parameters are sourced from Mazier et al. (2012); relative pollen productivities (RRPs) used are averages of all three datasets presented by Mazier et al. (2012)

Step 3: identifying the main environmental constraints on past vegetation distribution

Three categories of environmental constraint are considered most relevant to the HHL: substrate, topography and palaeohydrology (see ESM 1 for more explanation). These constraints are incorporated into the model in the form of static maps (i.e. displaying no changes through time).

Differences in substrate were incorporated into the model using two grids, the bedrock geology and the surficial (Quaternary) geology, both derived from British Geological Survey SHAPE geospatial data provided by EDINA Digimap at a scale of 1:10,000 (see ESM 1 for more detail).

Topography was included via a Digital Terrain Model (DTM) of modern elevations derived from 'Ordnance Survey Terrain 5 DTM' geospatial data supplied by EDINA Digimap at a scale of 1:10,000 (see ESM 1 for full reference and access information). The range of elevation change within the area chosen for MSA analysis is relatively small (from −12.91 m to 163.94 m) and there are a number of known processes which have significantly altered the elevation over the course of the Holocene, including RSL rise, changing groundwater table levels and human land management (van de Noort and Ellis 2000). In particular, peatland (mire and floodplain) development is likely to have impacted localised elevation over time. Elevation across the peatlands was significantly different in the relatively recent past, with historical values of up to 8 m of peat depth recorded for Thorne Moors (Heathwaite 1994). However, at the landscape scale we have assumed that relative elevations remained broadly similar through time and although the actual altitude values used to generate reconstructions at different points in time are not exact, the spatial patterns produced should be similar.

Palaeohydrology is the most difficult environmental constraint to quantify due to local complexity in processes affecting the physical environment over time and due to human activity. These processes include changing rates of RSL and position of hydrological base levels; extensive paludification both around river basins and through the formation of raised mires on interfluves; changing river patterns and alluviation; appearance and infilling of meres; human modification and management of the drainage network; warping (a process of land improvement which increases the land height through controlled deposition of river sediment); and shrinkage of sediments following drainage for agriculture, see Gaunt (2021).

The primary driver of land cover dynamics is changes in RSL, with secondary influences arising from river alluviation (primarily caused by increased sediment input into rivers due to soil erosion following prehistoric woodland clearance), agricultural practices, and peat extraction (Buckland and Sadler 1985; Mansell 2012).

The pattern of baseline Holocene RSL change is reasonably well constrained for the Humber estuary (Best et al. 2022) but less is known about the extent and hydrological impacts in the HHL headwater area. Schematic palaeogeographical maps capture the sequence of hydrological changes (Mansell 2012; Metcalfe et al. 2000) but currently there is no detailed sequence of palaeogeographical maps showing the co-evolution of sedimentation, hydrology and vegetation in this region, and producing a fully detailed map of these was beyond the scope of this research. To create a set of assumptions for use in the MSA modelling, we therefore created a simple map to broadly represent the palaeohydrology of the later historic HHL (see ESM 1 for more detail). Historical maps which pre-date much of the known anthropogenic manipulation (in particular the 17th century drainage and channel alterations) were overlain onto modern maps, and channels associated with more recent activities were removed. Interpretation of LiDAR imagery was then used to map channels that are no longer active (palaeochannels). The age of many of these palaeochannels is unknown, so the hydrology layer cannot take into account the likely evolution of this landscape through time. However, it still provides a closer representation of the prehistoric landscape than the modern hydrology does. This palaeohydrology map does not, however, take into account marine incursions and associated sedimentary environments in the northwest of the region, west of the confluence of the rivers Ouse and Trent ('Marshland' on Fig. 1).

Steps 4–7: running the MSA

Once the environmental constraint grids had been prepared, the MSA was run as shown in ESM 1. The MSA uses the Prentice–Sugita model (Prentice 1985, 1988; Sugita 1993, 1994) to simulate pollen assemblages for a number of hypothetical vegetation maps produced using the environmental constraints outlined in Step 3. Scenarios were created by varying seven parameters: (i) the probability of alder occurring in low lying areas; (ii) the definition of low lying for alder placement (i.e. the height boundary); (iii) the definition of low lying (i.e. the height boundary, which could differ from the boundary for alder) for wet grassland placement; (iv) the probability of pinewoods occurring on a sandy substrate; (v) the probability of lime woods occurring on an area of alkaline bedrock; (vi) the probability of a pixel in the higher areas to the east being assigned to pasture rather than woodland; and (vii) the probability of a pixel in the higher areas to the west being assigned to pasture rather than woodland. The ranges of values tested for each parameter are given in ESM 1. Several runs of the MSA were carried out, adjusting the ranges of values tested in response to the results of previous runs (see ESM 1 for more details).

All scenarios with a per-site average fit score below 25 were considered possible 'good fit' reconstructions, as discussed above. We chose to present the results using a combination of multiple maps for each time window and summary bar charts of land cover proportions, and used an adjusted Bray-Curtis difference index to compare the proportions of the various land cover parameters found in different sets of outputs (e.g. all scenarios considered versus all scenarios with a per-site average fit score below 25). and we discuss in detail how we made those choices in the first section of the results using the example of the Iron Age time window. The Iron Age window was chosen as it includes the largest number of pollen records and, therefore, is computationally the most complex window we consider as part of this study.

Thought experiment

Several good fit scenarios from each time window were then used to explore the detectability of small-scale human activity in the landscape by the available pollen records which were collected from large wetland complexes. We added a hypothetical prehistoric settlement on the Isle of Axholme (modelled as a patch of pasture around 1 km in radius with a 100 m radius cereal field at its centre) to each scenario grid, then we used LandPolFlow to simulate the pollen assemblage at the two coring points on Hatfield Moor which have produced deep peat records (HM1 and HM2). The simulated settlement is approximately 1.6 km from the coring locations. The purpose of this simulation was not to compare the results with actual pollen counts, but to use the 'thought experiment' approach (e.g. Caseldine and Fyfe 2006; Caseldine et al. 2007; Farrell et al. 2020) to determine if and how pollen sequences from those locations might record human activity on the Isle of Axholme.

Results and interpretation

Iron age land cover reconstruction

This section presents the results of the HHL MSA reconstruction for the Iron Age time window (steps 4–7), illustrating the process and detailing the assumptions made at each stage.

Specifying scenario swarms

Nine pollen records are available for the Iron Age time window (800–300 BCE), mostly from peat cores from raised mires (Fig. 2). Using the input grids described in the methods, we carried out three sequential LandPolFlow runs; two scoping runs, where each unique combination of landscape parameters was tested in order to determine the range of landscape parameters which produced better fit land cover scenarios, and one focus run where multiple replicate land cover maps were produced for each combination of parameters that gave the better fit scenarios in the scoping runs. Analysis of the results from one run was used to determine the range of parameter values for the next. In the focus run (FR), the script included ten replicates of each land cover parameter combination which varied only in the random placement of individual pixels of land cover types within the relevant parts of the landscape. This is because pollen assemblages, both real and modelled, can be quite sensitive to the placement of individual vegetation patches in the immediate landscape around the sampled sedimentary basin (that is, within the Relevant Source Area of Pollen *sensu* Sugita 1994), where the patches are larger than the size of the sedimentary basin.

Using run outputs to identify the good fit swarm

As nine empirical pollen sites were included in the Iron Age time window, and the threshold for a good fit between simulated and empirical pollen assemblages at a single site is defined as 25, a good fit scenario for the Iron Age had a total fit score of 225 or less (i.e. an average fit score at each individual site of 25 or lower). The focusing process is shown in Fig. 3a, which displays plots of all summed fit scores, ordered from lowest to highest (best to worst) for each of the three runs–since different numbers of scenarios were created in each run, the lowest 1000 fit scores are also plotted to make comparison easier. Out of 4320 scenarios tested in the FR, 1500 produced a summed fit score < 225.0 (Fig. 3b), and these are therefore considered 'good fit' reconstructions of past land cover.

Individual pollen site results

Figure 3c shows the FR fit scores for each of the individual pollen sites from the 100 overall (summed) best fit scenarios. The variability in each plot indicates the sensitivity of the sites to the relatively small differences between these scenarios. The sites designated as Hatfield 1 and 2 (HM1 and HM2) and Goole (GM) show the least variability, whilst Hirst Courtney (HC) and Sutton Common (SC) show the most, but the differences are not large in this subsample of scenarios.

When applying the threshold of a fit score of 25 or below to indicate a good fit for an individual site, it is apparent that the empirical pollen assemblages from some of the sites are not well matched with the simulated pollen assemblages from the scenarios. The peatland cores Crowle (CM), Hatfield 1 (HM1), Hatfield 2 (HM2) and Rawcliffe (RM) all have fit scores consistently above 25 (Fig. 3c). Given the relative stability of the scores in response to variations in the wider land cover, we think it most likely that the poor fits from these sites arise because our assumptions about the composition of vegetation at and around the coring locations are incorrect. Thought experiments by Farrell et al. (2020) have demonstrated the significant impact that local wetland vegetation can have on the pollen signal from a particular site, and therefore it is important to reconstruct the local plant community at each coring point as accurately as possible. Assumptions about local vegetation composition could be improved by drawing on data from core stratigraphy and other proxies such as plant macrofossils and coleopteran remains (e.g. Smith 1985, 2002; Whitehouse 1997, 2000, 2004).

Another source of mismatch between simulated and actual pollen assemblages may arise from the parameters used to simulate the pollen counts. The estimates of Relative Pollen Productivity used here are derived from modern pollen and vegetation datasets collected from largely dry landscapes across north-west Europe, and so local variations in pollen production may occur in the specific wetland conditions at the coring points. For example, an estimate of Relative Pollen Productivity for *Alnus glutinosa* based on a modern empirical dataset from a landscape containing extensive alder carr (National Vegetation Classification community W5 see Rodwell 1991) reported a value three times higher than an estimate derived from a predominantly dry landscape (Broström et al. 2004; Bunting et al. 2005). In dryland spaces, alder likely occurred mostly in mixed stands and in isolated stream or pond side locations, whereas samples from alder carr probably reflect the higher flowering, greater deposition, or better preservation of inflorescences in these environments. Some of the poor fits derived from individual sites (e.g. Rawcliffe, RM) may be because the RPP used in this study is too low for this alder carr dominated site, meaning that alder is under-represented in the simulated pollen assemblages, thereby resulting in a poor fit with the empirical pollen assemblages from the site.

Land cover reconstructions

The FR swarm consisted of 4320 scenarios from 432 families and produced a good fit swarm of 1500 scenarios. Figure 3b shows the ranked fit scores, with an inset of the top 100 scores. Closer examination of the top ranked scenarios allows visual identification of a small number of "best fit" scenarios, separated from the next in rank order by small but distinct "steps" in the total fit score at rank 23, 10 and 3 (top three highlighted in yellow on Fig. 3b). The overall range of fit scores within the good fit swarm of 1500 scenarios is small (221.2–224.9), suggesting that there is little to

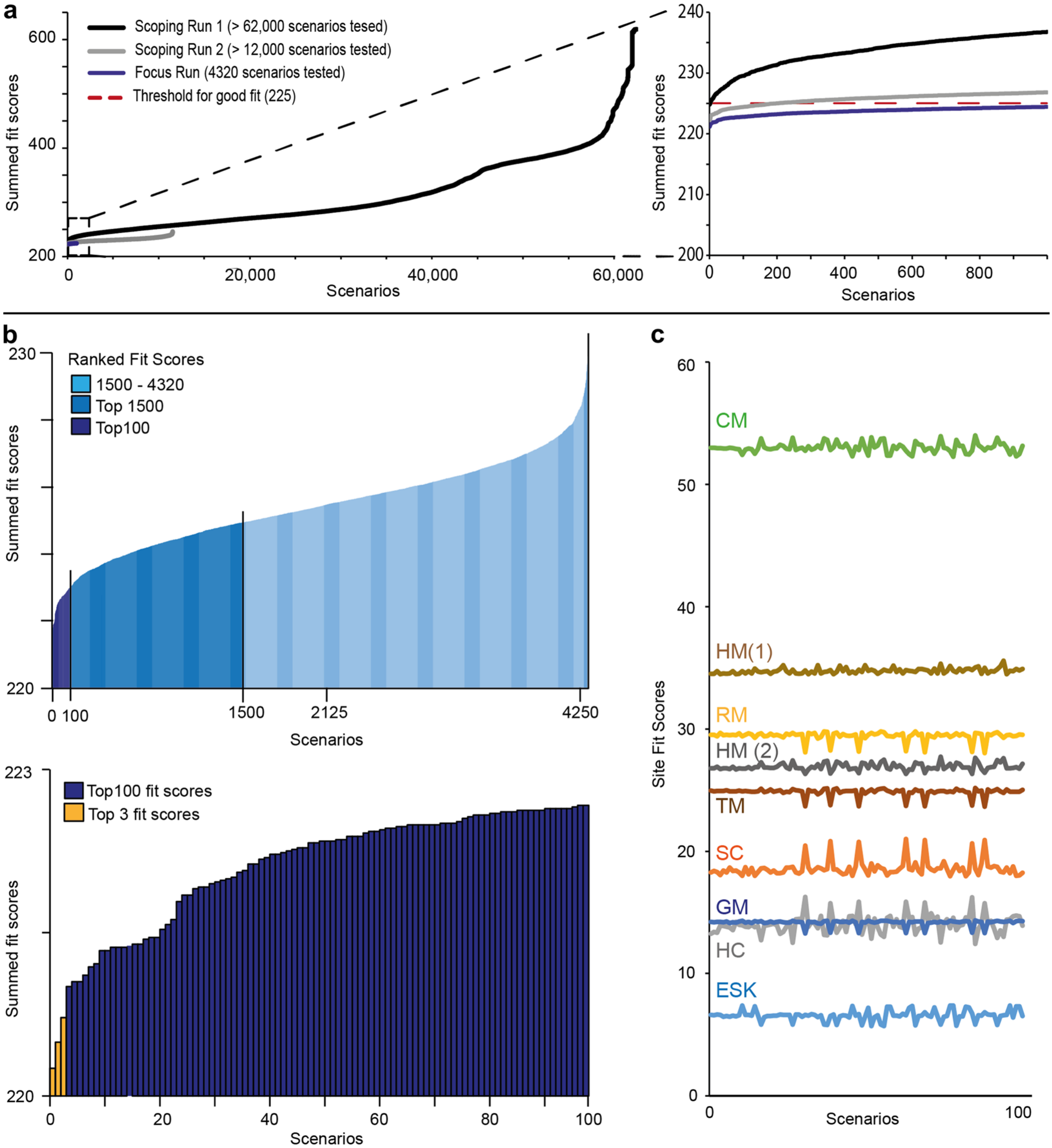


Fig. 3 Summary of fit scores for the Iron Age time window MSA runs. **a** Fit score comparisons. The left plot shows all scenarios; on the right we plot a subset of only the fit scores of the first 1000 scenarios from each run. The red dashed line marks the point at which the average fit score for a single site is 25, the threshold for considering that the scenario is a good fit. The y-axis is the summed fit score for all sites in the time window, and the x-axis is the position of scenario in ranked list of summed fit scores for all sites, ordered from lowest to highest. **b** Fit scores from the focus run scenarios illustrating the pattern of summed fit scores for all sites in the time window. The top panel shows all 4320 scenarios tested in this run, whilst the bottom panel focuses on the top 100 fit scores and highlights a stepped reduction in the summed fit scores. The best three scenarios are highlighted as yellow bars. The y-axis is summed fit score for all sites in the time window, x-axis is position of scenario in the ranked list of summed fit scores for all sites, ordered from lowest to highest. **c** Plots of fit scores for all 9 individual sites in the Iron Age time window taken from the 100 scenarios with the lowest summed fits as shown in b. The y axis shows individual fit scores for each site, x-axis is position of scenario in ranked list of summed fit scores for all sites, as in part b

distinguish these scenarios in terms of fit, and that the pollen sites included as targets are actually quite insensitive to one or more of the parameters varied in these scenarios, since the FR included ten replicates in each family and therefore at least 150 families must be present in this narrow range of fit scores. This relative insensitivity is inferred to arise from two main factors: the position of the cores within the landscape near the centre of large wetland bodies (some cores come from locations where the vegetation within 1–2 km is invariant across the swarm, and so the pollen signal can only reflect differences beyond that distance); and the relatively high contribution to the pollen signal of the main wetland plant communities present (an alder carr produces more pollen for dispersal than a *Sphagnum*-dominated mire with occasional sedges, and alder produces more pollen per unit area than a pasture or crop field). Five of the Iron Age target pollen records come from the peatlands (Goole (GM), Rawcliffe (RM), Hatfield 1 (HM1), Hatfield 2 (HM2), and Crowle (CM), and at this point in time, all of these peat bodies covered a substantial area of the landscape (Chapman and Gearey 2013). Therefore, the distance from the coring point to a different vegetation community from the local one is several hundred meters.

Two of the target sites, Eskamhorn (ESK) and Hirst Courtney (HC), come from floodplain alder carrs, developed in the wider floodplains that were created by the earliest phases of river incision during the early Holocene when RSL was substantially lower than present. By the Iron Age, these sites formed part of extensive carr areas no longer confined by the original valleys, large enough to dilute the pollen signal from non-carr vegetation. Sutton Common (SC) is the only record taken from a topographically restricted sedimentary setting where the pollen assemblage may contain a stronger signal from the dryland communities around the site. In summary, all nine sites are located in the lowlands of the HHL, and the local and/or adjacent land cover is likely to have consisted of either wet grassland or alder carr, both of which have strong pollen signals comprising a similar suite of taxa compared with other wider landscape communities. This relative lack of sensitivity means that variations in the random placement of vegetation communities within the wider landscape (e.g. where a stand of pine trees is relative to the coring point) have minimal effect on the pollen assemblage deposited at the coring point. The dominant signal in the pollen assemblages will reflect the proportion of different vegetation communities in the landscape (e.g. whether the land cover includes 5% or 35% pine stands) rather than their placement, and therefore our analysis of land cover focuses on these broad proportions.

The three best fit reconstructions identified from Fig. 3b come from different families, and so were all included as output maps (Fig. 4). Differences between the maps are small, both visually and quantitatively, but are detectable in locations away from the coring points (Fig. 4c).

Figure 5 compares the proportion of scenarios based on each of the tested values of the land cover parameters in three groups: the whole FR swarm (4320 scenarios), the 'good fit' swarm (1500 scenarios) and the 'best fit' swarm (23 scenarios). There are differences in the sensitivity of the pollen records to different parameters, as shown by the extent to which each possible value for a particular parameter occurs in the best fit swarm. This can be quantified by comparing the proportions of the various land cover parameters found in the whole FR swarm with the proportions found in the 'best fit' swarm using an adjusted Bray-Curtis difference index (DAdj); higher indices indicate larger differences in proportions of different parameter values between the whole

a

Community	F1	F2	F3
Water	0.036	0.036	0.036
Wetwoodland 1	0.186	0.184	0.178
Birch	0.019	0.019	0.019
Pasture	0.061	0.060	0.062
Oakwood	0.270	0.269	0.273
Hazel	0.018	0.018	0.019
Mire	0.100	0.100	0.100
Wetwood 2	0.016	0.015	0.015
Pine wood	0.033	0.033	0.033
Limeash 2	0.165	0.165	0.167
Wetgrass	0.001	0.003	0.001
Reedbed	0.097	0.097	0.097

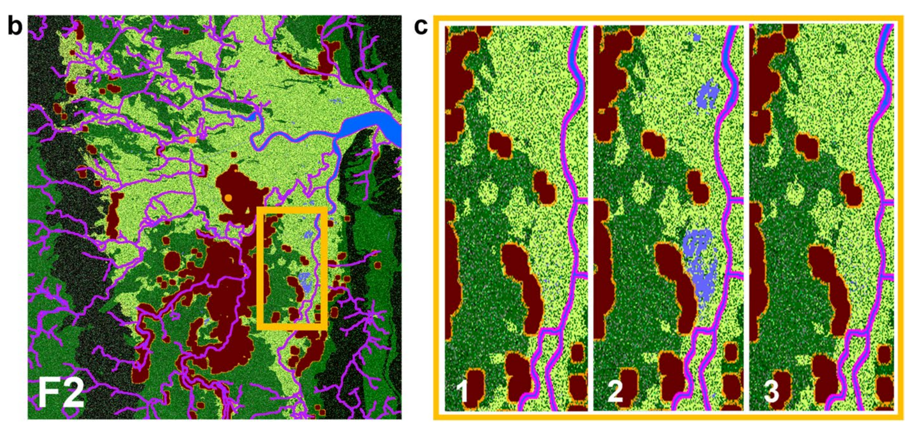


Fig. 4 The top three Iron Age land cover scenario families identified from the Multiple Scenario Approach runs in this study. A "family" is a group of scenarios with the same land cover parameters, differing only in the random placement of vegetation patches. **a** Table summarising the proportions of each community present in the whole landscape square for families 1–3 (see Table 1 for community descriptions and compositions). Values highlighted in blue font show where the proportions for families 2 and/or 3 differ from the value for family (1) **b** Mapped representation of family (2) **c** Example of a specific location (indicated by the orange rectangle on b) where reconstructed land cover differs between families

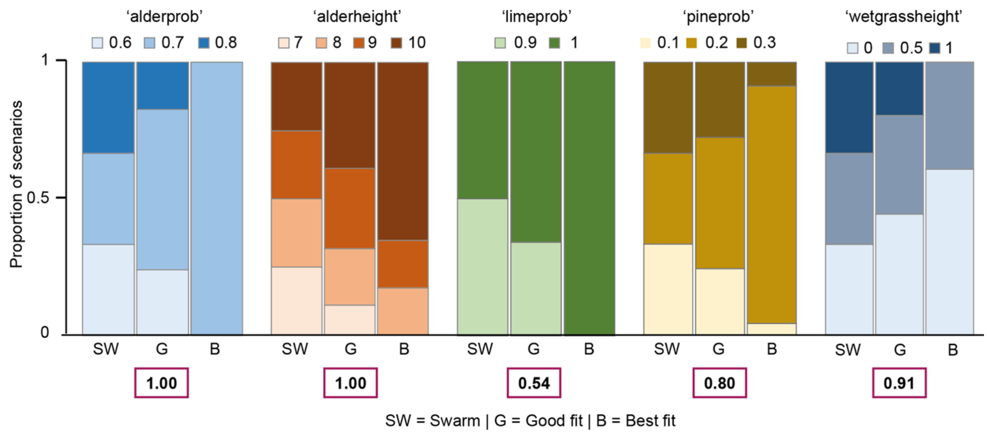


Fig. 5 Proportion of possible values of land cover parameters in groups of scenarios tested against the pollen targets from the Iron Age Focus Run: SW=whole FR swarm (all 4320 scenarios), G=good fit swarm (1500 scenarios with summed fit score<225) and B=best fit swarm (the 23 scenarios with the lowest summed fit scores). For the definition of parameters see ESM 1 Tables S3–S5. Numbers in red boxes are the adjusted Bray-Curtis indices comparing the whole FR swarm (SW) proportions with the best fit (B) proportions, a measure of the strength of selection for a single parameter in the best fit swarm (higher values show stronger selection). 'alderprob' = probability of alder occurring within the height limit defined by 'alderheight'; 'alderheight' = upper altitudinal limit for placement of alder (m a.s.l.); 'limeprob'=probability of placement of lime woodland on areas with alkaline bedrock; 'pineprob' = probability of placement of pine on areas with sandy substrate; 'wetgrassheight' = upper altitudinal limit for placement of wet grassland (m a.s.l.)

FR and 'best fit' swarms and therefore stronger selection for particular parameters in the 'best fit' swarm.

The plots show that for some land cover parameters, all best fit scenarios are based on one value for that parameter ('alderprob' and 'limeprob'), whilst for the other three land cover parameters the good fit and best fit swarms are both selecting preferentially for one value over the other. For example, 'pineprob' shows a clear preference for scenarios with 0.2 (20%) coverage of pine woodland on sandy substrates, and the Bray-Curtis index of 0.8 suggests a relatively strong selection for this coverage of pine in the 'best fit' swarm. On the other hand, whilst all of the 'best fit' swarm scenarios contain 'limeprob' of 1 (100% lime woodland on alkaline bedrock), the Bray-Curtis index of 0.54 indicates that this is not a particularly strong preference. Some parameter values are quite closely connected; for example, a similar coverage of alder carr could be achieved with low 'alderprob' and high 'alderheight' (scattered patches of carr over a larger part of the HHL, since the upper elevation limit for alder carr is set higher) or with high 'alderprob' and low 'alderheight' (dense stands of carr over a smaller part of the HHL, since the upper elevation limit for alder carr is set lower). Figure 5 shows the dominance of one combination of 'alderprob' and 'alderheight' in the best fit swarm (70% coverage, 10 m upper limit) over the others, suggesting that despite the relative insensitivity of individual sites, analysing the whole datasets enables us to explore properties of the wider landscape and identify more and less likely reconstruction scenarios.

Changes in reconstructed land cover through the prehistoric period

Three "best fit" land cover visualisations were selected for each time window, as described above. Addressing equifinality is a key strength of the MSA as it provides a clear demonstration that multiple ecologically and visually distinct vegetation mosaics can produce identical pollen signals, thereby identifying multiple hypotheses for further testing either through additional palynological work or the use of other palaeoecological proxies (Bunting and Middleton 2009; Bunting and Farrell 2018). The reconstructions themselves are shown in Fig. 6, clearly illustrating change over time, as well as the range of possible land cover maps for each time window, whilst Fig. 7 shows the proportions of each of the main land cover communities in the individual reconstructions, which better shows the range of variability in vegetation composition within the time windows. The reconstructions show a decrease in oakwood, wetwoodland 1 (alder-dominated carr) and wetgrass (seasonally flooded meadow) communities over time within the study area, an increase in mire, and that pinewood becomes more widespread during the Neolithic and Bronze Age. The presence of wetgrass communities in the south-central part of the area is marked in some of the Mesolithic and Neolithic reconstructions, in an area which later saw the expansion of raised mire from small wetland nuclei in the Mesolithic Neolithic to extensive tracts in the Iron Age.

The input pollen data includes records from the Aire valley to the north, where open vegetation associated with intertidal habitats would be expected to develop from the

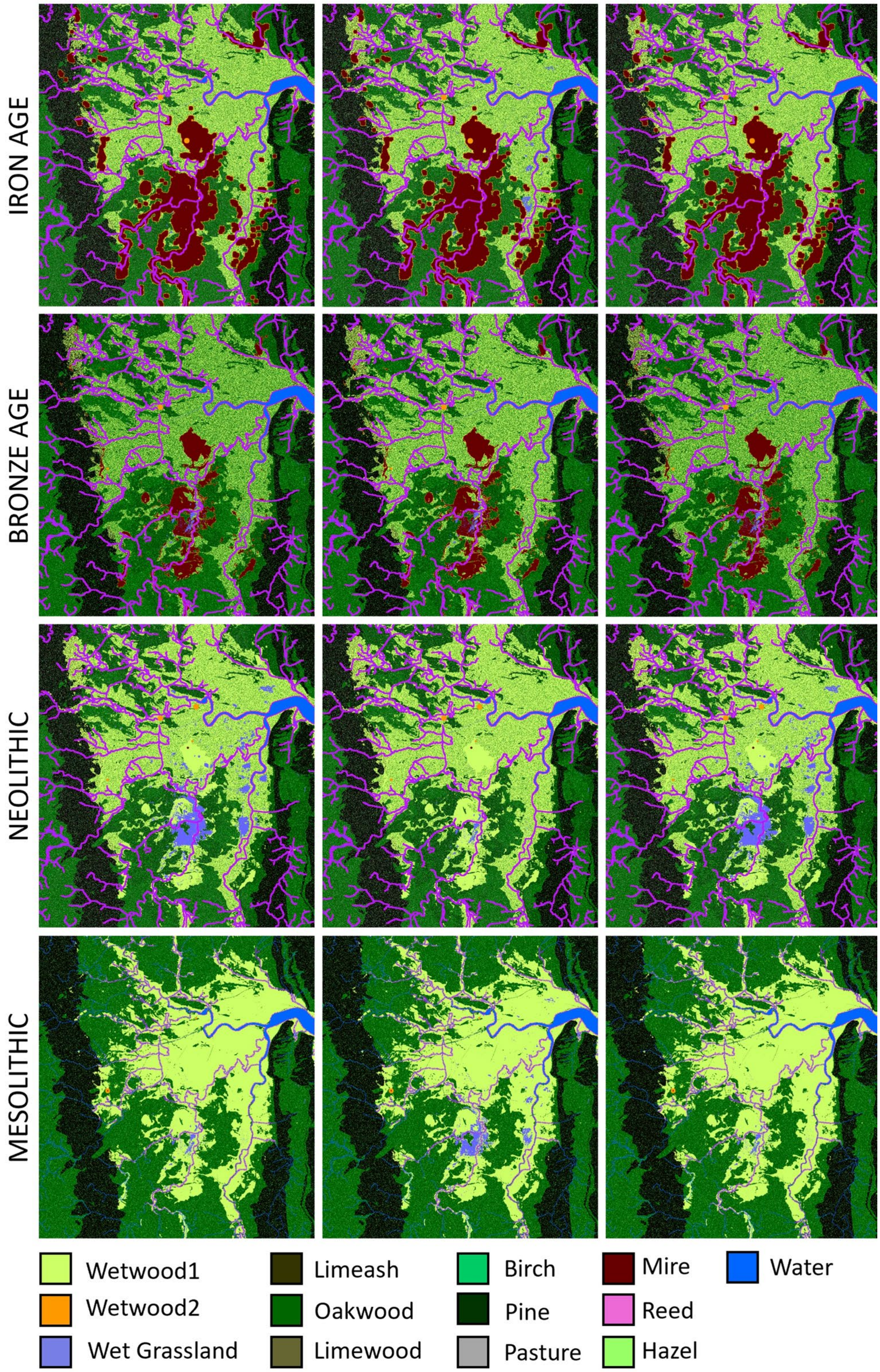


Fig. 6 The top three MSA best fit reconstructions for the four time windows, Mesolithic (4750–4250 BCE), Neolithic (3350–2850 BCE), Bronze Age (2350–1850 BCE) and Iron Age (800–300 BCE). Communities listed in the key are defined in Table 1. "wetwood1" and "wetwood2" are alder carr communities; wetwood2 includes small amounts of oak, representing a transitional community between oak woodland and true alder carr

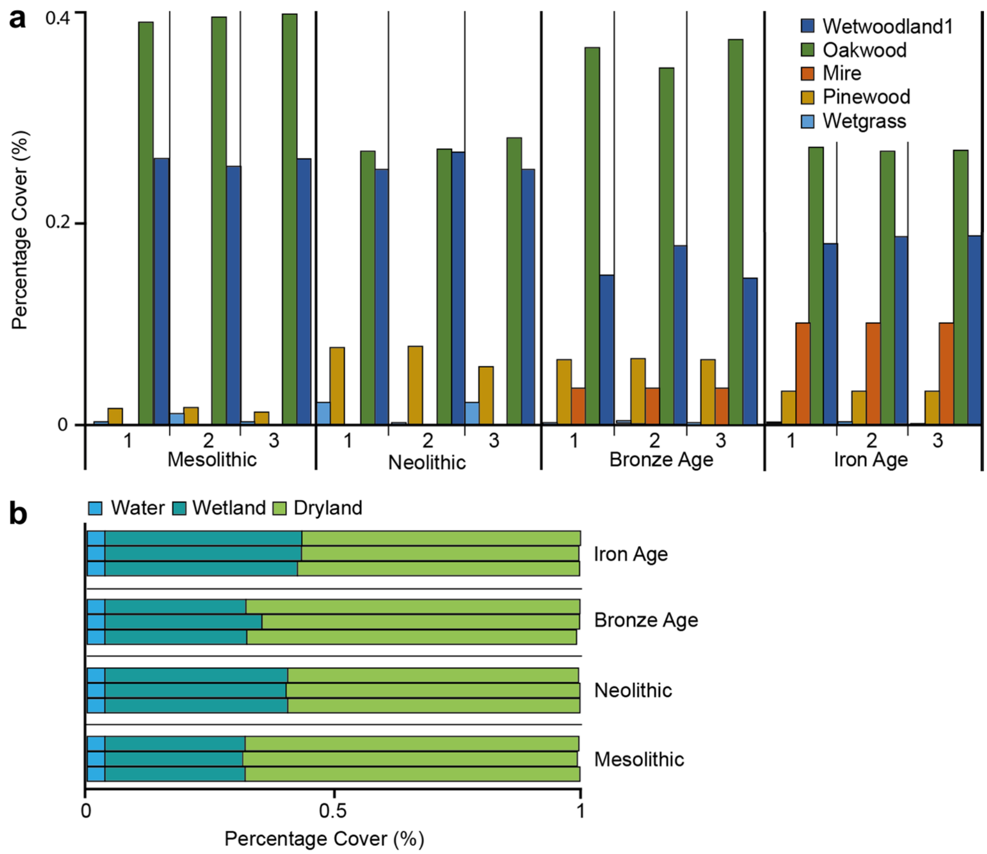


Fig. 7 Proportions of land cover within the study area extracted from the three best fit reconstructions from each of the four time windows shown in Fig. 6. **a** Examples of the main land cover types; **b** the division of wetland / dryland vegetation types

conceptual framework described in the *Iron Age landcover reconstructions* section above and schematically presented by Metcalfe et al. (2000), but these vegetation communities are not seen in the reconstructions presented here. This may be partly due to not overtly modelling a difference in openness close to rivers in different parts of the HHL, or to a lack of detail in the palaeogeography map.

Thought experiment

For each time window the three best fit landcover scenarios were selected, the hypothetical settlement added, and pollen assemblages simulated at the location of two existing pollen records (Hatfield 1 and 2). Results are shown in Fig. 8. The sum of the three anthropogenic indicator taxa (cereals, *Plantago lanceolata* and *Rumex)* is always below 0.5% of the total, despite the presence of the modelled settlement on the Isle of Axholme. These results illustrate the relative insensitivity of available pollen records to prehistoric human activity occurring at the edges of the mire, at a distance of 1–2 km from the coring points. The location of these pollen cores was determined by earlier investigators, whose research focused on establishing the environmental context of the raised bog systems, rather than detection of prehistoric human activity. Apparent low levels or absence of human activity may therefore reflect the insensitivity of the pollen records due to their locations rather than a true lack of human activity in prehistory. Thought experiments like this allow researchers to test the sensitivity of potential coring sites before investing time and money in fieldwork, radiocarbon dates and pollen counts, to ensure that they can detect potential events of interest.

Discussion

This paper has presented the application of the Multiple Scenario Approach (MSA) to four prehistoric time windows in the Humberhead Levels (HHL). Throughout the middle and late Holocene, the reconstructions show the importance of alder-dominated wet woodland. These communities thrive in waterlogged and periodically flooded conditions, with a tree canopy either dominated by alder or with a mix of wet-adapted tree species, and they formerly occupied much of the basin of former Palaeolake Humber, within floodplains and at the margins of the meres (Gaunt 1994; Fairburn and Bateman 2016). Drier areas, formed by islands of better drained or slightly elevated land within the basin, supported oak-dominated woodland within the HHL, with lime-ash and oak woodlands on surrounding hills. As the extent of raised mire during each time period was largely determined by surficial geology and previous modelling of

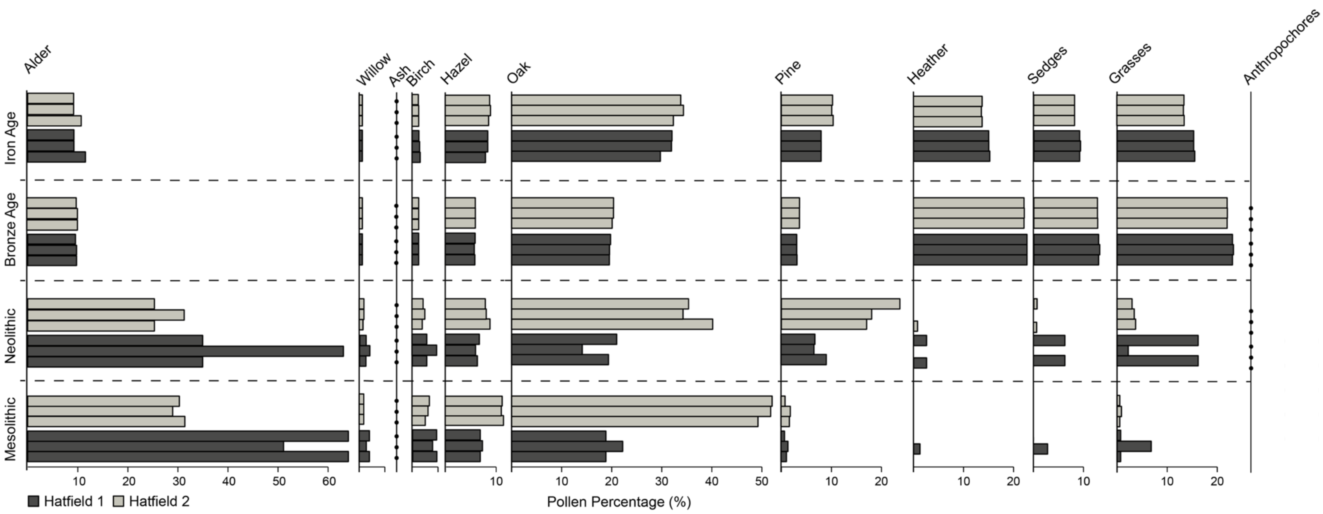


Fig. 8 Thought experiment results. Dashed lines separate the four time periods that were simulated. In each period, three Multiple Scenario Approach simulated pollen assemblages from Hatfield 1 (light grey, upper bars) and Hatfield 2 (dark grey, lower bars) are shown. Black circles indicate pollen values under 0.5%

the main mire complexes (Chapman and Gearey 2013), the extent of raised mire was not effectively explored by these reconstructions and is therefore not discussed in any detail.

Aim 1: reconstructions of past land cover for four time windows in the Humberhead levels

Figure 6 summarises the reconstructed land cover for the four time windows, late Mesolithic (4750–4250 BCE), middle Neolithic (3350–2850 BCE), early Bronze Age (2350–1850 BCE), and Iron Age (800–300 BCE). Wet grassland or fen increased in the HHL during the Neolithic, and alder-dominated carr woodland (wetwoodland 1) spread northwards compared to the Mesolithic reconstruction, coupled with an increase in reedbeds along watercourses. In the later Neolithic, raised mire patches were present, but substantially smaller than the extensive mires of later periods, creating a marked visual difference between the Neolithic reconstruction and those for the Bronze and Iron Age time windows. In the Bronze Age, carr woodland decreased in extent, due to a marked increase in oak, birch and hazel, which is then reversed in the Iron Age reconstruction. The MSA provides a much-improved understanding of the spatial structure of vegetation structure not fully captured within traditional pollen interpretations. For example, the increase in deciduous woodland noted in the Bronze Age contrasts with previous accounts which suggest that during this period there was intensive woodland clearance (Smith 1985). It is likely that clearance was happening on small higher, drier areas, such as the Isle of Axholme, Lindholme Island in the centre of Hatfield Moors, and at Wroot, an island within the wetlands to the south of Hatfield, since floodplain communities adjacent to the rivers Idle and Torne demonstrate a strong dominance of mixed alder, oak and hazel woodland (Mansell et al. 2014). Consequently, anthropogenic activities seem likely to have registered diverse impacts in the HHL, but identification of human impacts is particularly challenging in this extensive wetland landscape (Whitehouse and Karhapää 2022). The work outlined here supports previously inferred general spatial patterns but also emphasises the difficulties of identifying modest anthropogenic clearances within a wider landscape of extensive woodland cover.

Other elements of the MSA reconstructions do not fully align with previous narratives of land cover development. For example, the apparent decrease in wetland community extent during the Bronze Age time window (Fig. 7) is contrary to interpretations developed by analysts studying the records from the raised mire complexes at Thorne and Hatfield which suggest conditions in the HHL became increasingly wet, peaking in the Iron Age (Smith 1985; Whitehouse 2004). One possible explanation is that the model uses simplified community compositions; a wetter fen or marsh typically has less overall vegetation cover, therefore a lower pollen signal contribution per unit area than one experiencing lower average water level or shorter inundation periods. This could be addressed in future analyses by adding more community types to the model or by creating communities as a mosaic of open water and vegetation stands and allowing the ratio of those two elements to vary, increasing the range of possible scenarios tested. Comparison with the conceptual model of land cover within the HHL proposed by Metcalfe et al. (2000) shows obvious differences in the north-eastern parts of the map; the Metcalfe et al. (2000) palaeogeography shows extensive intertidal communities and areas of permanent inundation around the main river channels inland of the Humber Gap in the later Holocene. The reconstructions reported here were not set up to capture those communities, due partly to the lack of spatially resolved palaeogeographical mapping (see below).

The reconstructions are also highly insensitive to changes in the higher parts of the landscape within and around the HHL. Archaeological and palaeoecological evidence indicates reasonably large-scale deforestation coinciding with the intensification of agriculture between the Neolithic and Bronze Age in these areas (e.g. Mansell 2012; Mansell et al. 2014), yet the reconstructions presented here show little change in the woodland cover. The brief 'thought experiment' presented here confirms the innate insensitivity of pollen records from central locations in large wetlands to landscape transformation of a small area on the wetland margin.

The role of spatial distribution of available pollen records in constraining what aspects of past land cover can and cannot be reconstructed is apparent when the HHL results are compared with a similar MSA reconstruction of the Neolithic landscapes of the Somerset Levels (Bunting et al. 2018; Farrell et al. 2020), another extensive lowland wetland complex that experienced marine inundation in the mid-Holocene. This area also lacked detailed palaeogeography at an appropriate spatial scale which limited the reconstructions that could be developed, but in comparison with the HHL, pollen records were more widely dispersed across the study area and came from sedimentary basins towards the edges of the wetland complex as well as from central areas and river channel fills. As a result, the Somerset Levels reconstruction shows that the pollen records collectively are able to detect variations in the openness of the surrounding dryland landscape in response to changing intensity of human activity from the late Mesolithic to early Bronze Age, whereas the HHL reconstructions are largely insensitive to variations in that wider landscape due to the more central locations of the available pollen sites.

Aim 2: evaluating the impact of MSA model inputs on reconstruction of land cover in blue-green landscapes and identifying sources of uncertainty

The findings from the HHL case study identify three major sources of uncertainty in the model outputs and insensitivity of the available pollen data to land cover changes of most interest to archaeologists and others interested in the nature and extent of prehistoric human impact in blue-green landscapes: a lack of detailed palaeogeographical information, the distribution of available pollen sites, and chronology. Whilst other sources of uncertainty exist within quantitative land cover reconstruction more generally, for example the choice of RPP estimates used (since these are known to vary for a single taxon across its geographic range), and the limitations imposed by available radiocarbon chronologies, these have been discussed in detail elsewhere (e.g. Broström et al. 2008; Bunting et al. 2013; Bunting and Farrell 2022), and so here we focus on the aspects which we believe are most significant for our study area and for blue-green landscapes in general.

In blue-green landscapes like the HHL, the many wetlands create a rich sedimentary archive, but this makes it challenging to reconstruct past geographies since much of the evidence is buried beneath later sediments or human structures. The MSA reconstructions presented here constrained the possible distribution of land cover units using topography, surficial geology and hydrological network, although all three aspects of palaeogeography are poorly mapped for the time windows of interest, especially in the north-east of the study area where marine inundation adds extra complications and depth of sediment. This part of the HHL, called 'Marshland', lies between the two major river channels inland of the Humber Gap, and the Metcalfe et al. (2000) conceptual model shows extensive intertidal communities and areas of tidal inundation. This area has been subjected to substantial modification by human populations since the Iron Age through both drainage realignment and warping, and whilst there are a range of borehole records from construction activities, sediment stratigraphy is often poorly reported, lacks accurate depth information, and/or is undated.

It was beyond the scope of the project to carry out the necessary work to create 3-D, dated mapping of the underlying geographies and the complex sedimentary architecture associated with marine incursion, which would enable placement of vegetation communities within the MSA scenarios to be better constrained. Furthermore, using a very wide range of possible distribution limits for saline-influenced plant communities substantially increases the model run-time (multiple months for a single time window scoping run), but could usefully form part of future research in the region. When defining the possible communities, the open wetland community 'marsh' was used to represent all open wetland communities. However, marsh was not widespread in the north-eastern area in good fit reconstructions, although previous work (Metcalfe et al. 2000) interpreted this area as open intertidal and brackish-influenced vegetation. Either the pollen signal of this modelled community was too different from that of the actual intertidal and brackish communities to be an effective option, the previous interpretation was wrong, or the available pollen records were not picking up a detectable signal from these communities. Similar reconstructions from the Somerset Levels (Farrell et al. 2020), where pollen records were spread across the salinity gradient within the wetland complex, showed a clear increase in wetland openness in best fit scenarios from the western, marine-influenced part of the wetland complex compared with the eastern inland freshwater areas.

Site distribution also affects the ability of pollen records to clearly record the impacts of human activity on land cover, such as forest clearance or changes in land use such as crop cultivation or pastoral intensification, since many records were not located with these questions in mind. Pollen records used in the HHL MSA are taken from projects investigating activity at a specific archaeological site (Gearey et al. 2009) or recording the early stages of mire development at Hatfield Moors (Smith 1985, 2002) or tracing sea-level incursion (e.g. Hirst Courtney, Eskamholm and Hook Lane; Kirby 1999; Best et al. 2022). The age range of pollen records varies (Fig. 2), reflecting the contrasting developmental history of different sedimentary units, which leads to a clear geographical shift in the location of the empirical pollen targets from the river valleys towards the edge of the wetland area to the more centrally located moors over the time period of interest (ESM 3). As a result, the extent to which different parts of the landscape are included within the pollen source area of each site, and therefore the confidence with which they can be reconstructed, varies across the study area and between time periods.

The ability of a pollen record to "sense" vegetation in the wider landscape (often defined in terms of pollen source area) depends on multiple factors relating both to the sampled sedimentary system (its location within the wider landscape, site size, the local vegetation present at the site; Bunting 2008) and the spatial patterning of land cover in the wider landscape (Bunting et al. 2004). In largely dryland "green" landscapes where pollen records come from relatively small, discrete, well-defined wetland basins, these issues are less problematic. For example, application of the MSA to Neolithic landscapes in Orkney showed clear variations in dryland land-cover that correlated well with changes seen in the archaeological record (Bunting et al. 2022). However, in blue-green landscapes such as the HHL, basin and hydrological properties and hence pollen source areas are more complex and dynamic. Temporal changes occur in the type of vegetation (e.g. fen to raised mire or alder carr to saltmarsh), the size of the wetland, the position of the dryland-wetland interface relative to sampling location, and the structure of the land cover mosaic in the surrounding landscape (Bunting et al. 2004; Waller and Kirby 2021). The MSA can include variations in these factors in the scenarios generated, thereby incorporating changes in effective pollen source area into the reconstruction (see discussion in Farrell et al. 2020).

Pollen records available from the HHL are mostly from either floodplain peats or from the raised mires. The pollen dispersal and deposition model used for these reconstructions assumes that aerial transport of pollen dominates, but at certain points in floodplain development, pollen input from overbank events or tidal incursion may be significant. Pollen records from within alder carr environments are known to be relatively insensitive to changes in the surrounding dryland vegetation and hence difficult to interpret, especially where only one record is available from an area (Waller et al. 1999; Binney et al. 2005; Bunting 2008). Many later Holocene records available in the HHL come from raised mires, which are mostly ombrotrophic and therefore the assumption of dominant aerial pollen input is more confidently assumed.

The cored locations evolved from fen into raised mires with varying levels of *Sphagnum* dominance (Smith 1985; Whitehouse 2004); as the mire complex grew, the records will have become less sensitive to the position of vegetation patches within the wider landscape, only reflecting the proportions of different types (Sugita 1994). For the MSA, an assumption about the local vegetation present at the coring point for every pollen target location in each time window needed to be made, and whilst this was based on the recorded and interpreted sediment stratigraphy of the location or its palaeogeography wherever possible, some sources contained minimal (e.g. "peat") or no information about the local stratigraphy, which imposes a limit on how well local on-site vegetation could be included in the reconstructions. Allowing more flexibility within the communities defined (e.g. conceptualising marsh as a mosaic of open water and emergent vegetation, or raised mire as a mosaic of pure *Sphagnum* moss, *Sphagnum* with some vascular plants, and drier tussocks dominated by graminoids and ericoids, and exploring the effects of variations in the ratio and placement of those elements) in future analyses will allow the model greater scope to identify shifts within community limits, albeit at the cost of greatly increasing the number of scenarios to be tested and therefore the time required to run the models.

A third source of uncertainty arises from chronologies. The number of radiocarbon dates available for age model construction and the available level of information about the sedimentary sequence both affect the confidence with which the age model can be used to correlate between sites and assign pollen counts to each time window (see ESM 2 for details of individual site age models). A 500-year time window depth was chosen because of the relatively low resolution of some available pollen records and chronologies, but this requires the assumption that land cover was relatively stable during the whole window. Windows of 200 years were used in studies of the Neolithic of Somerset and Orkney (Bunting et al. 2018, 2022; Farrell et al. 2020), and 100-year windows used in REVEALS-based reconstructions of regional land cover (Mazier et al. 2012), show that this assumption may add another level of uncertainty to reconstructions.

MSA reconstructions can usefully generate hypotheses and identify directions for future research. In the HHL, clear research questions can be identified around improving our understanding of the stratigraphy of Marshland and the timing of switches in regime in that region, mapping the extent achieved by the raised mire complexes of the Moors before active cutting and drainage began to convert their margins to farmland, and targeted searches for pollen-preserving sediments located close to "islands" and other blue-green boundaries which are best able to capture early and local human impacts on land cover through agriculture and other land management practices. Comparison of MSA results with other datasets, such as archaeological finds from relevant periods, can also both test and enrich reconstructions of past landscape occupation.

Recommendations for future research application of the MSA in the Humberhead levels and adjacent landscapes

An important limitation on the reconstructions presented here is the current lack of spatially and temporally constrained reconstructions of palaeogeography, particularly in the Marshland area where marine incursion and the probable northwards extension of the raised mire complex are believed to have interacted dynamically throughout the later Holocene. In the MSA, palaeogeography is included in the form of input grids which map environmental factors influencing the distribution of past land cover. The parts of the landscape underlain by solid geology can be assumed to have constant topography over the mid and late Holocene, given smaller scale features such as landslides or quarries are mostly smoothed out of the grid. In areas where active deposition or reworking has taken place during or after the time window of interest, mapping the contemporaneous surficial geology and topography and the location of the main elements of the drainage network is more complicated. Whilst there is a well-founded understanding of the overall processes and changes within the HHL during the Holocene (see e.g. Metcalfe et al. 2000; Whitehouse and Karhapää 2022), and of trajectories of RSL change (Best et al. 2022), the paucity of detailed, dated and georeferenced palaeogeographic maps is a major source of uncertainty in land cover reconstruction. Other blue-green coastal landscapes in the UK where there are pollen records within a well-constrained palaeogeography, such as Romney Marsh (Waller et al. 1999; Long et al. 2006), offer a potential testing ground for developing a better integration of marine influence into landcover reconstruction in blue-green landscapes.

The results presented here are based on clearly defined and replicable grids of data, which are strictly not 'correct'. Constructing a better understanding of the dynamic river network and the landscape prior to seventeenth century drainage modifications via synthesis of existing borehole data, radiocarbon age estimates, LiDAR interpretation, and historic mapping coupled with a limited campaign of additional coring and dating of river-associated sediment, and mapping of the layering and distribution of marine and brackish-associated sedimentary units in the north-eastern part of the study area (Marshland), would greatly improve our understanding of the response of the landscape to past changes in RSL and prediction of possible futures. This is particularly relevant as current rates of global sea-level rise are around 4 mm yr^{-1}, comparable to rates in the early–mid Holocene in this region (8000–4000 ka BP; Best et al. 2022) when major expansion of brackish and freshwater wetlands occurred in response to rising base levels. Organic deposits from former floodplain and saltmarsh wetlands, many now buried under agricultural soils, are invisibly undergoing desiccation, degradation, compaction and carbon release (see Waller and Kirby 2021), leading to lowering and destabilisation of the land surface, especially following flood events or near abandoned mine workings in the southern area which are prone to subsidence. Recent severe flood events in the area have revealed the old courses of the rivers and their wetlands, and improved mapping of these deposits, especially where peats are layered with more cohesive sediments from meandering rivers, tidal intrusion or warping, could provide insights into the geographies of vulnerability to future changes.

Additional MSA investigations including brackish and saltmarsh communities would also improve understanding of prehistoric land cover patterns in the area east of the Humber Gap. Specifying the composition of communities (proportions of taxa present) requires making additional assumptions, and this can be especially problematic for dynamic, patchy vegetation types such as saltmarshes. Targeted palaeoecological investigation of marine-influenced sediments to better characterise the likely plant communities would improve reconstructions and understanding of the natural wet ecosystems, which are likely targets for future restoration and nature-based solutions in the HHL given predicted increases in flood risk from both rivers and marine incursion.

The resolution of the grids used to define the palaeogeography constrain the land cover reconstructions, since if the pixel is large relative to the size of individual plants or stands, each pixel has to be conceptualised as a patch of a community, and typically communities contain a mixture of dominant taxa. Using a smaller pixel size allows better modelling of patchy habitats but also increases the processing (memory) demands of the analysis. A 10×10 m^2 pixel allows conceptualisation of a pixel as either a mature tree or a habitat patch of a forb or dwarf shrub community, and a 2×2 m^2 pixel allows more realistic modelling of vegetation and mudflat structures in a dynamic saltmarsh or in hummock-lawn structures within a wet mire, whereas a 50×50 m^2 pixel generalises to a woodland stand, glade, or meso-scale mire community. Nesting grids of different sizes to enable finer resolution modelling of and therefore improved model sensitivity to vegetation arrangements at and around coring points, or a finer scale MSA reconstruction specifically of the vegetation structures on one or more of the raised mire complexes, where data-rich models of the basal topography (Chapman and Gearey 2013) and multiple dated pollen records are already available (e.g. Hatfield Moors; Smith 1985; Chapman and Gearey 2013), would provide useful insights into the dynamics of raised mires and their development. Methods for rehabilitation/restoration of raised mire habitats, increasingly urgently needed to help retain existing carbon stores and restore or increase carbon sinks and biodiversity within the landscape, can be enhanced by an understanding of the natural processes of mire evolution.

Wider implications for palaeoenvironmental research

Using an approach like the MSA enables translation of pollen records into estimates of the proportion and spatial arrangement of different land cover types. These reconstructions are very useful for communication of findings to non-specialists and for the development of clear, testable hypotheses for further research and improved targeting of future research effort, especially in collaboration with other specialists such as archaeologists or conservation practitioners. Developing better methods for the visual representation of uncertainty in the reconstructions will further improve communication of findings; balancing the easily readable format of a map with the need to convey the uncertainty of a model is complicated.

The workflow for application of the MSA is explained in some detail in this paper and in ESM 1, and offers a starting point for future researchers. Presenting the results in ways which are easily readable by non-specialists (from archaeologists and conservation practitioners to local land managers) without conveying false levels of confidence in the reconstructions is an ongoing challenge in MSA investigations. Clear communication of findings along with the inherent uncertainty associated with the data is a challenge across the field of environmental archaeology whenever modelling approaches are deployed. Model outputs often ‘look too good’; the maps shown in Fig. 6 are naturally viewed as actual reconstructions of what the world was like rather than ‘data visualisations’, whatever the authors’ intent (Caseldine et al. 2008; Fyfe et al. 2010). Differences between mapped reconstructions can also be hard to detect; Fig. 7 presents the areal coverage of pixels assigned to some of the main communities of interest extracted from the maps presented in Fig. 6, and an increase in pine woodland abundance between the Mesolithic and Neolithic time windows is clearly visible in the bar charts (Fig. 7) but not on the maps (Fig. 6). Combining best fit maps with bar chart summaries increases the amount of information presented but does not address the inherent uncertainties in the reconstructions. Showing a larger number of the good fit reconstructions through, for example, the summary bar charts showing the properties of good fit grids presented for the Iron Age (Fig. 5) offers an alternative way of presenting reconstructions, although it removes the spatial component which is one of the strengths of the MSA, especially where reconstructions are required for communication with other spatial sciences. The clear next step is to explore probability mapping (e.g. the probability of each pixel supporting a specific vegetation type (e.g. Pirzamanbein et al. 2014), which would lead to larger, more complex figures but would clearly show the uncertainty associated with the reconstructions. Incorporation of error estimates into mapped outputs, for example pollen counting error, chronological uncertainties, or smoothing effects on altitude grids, may also offer a means of visualising uncertainties and the range of possibilities within reconstructions.

Available pollen records to use for MSA targets are dependent on the research questions being asked by the original studies that produced the records. One of the advantages of using model-based reconstruction methods is that they enable the analyst to extract additional information and scientific value from a collection of past studies. However, the results that are possible are limited by the choices of those past researchers, which were made in the context of different research programmes and sometimes different understanding of pollen signal sensitivity. In order to develop reconstructions, the analyst needs to overtly specify assumptions underlying the interpretation of pollen records, from the relative pollen productivity of the different types counted, to the palaeogeography of the landscape of interest. MSA-type methods encourage and support exploration of the limitations of knowledge about past environments.

Adding the MSA to the palaeoecologist’s toolkit has multiple possible benefits. First, the ‘thought experiment’ type approach described here using a limited number of scenarios to explore the detectability of landcover changes of interest can improve site selection, allowing analysts to select sites and coring locations within sites which have the greatest probability of detecting hypothesised changes in land cover.

Second, simulations allow more targeted allocation of time during the data collection stage–'thought experiments' show the likely impact of a change in land cover on the pollen signal, which can be used to determine appropriate count sizes to detect differences by drawing on understanding of the interaction between pollen sum and confidence intervals (e.g. Maher 1972) to, for example, target higher counts where the anticipated difference is 1–5% and lower counts where it is greater than 25%. Thirdly, the products of MSA analysis provide a solid basis for developing hypotheses for future work, either by indicating coring locations for new pollen sequences which can be used to test or further refine the reconstructions already obtained for a landscape, or by creating hypotheses which can be tested via other palaeoecological techniques (for example, where *Tilia* is modelled as abundant in local woodlands, this should be reflected in the presence of specialist beetles in the Coleopteran record). Reconstructions highlight aspects of the landscape which are not readily visible in existing pollen records, and thought experiments can be used to test the sensitivity of potential sites to changes of interest. Incorporating quantitative elements into sample size and site selection choices is an area where palaeoecological research lags other ecological disciplines, and the MSA and thought experiment approaches are appropriate tools to address this.

This paper emphasises areas of uncertainty in the complex palaeogeographies of blue-green landscapes, and topics for future investigation. These include understanding the wetland-dryland interface areas, models of mire formation, the evolution of fluvial pathways through space and time and capturing the sedimentary complexity of underlying basins that can impact not only vegetation placement but also landscape topography and biotic and abiotic interactions. For this reason, in an ideal situation, basal palaeogeography mapping would be undertaken in advance of applying the MSA. Combining palaeogeography with land cover mapping offers the opportunity to embed hydrological catchment models within landscape modelling, not only for past understanding of landscape and land cover interactions but also for future scenario planning, informed by past land cover patterns.

Once maps of past land cover are available, they have many potential uses, providing useful long-term perspectives on the ongoing processes of landscape formation and change. They can improve understanding of the dynamic nature of land cover change and expand the possibilities considered for management and planning in multi-use landscapes, where delivery of ecosystem services and wildlife conservation need to be balanced with the needs and wants of a broader range of stakeholders and local inhabitants within a complex socioeconomic framework. Understanding the distribution of past wetlands and land cover can help us to better understand carbon storage potential, provide inputs from past scenarios with known outcomes to test and improve the earth system models of processes such as catchment hydrology and flood risk which are used to support planning for future change, and support communication with a range of stakeholders about the risks and potential futures of their landscape. Visual reconstruction of past land cover is an important component in telling the stories of a place and a powerful tool in improving public understanding and communicating the dynamic nature of place.

Conclusions

Applying the MSA in the Humberhead Levels has demonstrated both the challenges of clearly setting out assumptions about past landscapes and land cover (e.g. palaeogeography, vegetation community composition), as well as the potential for model-based reconstruction approaches to bring together data from multiple pollen records, originally produced as part of different research agendas, and add value by creating a spatially-informed reconstruction. In the HHL example, landuse was not effectively reconstructed because the available pollen records were not sensitive to changes in landuse, and simulation testing of the sensitivity of pollen records to landuse on dry areas of a blue-green system would help refine areas in which to collect new records to address this gap in future, allowing better targeting of resources. Presenting the uncertainties associated with these reconstructions is an ongoing challenge.

The reconstructions of land cover for four prehistoric time windows in the HHL largely align with existing interpretations for the overall area and highlight a present lack of understanding in the area east and south of the Humber Gap, where dated palaeoecological records are not available outside of the major river floodplains. On this basis, combined with a clearer understanding of the insensitivity of existing records to human activity on dryland areas, we propose several next steps for research in the region:

- Improving the mapping of palaeogeography, especially in the north and east, as a basis for improved reconstruction of the whole region.
- Further MSA investigation of different time frames and specific areas within the HHL where appropriate data already exist, such as Hatfield Moors.
- Using the MSA to help identify potential locations for coring sites for future investigations of human activity on the dryland 'islands' and former Lake Humber shorelines adjacent to the wetlands.

The paper also illustrates how the addition of the MSA to the palaeoecologist's toolkit can contribute to both better use of research resources through, for example, providing objective support for strategic site selection and better integration of palaeoecology into the work of other disciplines such as archaeology or landscape planning through translation of opaque stratigraphic diagrams into widely understandable formats.

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Software availability Software for carrying out the Multiple Scenario Approach is currently only available as a windows package created in Borland Delphi by Mr R. Middleton (retired), LandPolFlow. MJB is happy to share copies of the software, its manuals and sample files and training materials with anyone interested – email m.j.bunting@hull.ac.uk. An alternative software package, MSAQ, is in the final stages of preparation as a product of the 2025 PhD of T.W.B. van den Berg (van den Berg 2025). This version is created in QGIS/Python and will be available shortly as an open-source package via Github.

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of financial or commercial conflicts of interest.

References

Best L, Kirby JR, Selby K (2022) System responses to holocene relative sea-level rise and sediment supply in a macrotidal estuary. Holocene 32:1,091–1103. https://doi.org/10.1177/09596836221106971

Binney HA, Waller MP, Bunting MJ, Armitage RA (2005) The interpretation of Fen Carr pollen diagrams: the representation of the dry land vegetation. Rev Palaeobot Palynol 134:197–218. https://doi.org/10.1016/j.revpalbo.2004.12.006

Broström A, Sugita S, Gaillard M-J (2004) Pollen productivity estimates for the reconstruction of past vegetation cover in the cultural landscape of Southern Sweden. Holocene 14:368–381. https://doi.org/10.1191/0959683604hl713rp

Broström A, Nielsen AB, Gaillard M-J et al (2008) Pollen productivity estimates of key European plant taxa for quantitative reconstruction of past vegetation: a review. Veget Hist Archaeobot 17:461–478. https://doi.org/10.1007/s00334-008-0148-8

Buckland PC, Sadler J (1985) The nature of late Flandrian alluviation in the Humberhead levels. East Midl Geogr 8:239–251

Bunting MJ (2008) Pollen in wetlands: using simulations of pollen dispersal and deposition to better interpret the pollen signal. Biodivers Conserv 17:2079–2096. https://doi.org/10.1007/s10531-007-9219-x

Bunting MJ, Farrell M (2018) Seeing the wood for the trees: recent advances in the reconstruction of woodland in archaeological landscapes using pollen data. Environ Archaeol 23:228–239

Bunting MJ, Farrell M (2022) Do local habitat conditions affect estimates of relative pollen productivity and source area in heathlands? Front Ecol Evol 10:787345. https://doi.org/10.3389/fevo.2022.787345

Bunting MJ, Middleton D (2005) Modelling pollen dispersal and deposition using HUMPOL software, including simulating windroses and irregular lakes. Rev Palaeobot Palynol 134:185–196. https://doi.org/10.1016/j.revpalbo.2004.12.009

Bunting MJ, Middleton R (2009) Equifinality and uncertainty in the interpretation of pollen data: the multiple scenario approach to reconstruction of past vegetation mosaics. Holocene 19:799–803. https://doi.org/10.1177/0959683609105304

Bunting MJ, Gaillard M-J, Sugita S, Middleton R, Broström A (2004) Vegetation structure and pollen source area. Holocene 14:651–660. https://doi.org/10.1191/0959683604hl744rp

Bunting MJ, Armitage R, Binney HA, Waller M (2005) Estimates of 'relative pollen productivity' and 'relevant source area of pollen' for major tree taxa in two Norfolk (UK) woodlands. Holocene 15:459–465. https://doi.org/10.1191/0959683605hl821rr

Bunting MJ, Farrell M, Broström A et al (2013) Palynological perspectives on vegetation survey: a critical step for model-based reconstruction of quaternary land cover. Quat Sci Revi 82:41–55

Bunting MJ, Farrell M, Bayliss A, Marshall P, Whittle A (2018) Maps from Mud—using the multiple scenario approach to reconstruct land cover dynamics from pollen records: a case study of two neolithic landscapes. Front Ecol Evol 6:36. https://doi.org/10.3389/fevo.2018.00036

Bunting MJ, Farrell M, Dunbar E, Reimer P, Bayliss A, Marshall P, Whittle A (2022) Landscapes for neolithic people in Mainland, Orkney. J World Prehist 35:87–107. https://doi.org/10.1007/s10963-022-09166-y

Caseldine C, Fyfe R (2006) A modelling approach to locating and characterising elm decline/landnam landscapes. Quat Sci Rev 25:632–644. https://doi.org/10.1016/j.quascirev.2005.07.015

Caseldine C, Fyfe R, Langdon C, Thompson G (2007) Simulating the nature of vegetation communities at the opening of the neolithic on achill Island, Co. Mayo, Ireland–the potential role of models of pollen dispersal and deposition. Rev Palaeobot Palynol 144:135–144. https://doi.org/10.1016/j.revpalbo.2006.07.002

Caseldine C, Fyfe R, Hjelle K (2008) Pollen modelling, palaeoecology and archaeology: virtualisation and/or visualisation of the past? Veget Hist Archaeobot 17:543–549. https://doi.org/10.1007/s00334-007-0093-y

Chapman HP, Gearey BR (2013) Modelling archaeology and palaeoenvironments in wetlands: the hidden landscape archaeology of Hatfield and Thorne Moors, Eastern England. Oxbow Books, Oxford

Fairburn WA, Bateman MD (2016) A new multi-stage recession model for proglacial lake Humber during the retreat of the last British–Irish ice sheet. Boreas 45:133–151

Farrell M, Bunting MJ (2018) Vegetation modelling using pollen data. In: López Varela SL (ed) The encyclopedia of archaeological sciences. Wiley, Hoboken

Farrell M, Bunting MJ, Sturt F et al (2020) Opening the woods: towards a quantification of neolithic clearance around the Somerset levels and Moors. J Archaeol Method Th 27:271–301. https://doi.org/10.1007/s10816-019-09427-9

Fyfe R, Caseldine C, Gillings M (2010) Pushing the boundaries of data? Issues in the construction of rich visual past landscapes. Quat Int 220:153–159. https://doi.org/10.1016/j.quaint.2009.09.005

Fyfe RM, Twiddle C, Sugita et al (2013) The holocene vegetation cover of Britain and ireland: overcoming problems of scale and discerning patterns of openness. Quat Sci Rev 73:132–148

Gaunt GD (1994) Geology of the country around Goole, Doncaster and the Isle of Axholme. Memoir for one-inch sheets 79 and 88 (England and Wales). HMSO, London

Gaunt GD (2012) A review of large-scale man-made river and stream diversions in the Humberhead region. Yorks Archaeol J 84:59–76. https://doi.org/10.1179/0084427612Z.00000000004

Gaunt GD (2021) Quaternary geology of the Southern part of the Vale of York. Thorne and Hatfield Moors Conservation Forum, Doncaster

Gearey BR, Marshall P, Hamilton D (2009) Correlating archaeological and palaeoenvironmental records using a bayesian approach: a case study from Sutton Common, South Yorkshire, England. J Archaeol Sci 36:1477–1487

Githumbi E, Fyfe R, Gaillard M-J et al (2022) European pollen-based REVEALS land-cover reconstructions for the Holocene: methodology, mapping and potentials. Earth Syst Sci Data 14:1581–1619. https://doi.org/10.5194/essd-14-1581-2022

Hamilton CA, Kirby JR, Lane TP et al (2019) Sediment supply and barrier dynamics as driving mechanisms of holocene coastal change for the Southern North sea basin. Quat Int 500:147–158

Heathwaite AL (1994) Hydrological management of a cutover peatland. Hydrol Process 8:245–262

Jones P (1995) Two early Roman canals? The origins of the turnbridgedike and Bycarrsdike. J Rly Canal Hist Soc 31:522–531

Kirby JR (1999) Holocene floodplain vegetation dynamics and sea-level change in the lower Aire valley, Yorkshire. Unpublished PhD thesis, University of Hull, Hull

Li Z, Wang Y, Herzschuh U, Cao X, Ni J, Zhao Y (2022) Pollen-based biome reconstruction on the Qinghai–Tibetan plateau during the past 15,000 years. Palaeogeogr Palaeoclimatol Palaeoecol 604:111190. https://doi.org/10.1016/j.palaeo.2022.111190

Long AJ, Innes JB, Kirby JR, Lloyd JM, Rutherford MM, Shennan I, Tooley MJ (1998) Holocene sea-level change and coastal evolution in the Humber estuary, Eastern England: an assessment of rapid coastal change. Holocene 8:229–247

Long AJ, Waller MP, Plater AJ (2006) Coastal resilience and late holocene tidal Inlet history: the evolution of Dungeness foreland and the Romney marsh depositional complex (UK). Geomorphology 82:309–330

Maher LJ Jr (1972) Nomograms for computing 0.95 confidence limits of pollen data. Rev Palaeobot Palynol 13:85–93

Mansell LJ (2012) Floodplain-mire interactions and palaeoecology: implications for wetland ontogeny and Holocene climate change. Doctoral dissertation, Queen's University Belfast, Belfast

Mansell LJ, Whitehouse NJ, Gearey BR, Barratt P, Roe HM (2014) Holocene floodplain palaeoecology of the Humberhead Levels; implications for regional wetland development. Quat Int 341:91–109

Mazier F, Gaillard M-J, Kuneš P, Sugita S, Trondman A-K, Broström A (2012) Testing the effect of site selection and parameter setting on REVEALS-model estimates of plant abundance using the Czech quaternary palynological database. Rev Palaeobot Palynol 187:38–49

McCoy MD, Ladefoged TN (2009) New developments in the use of Spatial technology in archaeology. J Archaeol Res 17:263–295. https://doi.org/10.1007/s10814-009-9030-1

Menotti F, O'Sullivan A (eds) (2012) The Oxford handbook of wetland archaeology. Oxford University Press, Oxford. https://doi.org/10.1093/oxfordhb/9780199573493.001.0001

Metcalfe SE, Ellis S, Horton BP et al (2000) The holocene evolution of the Humber estuary: reconstructing change in a dynamic environment. Geol Soc Spec Publ 166:97–118. https://doi.org/10.1144/GSL.SP.2000.166.01.07

Moore PD, Webb JA, Collinson ME (1991) Pollen analysis, 2nd edn. Blackwell, Oxford

Natural England (2014) National Character Area (NCA) Profile: 39 Humberhead Levels (NE339). https://publications.naturalengland.org.uk/publication/1843305

Overpeck JT, Webb T III, Prentice IC (1985) Quantitative interpretation of fossil pollen spectra: dissimilarity coefficients and the method of modern analogs. Quat Res 23:87–108

Pirzamanbein B, Lindström J, Poska A et al (2014) Creating spatially continuous maps of past land cover from point estimates: a new statistical approach applied to pollen data. Ecol Complex 20:127–141

Prentice IC (1985) Pollen representation, source area and basin size: towards a unified theory of pollen analysis. Quat Res 23:76–86

Prentice IC (1988) Records of vegetation in time and space: the principles of pollen analysis. In: Huntley B, Webb T III (eds) Vegetation history. Kluwer Academic, Dordrecht, pp 17–42

Rackham O (1980) Ancient woodland: its history, vegetation and uses in England. Edward Arnold, London

Richer S, Gearey B (2017) The medicine tree: unsettling palaeoecological perceptions of past environments and human activity. J Soc Archaeol 17:239–262. https://doi.org/10.1177/1469605317731013

Rodwell JS (ed) (1991) British plant Communities, vol 1: woodlands and scrub. Cambridge University Press, Cambridge

Smith B (1985) A palaeoecological study of raised mires in the hurnberhead levels. Unpublished PhD thesis, University of Wales, Wales

Smith BM (2002) A palaeoecological study of Raised mires in the Humberhead levels. BAR British Series, vol 336. British Archaeological Reports, Oxford

Southall HR, Burton N (2004) GIS of the ancient parishes of England and wales, 1500–1850 [data collection]. UK Data Service. SN:4828. https://doi.org/10.5255/UKDA-SN-4828-1

Sugita S (1993) A model of pollen source area for an entire lake surface. Quat Res 39:239–244

Sugita S (1994) Pollen representation of vegetation in quaternary sediments: theory and method in patchy vegetation. J Ecol 82:881–897. https://doi.org/10.2307/2261452

Sugita S (2007a) Theory of quantitative reconstruction of vegetation I: pollen from large sites REVEALS regional vegetation composition. Holocene 17:229–241. https://doi.org/10.1177/0959683607075837

Sugita S (2007b) Theory of quantitative reconstruction of vegetation II: all you need is LOVE. Holocene 17:243–257. https://doi.org/10.1177/0959683607075838

Trondman A-K, Gaillard M-J, Mazier F et al (2015) Pollen-based quantitative reconstructions of holocene regional vegetation cover (plant-functional types and land-cover types) in Europe suitable for climate modelling. Glob Chang Biol 21:676–697. https://doi.org/10.1111/gcb.12737

Van de Noort R, Davies P (1993) Wetland heritage: an archaeological assessment of the Humber wetlands. Humber wetland project. School of Geography and Earth Resources University of Hull, Hull

Van de Noort R, Ellis S (2000) Fifth Annual Report of the Humber Wetlands Survey (1998–99). University of Hull, Centre for Wetland Archaeology, Hull

Van den Berg TWB (2025) Refining reconstruction: discovering the capabilities and limitations of pollen analysis using the multiple scenario approach. Doctoral Thesis, University of Hull, Hull

Wahl ER (2004) A general framework for determining cutoff values to select pollen analogs with dissimilarity metrics in the modern analog technique. Rev Palaeobot Palynol 128:263–280

Waller M, Kirby J (2021) Coastal peat-beds and peatlands of the Southern North sea: their past, present and future. Biol Rev 96:408–432. https://doi.org/10.1111/brv.12662

Waller MP, Long AJ, Long D, Innes JB (1999) Patterns and processes in the development of coastal mire vegetation: multi-site investigations from Walland Marsh, Southeast England. Quat Sci Rev 18:1419–1444

Waller M, Carvalho F, Grant MJ, Bunting MJ, Brown K (2017) Disentangling the pollen signal from Fen systems: modern and holocene studies from Southern and Eastern England. Rev Palaeobot Palynol 238:15–33. https://doi.org/10.1016/j.revpalbo.2016.11.007

Whitehouse N (1997) Silent witnesses: an 'Urwald' fossil insect assemblage from Thorne Moors. Thorne Hatfield Moors Papers 4:19–54

Whitehouse NJ (2000) The evolution of the holocene wetland landscape of the humberhead levels from a fossil insect perspective. Doctoral dissertation, University of Sheffield, Sheffield

Whitehouse NJ (2004) Mire ontogeny, environmental and climatic change inferred from fossil beetle successions from Hatfield Moors, Eastern England. Holocene 14:79–93. https://doi.org/10.1191/0959683604hl691rp

Whitehouse NJ, Karhapää J (2022) Discovering Hatfield Chase and the Isle of Axholme. North Lincolnshire Council, Scunthorpe

Winterbottom SJ, Long D (2006) From abstract digital models to rich virtual environments: landscape contexts in Kilmartin Glen. Scotl J Archaeol Sci 33:1:356–1367. https://doi.org/10.1016/j.jas.2006.01.014